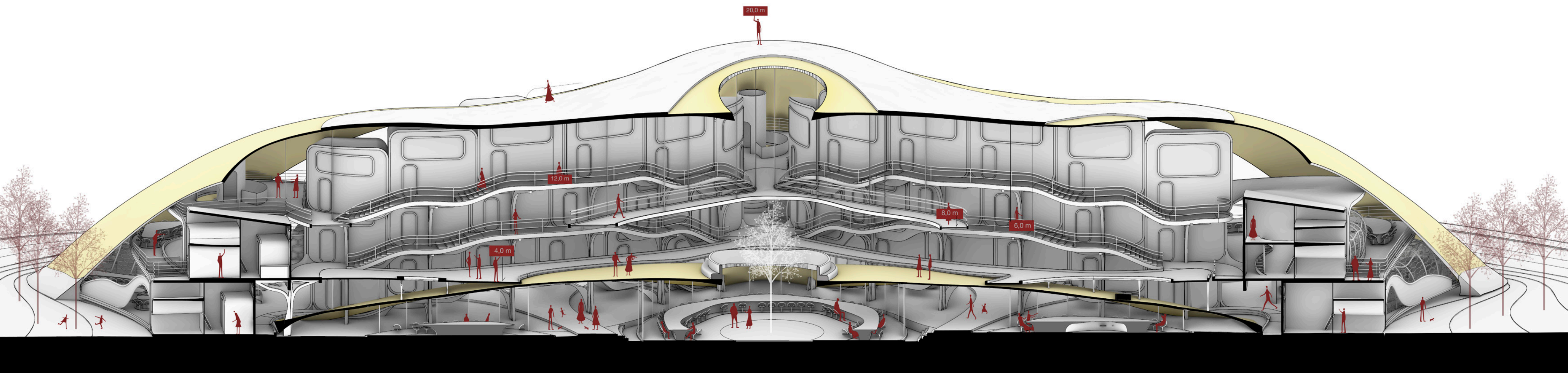
THE STUDENT NEST

PARAMETRIC EXPLORATIONS OF A PERFORMANCE-ORIENTED DESIGN



POLITECNICO DI TORINO - FACULTY OF ARCHITECTURE
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ABSTRACT

We are now experiencing the Fourth Industrial Revolution, and in this scenario, multidisciplinarity is imperative. Themes such as sustainability can be solved in a variety of ways by making effective use of digital parametric tools for architectural conception. The present work is an extensive research that converges into an explorative project with real demands. In this research, relevant themes are addressed for a design that uses digital techniques to generate optimized forms, directed to a specific performance. The structural behavior was prioritized as a starting point, anchored in a biomimetic approach as well as in the structural theory of purely compressed structures. In this theme, Form Finding methods are discussed, both digital and pre-digital, as a process to generate optimized forms.

Generating complexity is virtually a resource that has been available to architects since the 1990s, but the materialization of complex forms is challenging, and it is in this challenge that one finds the fascination before such forms. Digital manufacturing has narrowed the gap between virtuality and reality and, still in constant development, is revolutionizing the area of civil construction.

In the second part of the work a project is developed, putting into practice the previous theory. The project, proposed for the context of the University of Brasilia, is a student housing in which the university is an experimental stage for new techniques of generation and execution of complex forms in architecture. In the project, parametric tools were used for the generation of all elements, structural or not, as well as for bioclimatic analysis and application of construction standards. Concluding the theory, the design has an experimental and probative character of the themes previously worked on in the theoretical part.

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Introduction - Thesis Format

The present work aims to present a project in which its conception relies on contemporary Digital Tools. It was thought to be extremely necessary to first investigate the topic through an extensive research on this subject in order to arrive at a consistent and sustainable outcome. The logical sequence of the thesis is based on essential aspects to be incorporated into the final design. The wise use of digital tools since the early steps of design showed to be extremely efficient in the morphogenesis of a sustainably optimized creational process, incorporating structural knowledge with architectural expression.

Part one

1st chapter

In that way, the first part of the research is an historical analysis of the role of architects and their field of knowledge. The fields of research in architecture are changing, as now we walk towards multidisciplinarity, similar to what was the reality at the beginning of architecture's history. The reasons for such phenomenon are explained in the following chapters.

2nd chapter

Before going deeper into the subject of parametric architecture provided by digital tools, the second chapter consists of a brief introduction about structural systems and the importance of mastering it in the architectural field. This part is based on the atemporal book of the German architect Heino Engel. In order to reach an elegantly sustainable result, it is essential to understand how structural systems work and generate them simultaneously with the architectural conception. With digital tools, the design process is highly integrated, and the optimal use of materials is a consequence of the right conception of structural systems.

3rd chapter

The third chapter introduces the general aspects architecture based on parameters and the role of digital tools in this kind of design approach. In order to integrate structural and architectonical aspects into design, digital tools have been fundamental, and, through the manipulation of parameters, the designer can create a performance-oriented architecture with instantaneous feedback. Although digital architecture shifts the architects' power over their creation, it also demands from them a whole new range of expertises. The architect, to have full control over the holistic process of creation with parametric architecture, must deal with subjects like architectural expression, material properties, software manipulation and structural design.

4th chapter

Following the discussion, a performance-oriented design is often, if not always, linked to a material-based approach. In the fourth chapter, the discussion of form-finding as a morphogenic design method is presented. Although the development of digital tools has shifted form-finding processes, they exist since the pre-digital era, based on Form-Active structural systems. It has its grounds on the interpretation of parameters imposed by natural constraints, such as physical and chemical properties of materials and the effect of gravity upon them.

5th chapter

Another result of technological advancements is the rise of Biomimicry. The subject to be developed in the fifth chapter regards the observation and interpretation of Nature's physical principles applying them into the artificial world. Cutting edge technology has improved possibilities of extracting and interpret data, assimilating them into new technologies. Using this approach, innovative materials and assembling methods are being conceived, meaning a new era for architecture.

6th chapter

The gap between all the advantages provided by digital tools and their fabrication into the physical world has been a significant issue in the last years. Digital fabrication methods are improving and, by doing so, are narrowing the gap between reality and virtuality. The sixth chapter is about materialization and fabrication processes of the twenty-first century's new architecture, considering the tectonic approach of the contemporary's design materiality and fabrication techniques.

Part Two

The project's proposal is presented after discussing all pertinent topics in order to understand it. The second part presents the project's goals, context, drawings, diagrams and structural morphogenesis. Since the early steps of the design process, the use of digital tools is primordial to reach an integrated approach of architectural expression and structural optimization.

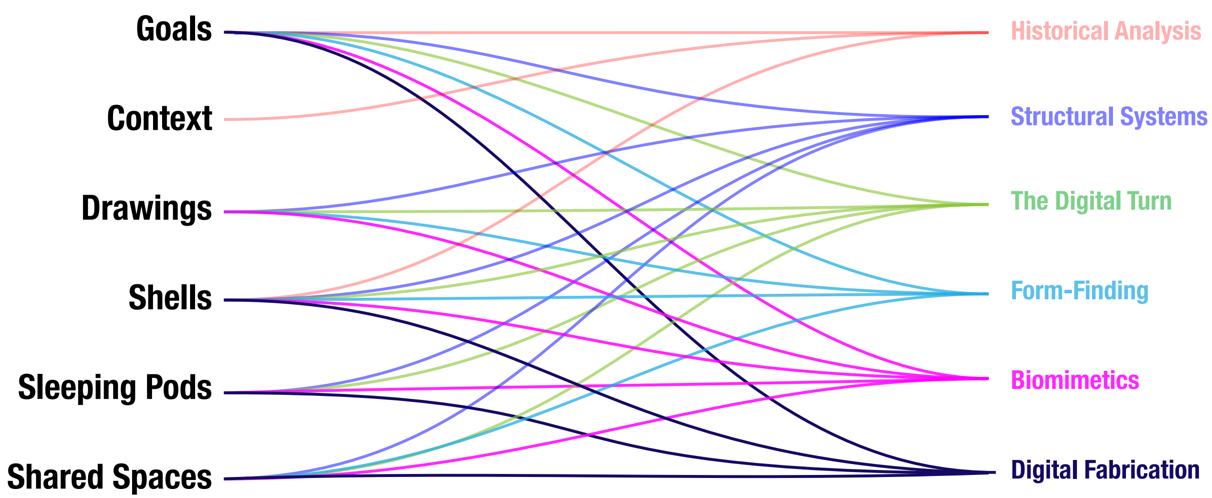
It aims the use of digital tools to reach beyond the mere architectural expression, not that this is not important, but such tools, when well used, can be powerful allies for a socially, environmentally and structurally optimized architecture.

Discussing the goals is the aim of the seventh chapter, the first of the second part and afterwards, in the eighth chapter the context is presented and analysed. The city of Brasilia is a delicate scenario to work with because it is listed as a Cultural Heritage of Humanity by UNESCO, and for this reason it was thought that special attention should be given to its urban ensemble. Approaching the place to be worked on, this chapter also deals with the peculiarities of the articulation of the campus of the University of Brasilia and the city.

Chapter 9 presents the project design, drawings and diagrams. These drawings start from the macro scale, relating the building to its immediate surroundings.

The use of biomimetic strategies and morphogenesis of complex structures in active form are explained and detailed in chapter 10. Putting into practice the theory discussed in the first part of this work, this chapter is where the application of digital tools for the generation and optimization of structures is exemplified.

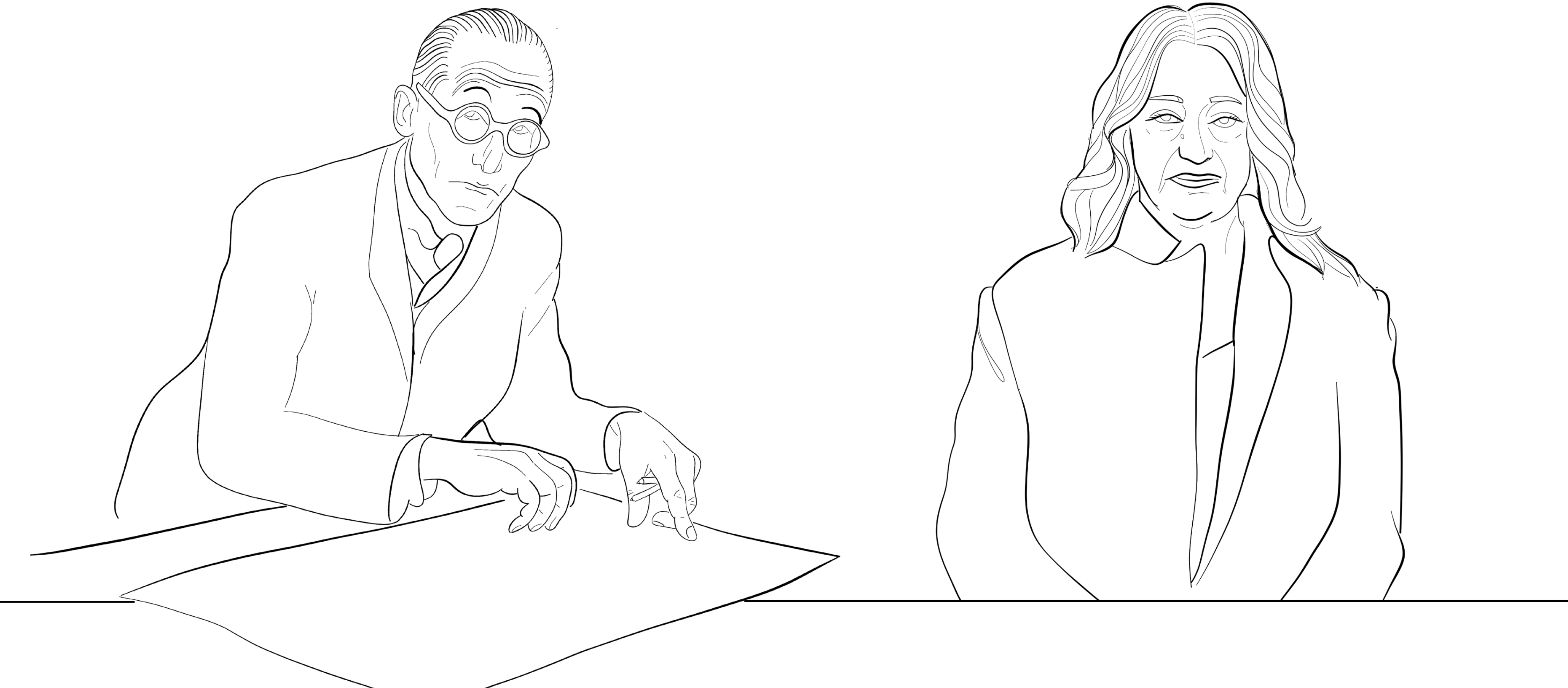
Deepening the counterpoint between public and private spaces, chapters 11 and 12 deal with the duality between the minimum space necessary for privacy - the sleeping pods - and the abundance and openness of shared spaces.



PART ONE

THE THEORY

Historical role of architects and architecture



1. Historical Analysis

The Role of Architects and Architecture

From Renaissance until the Digital Turn

The Historical Analysis is a brief review of the historical role of architecture and architects. Shortly will be pointed out the main changes through Renaissance, Baroque, Neo-Classical, Modernism and Post-Modernism, linking them to the current reality, the Digital Era. A brief highlight about the free-form in Modern architecture of Oscar Niemeyer is worth mentioning to contextualize the project to be proposed in the last chapter of the present work. The importance of these analyses is to verify changings in the role of architects and their field of domain. In Renaissance, the architect, as a professional, was linked with the rise of a wide range of expertise's fields, such as biology, physics and mathematics, mainly connected Nature's proportions and observations.

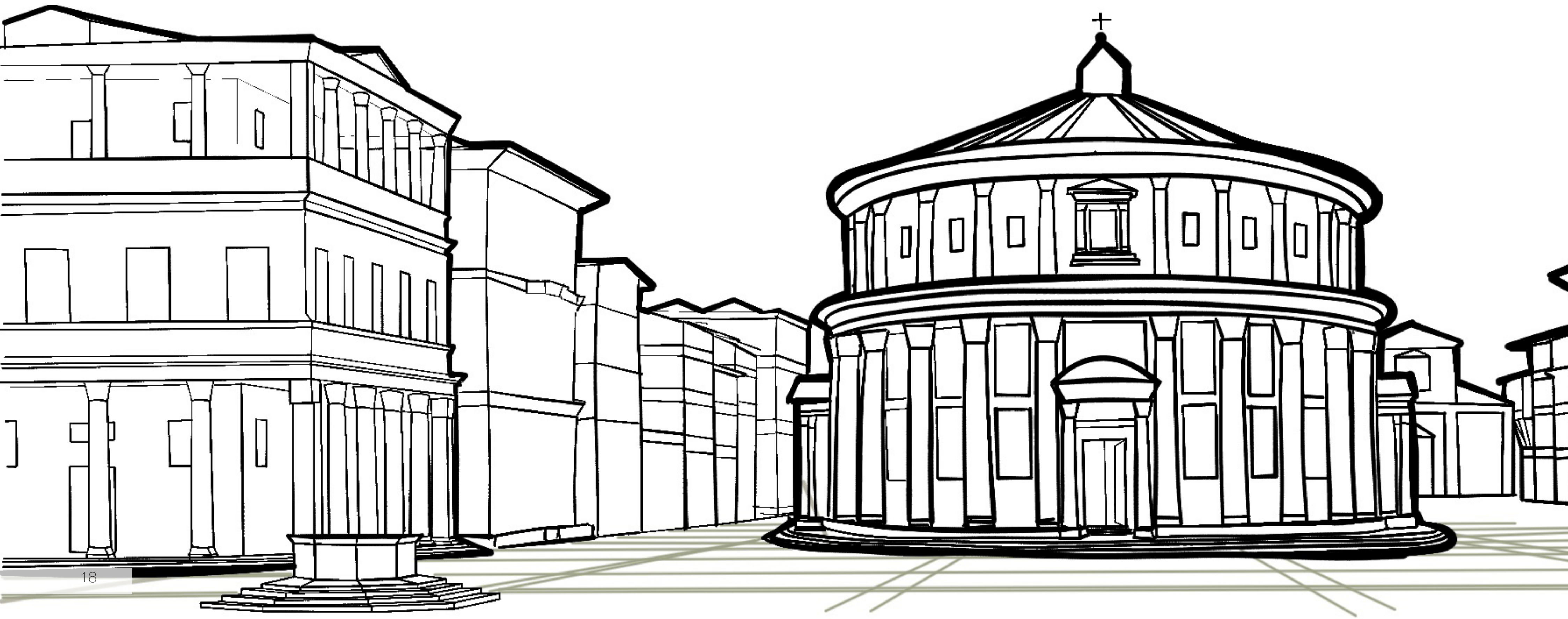
From that period until the twentieth century, the different fields of knowledge got gradually more segmented, growing apart from each other, setting rigid and clear boundaries among them. Now, in the Age of Information, we are walking towards a higher integration among disciplines, and arriving at an architecture more connected with Nature's constraints, something closer to what would be in the fifteen's century.

There is an unquestionable urge to review how digital tools have been used, making clever manipulation of it towards an optimized use of resources, both human and material, and go beyond the mere search for formal expression. As we now face new concerns, new solutions are needed, and for that, we must rethink the role of the architect in society. Digital tools have broader the possibilities to explore new solutions, but to make the best use it, architects need a better and broader knowledge. Current times are characterized by the speed of information, and the integration of new insights produced in different areas of cognition are mandatory to come up with new solutions for nowadays society.

The role of architects has gradually changed during the years, always following the social, technological and economical changing in the society. Schumacher (2011) argues about this evolution in his work. He establishes that the appearance of the figure of the architect as one defined human being comes together with the emergence of architecture itself. He also links the evolution of architecture according to the social, political and economic characteristics of each time.

Following his idea, the Gothic was the introduction to what we call now architecture. In this context, society and its evolution were deeply bonded with the clerical institution. Although there were significant technological improvements in the building sector, it was still a kind of proto-architecture, in which the figure of the master-builder as one individual figure, responsible for the conception and the representation of the project, was not clearly defined.

From Renaissance to the Industrial Revolution



Seeking progress through economic emancipation, the Renaissance was a historical period of constant growth, where society grew in complexity. It was also an era of economic evolution, in which credit institutions began its existence. These early steps of capitalism have financed the evolvement of the 'first active style of architecture' that was conceived by the 'pursuit of innovation' and under this context, the architect, as one defined author, had the leading role in representing the project via drawings and writings. (Schumacher, 2009)

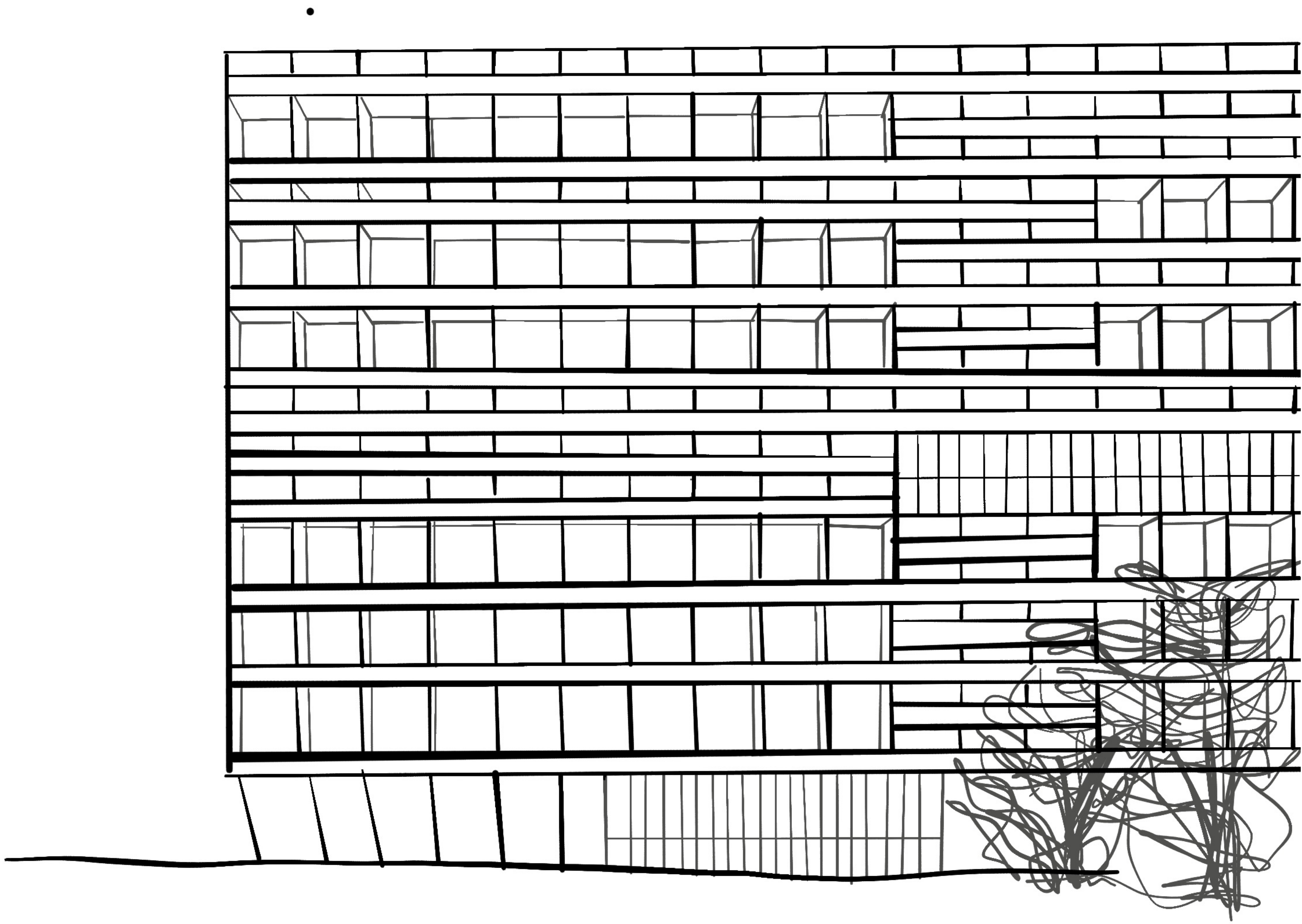
At that time, the architect should possess a broad spectrum, as the subjects evolved simultaneously and the boundaries between them were not clearly defined. The exploration of proportions, which was one of the main pursues in the Renaissance, was irrevocably inseparable from the studies on natural sciences. Based on the observation nature and the mathematical geometry behind it, the well-known geniuses of the time, were able to make considerable achievements in the fields of biology, mathematics, geometry, arts, engineering, and architecture.The segments of knowledge were still blended at the time.

After the enormous transformations brought by the Renaissance the Baroque era rised, coupled with the Absolutism and the Mercantilism, and their intrinsic characteristic of state control (Schumacher, 2011). Subsequently, the Neo-classicism, aligned with Traditional Bourgeois and the Napoleonic era, ought to accomplish with the dynamics of the increasingly diverse society.

As the history of architecture evolved, the role of the architect has defined its boundaries diverging its purpose from arts and engineering. The differentiation of roles from planner to builder grew stronger through time and, along with that, the need for new representational tools.

"Less is More"

Mies van der Rohe



With the arrival of Modernism in the first half of the XX century, the concept of space suffered a dramatic shift. These new conceptions of architecture and space were enabled by new technological realities, being deeply connected with it. The Second Industrial Revolution has brought new possibilities by the exploration of the steel and the concrete. In the architectural field, this meant the appearance of new solutions for the modern man, in a mass-production way.

Le Corbusier, in his first book 'Vers une Architecture' (1931), advocated for the need to update architecture and bringing it to modern times. He wrote that "modern problems demand modern solutions" and the house, as a machine for living in, should solve the problematics of the modern world as the airplane and the automobile solve them. In his writings, he defined the work of the engineers as more updated with the reality of the time, and also architecture should base its renewal on the modern reality. These changes meant a completely new architecture, inspired by the Fordist mass-production 'spirit', excluding everything that is beyond the necessary from its conception. He praised for the beauty of primary geometrical forms, as they could be understood by mathematics and easier to appreciate. (Corbusier, 1931)

In the same way that the twentieth century needed new answers based on their new problematics, the informational era also needs it. A contemporary answer needs to set its bases on contemporary realities, as the great historic intellectual revolutions have shown themselves. With the evolution of the digital also came a more sophisticated understanding of Nature and its manipulation. As before the pure and primary geometrical forms were the critical answer, now the solution lays on the complexity and the pursuit of simplifying it.

"The Plan is the generator.
Without a plan, you have lack of order, and wilfulness.
The Plan holds in itself the essence of sensation.
The great problems of to-morrow, dictated by collective necessities, put the question of "plan" in a new form.
Modern life demands, and is waiting for, a new kind of plan both for the house and for the city."

Le Corbusier, 1931

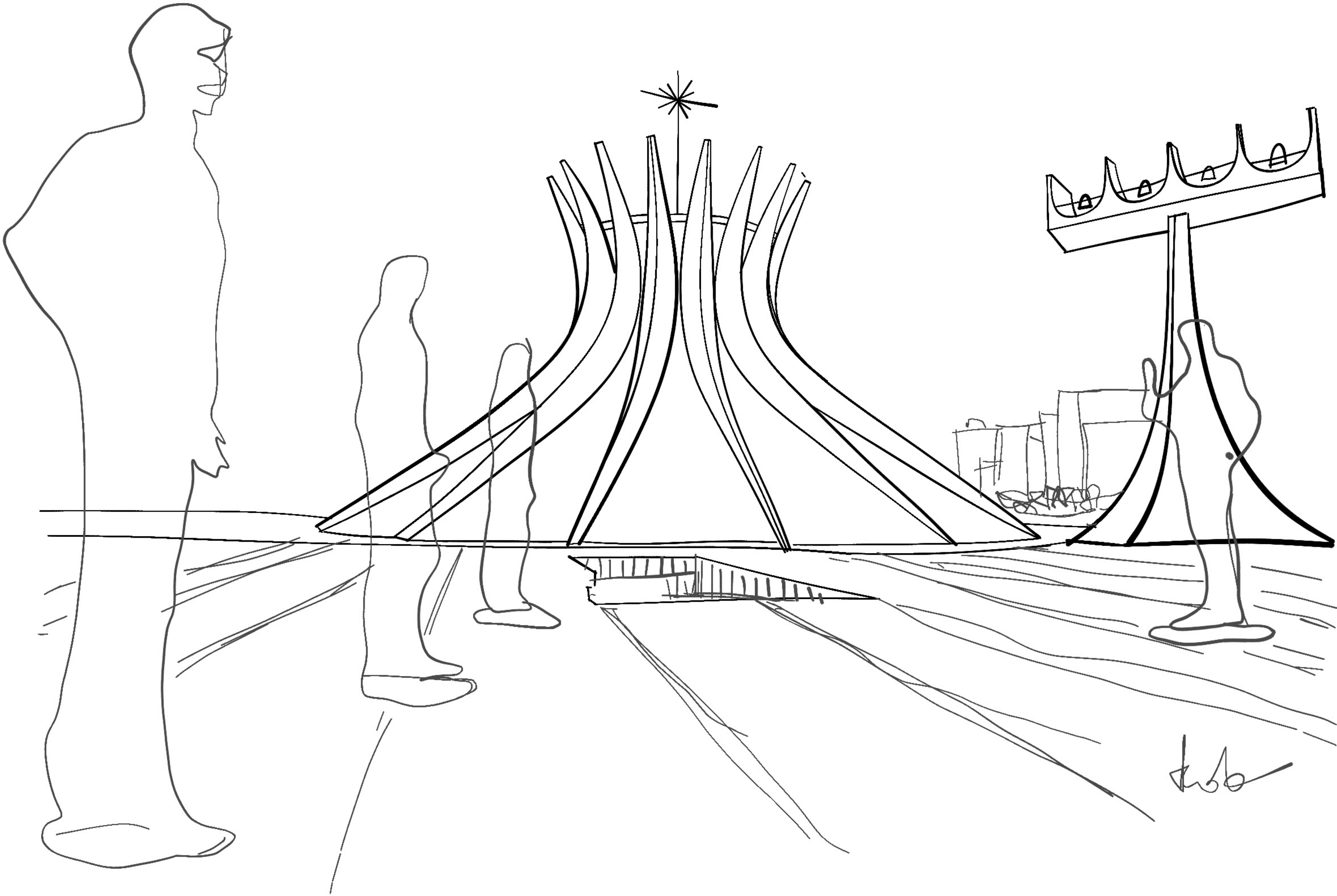
The Brazilian Modernity and Niemeyer's Free-Form

The exploration of new technologies was the key point for the development of Modernism. The reinforced concrete played a major role in Brazilian modernity, making possible the formal surrealism of Niemeyer's organic architecture in the 1940s. His first works were deeply influenced by Le Corbusier's ideas of the five points in modern architecture. The plasticity present in his later architecture was his materialized frustration with the modern machine and its unsuitability to answer the human needs regarding the creation of space (Underwood, 1993).

According to David Underwood (1993), the spread of the free-form in Modernism is a result of the disappointment with the machine as an aesthetic metaphor of the post-war and a rising interest in more organic architecture. Niemeyer's work is a strong turning point on the modern movement, influencing the late work of modern architects like Le Corbusier, Frank Lloyd Wright and Eero Saarinen.

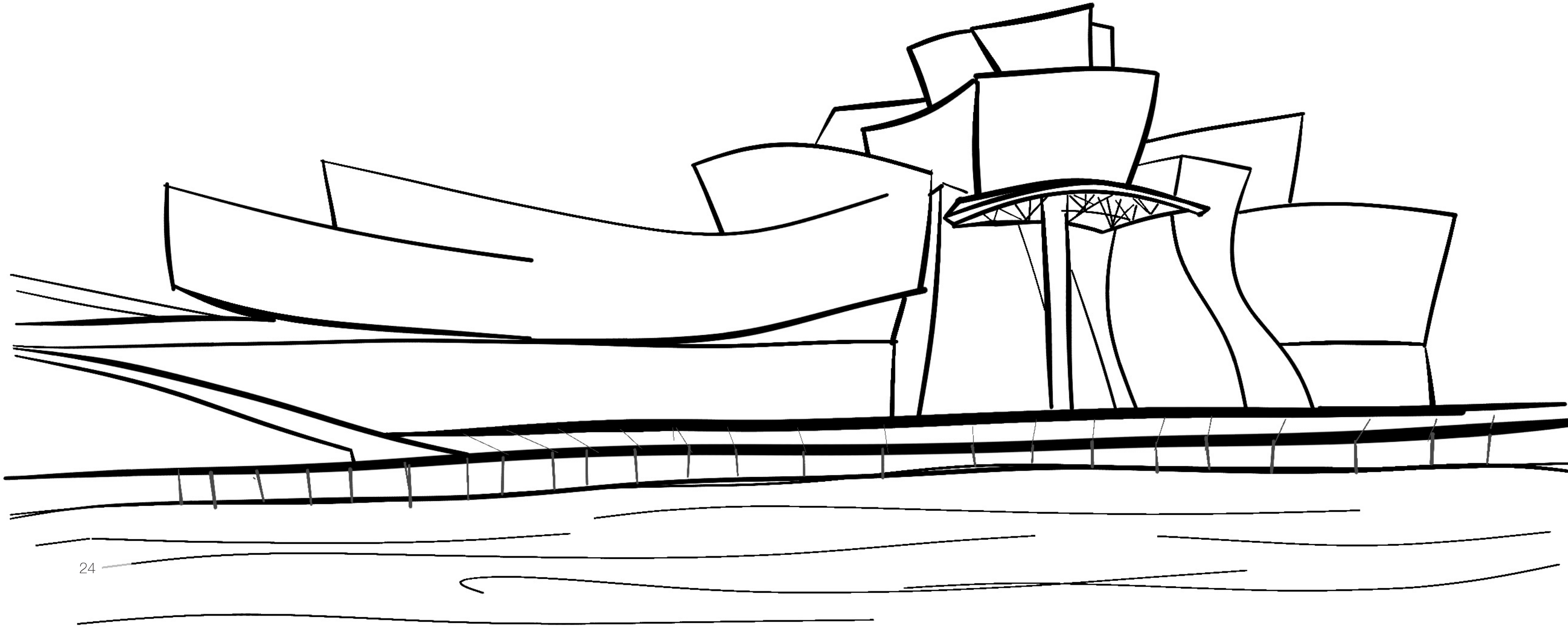
Brasilia holds a great part of Niemeyer's work using curvilinear forms. The city showcases both scenarios of the moden movement, the persue for linearity and Niemeyer's surrealistc shapes. At the end, they all test the limits of the new technology of the time: the reinforced concrete.

> *"I once wrote a poem about the curve.*
> *The curve I find in the mountains of my country,*
> *in the sinuousness of its rivers,*
> *in the waves of the ocean*
> *and on the body of the beloved woman."*
>
> Oscar Niemeyer



"Less is Bore"

Robert Venturi



Following the years of the modernist hegemony, critics about the oversimplification and its lack of ability to solve contemporary problematics arose among the architectural field. The twentieth century was characterized by substantial social, economic and technological changes, at speed like never seen before. An equally broad architectural solution should be found in order to keep up with all the advancements.

Venturi (1965) claims the need to renew the historical consciousness, and it is this that differentiates the modern from the postmodern architecture. He sharply criticized the “formalism of false simplification” and says that “complexity must be a constant in architecture”. The critics lay on the argument that the modern architecture, through simplification, selects the problems which it wants to solve, and that results in isolation of architecture from experience of life and the real needs of the society.

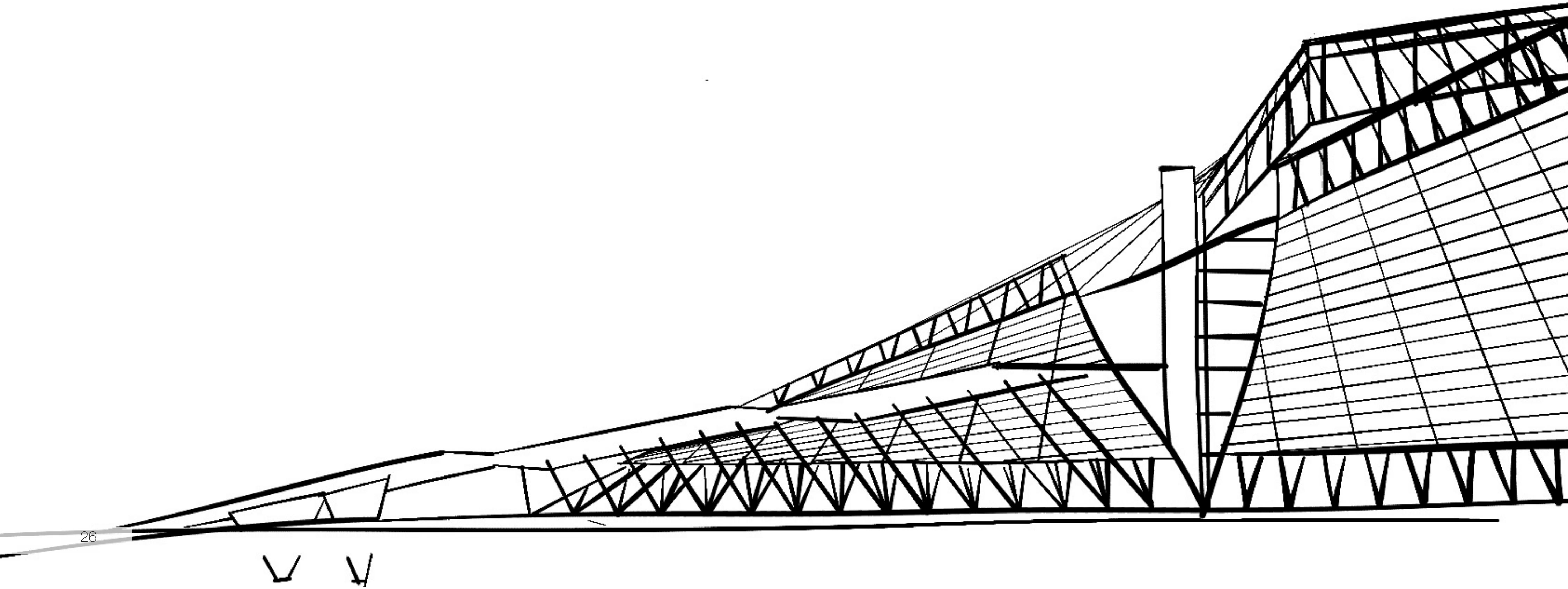
Patrik Shumacher (2011) says that Postmodernism and Deconstructivism were the initial architectural responses to the crisis of Modernism. As those were transitional phenomena, lasting about one decade, and did not have a significant impact on the built environment. Schumacher coins the term Parametricism to define the architectural avant-garde and more mature movement from the last decades affirming that it is impacting the 21st century like the Modernism had impacted the 20th century. (Schumacher, 2008)

Parametricism is a “type of design process characterized by the interrelation of design variables through computational tools and techniques” (Pole, Shvartzberg; 2015). Schumacher connects the hegemony of this new “style” deeply with the liberal democratic scenario in which we currently face. Beyond the economic and political scenario, it is an informational response in an informational era. (Schumacher, 2015)

The beginning of the digital era was outlined by the experimental use of this new promising technology. In this context, in the ’90s Zaha Hadid and Frank Gehry were the notable pioneers exploring those new formal possibilities and stepping ahead on a “digital utopia”. Firstly, this kind of architecture was marked by the high idealization and low materialization of the projects and, along with technological advancements, the gap between the real and virtual went narrower. Many critics are made regarding this overwhelming architecture principally on its general structural inefficiency, which has usually led to excessive use of material resources.

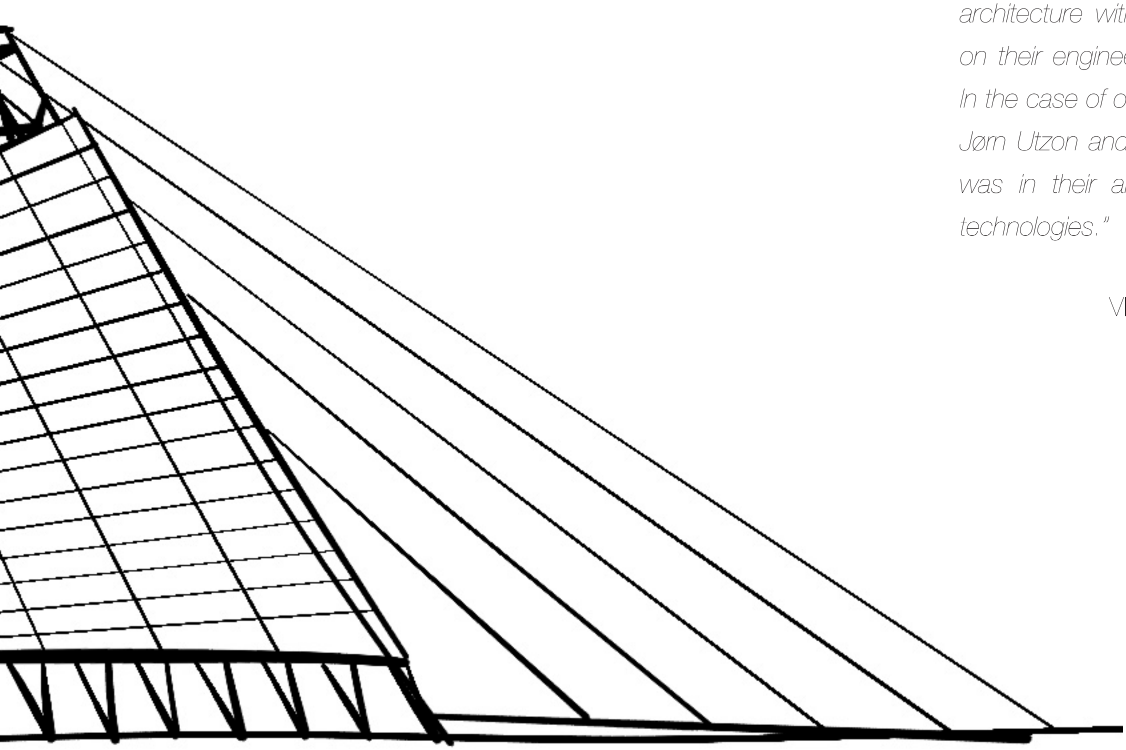
Due to the immaterial characteristic of information, the development of digital tools is irrevocable necessary for its optimal use. Digitally informed architecture provides us with a wide range of smart solutions, that goes much further than merely being a representational tool. Considering the speed in which information can spread, the level of integration in different fields of expertise exponentially rises, demanding an extensive knowledge from the world we live in and consequently enabling reaching better solutions. The wise use of the digital changes the whole creational process of architecture and demands from the figure of the architect a much plural profile, in an interdisciplinary approach.

Conclusion



"Architecture was aways about exploring technology. The two go hand-in-hand and can't possibly be separated. We have gone from Filippo Brunelleschi, who is credited with becoming the first modern engineer, to Le Corbusier's Five Points of Modern Architecture, which could only have come about as a response to the advancement of the modern building industry. Architects such as Antoni Gaudí, Felix Candela, Pier Luigi Nervi, Frei Otto and numerous others could never have achieved their architecture without fundamentally relying on their engineering mastery and insight. In the case of others like Oscar Niemeyer, Jørn Utzon and Zaha Hadid, their genius was in their ability to predict emerging technologies."

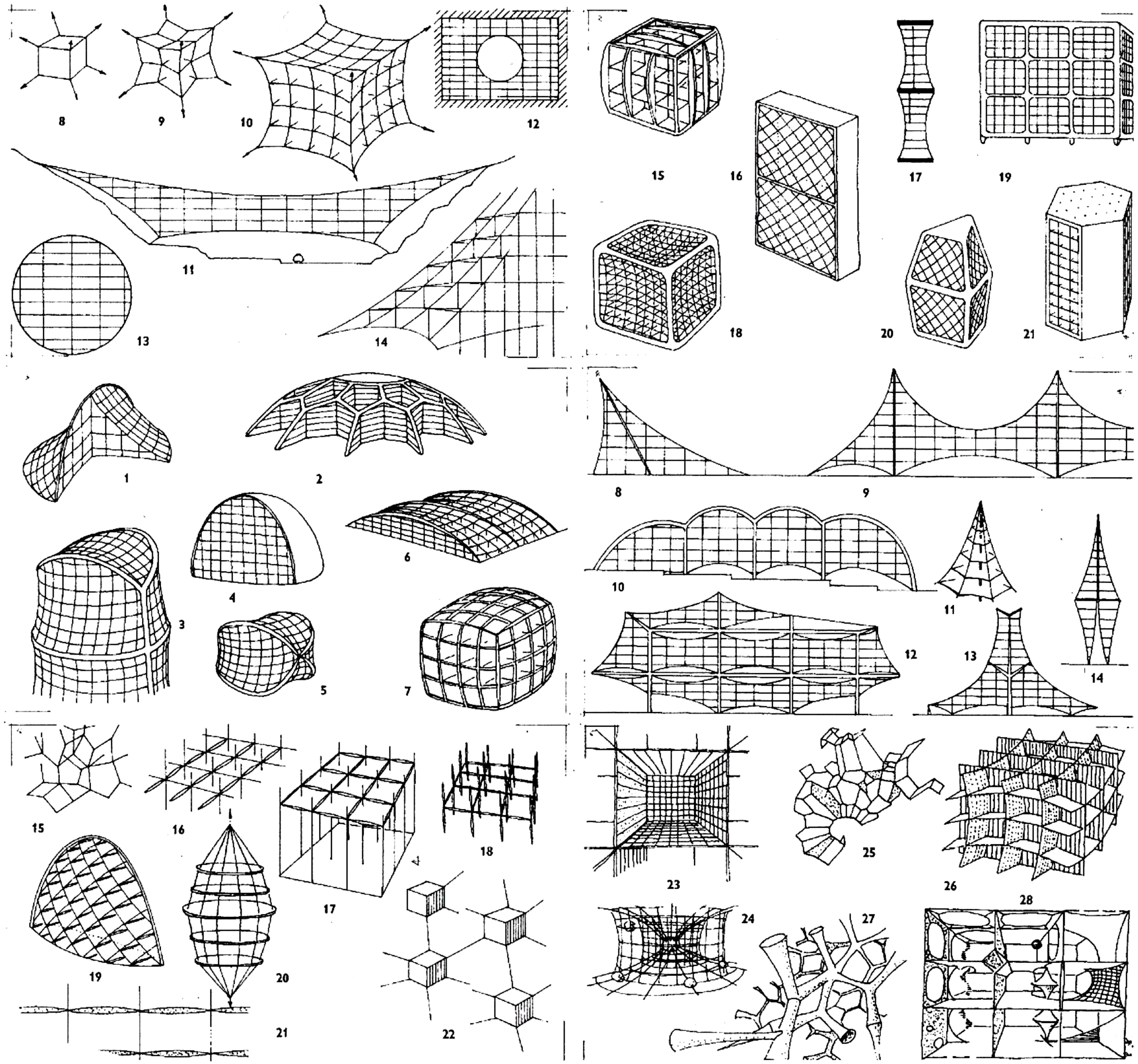
Vladimir Belogolovsky, 2019



Architecture responds to social, political and economic demands. "Like the development of the perspective in the XV century, digital design technology is today imposing a cultural shift of pervasive immanence and ubiquity" (Oxman & Oxman, 2014). As in the Renaissance, the figure of the architect was born due to political and economic developments that financed it, the Baroque was an echo of the absolute power of the monarchy and the Modernism tried to reach the needs an industrial "Fordist" society, the contemporary architecture tries to reach, through digital tools, the current environmental, economic and social demands.

The current moment is characterized by how fast trends disseminate. The demand has shifted from a mass production "Fordist" society to a mass customization "post-Fordist network society" and as Modernism has adapted to different social and political scenarios, Parametricism must also do. The Parametric architecture is based on the insertion of flexible inputs, and by doing so, the result is a more democratic output, that can be adaptable and transferable. This information-based adaptability is what makes the digital tools consistent with contemporaneity and makes of it.

2. Structural Systems



Frei-Otto - diagrams for *Zugbeanspruchte Konstruktionen II,* 1966. Source: Frei Otto. Thinking by Modeling, 2017

A building's structural system works in an integrated way. Their elements should be designed to withstand all kinds of external forces and distribute them internally, without losing the stability of the whole system. The individual elements work associated with one another in order to transfer the mechanical solicitations throughout the structure until reach the building's foundations. The designer's challenge is to develop a creative and economically viable solution, aiming for a sustainable and elegant outcome, the search for beauty in form and space.

Heino Engel, in his emblematic book 'Structure Systems', wrote about different types of structural systems and how the architect should appropriate of them in their designs. It was first published in 1967 and still a great source of structural knowledge for architects. He introduces his book with three postulates about the relationship between architect and structure.

> 1. *"Structure occupies in architecture a position that does both, bestows existence and sustains form."*
> 2. *"The agency responsible for architecture, its design and its realization is the architect."*
> 3. *"The architect develops the structure concept in his designs out of professional property."*
>
> Heino Engel, 1967

In the introductory part, Engel also explains the importance of structure in the built environment. The laws of Nature are responsible for generating efficient structures, and, at the same time, these structures generate form and space. They can sustain the form unnoticeably behind the building form, but they can also become the building form itself, architecture. Most importantly, the designer's creative process lays in the skill of combine form, material and forces.

This kind of design, integrated from structure to formal expression demands from the architect a vast knowledge in different fields. It is not a simple matter of artistic intuition and creativity, shifting to a combination between aesthetics, sociology, engineering and also a profound observation of natural sciences. The manipulation of digital tools is an instrumental skill because it gives instant visual feedback, speeding up the creative process. Although digital tools are fundamental to keep up with the speed of information required in the twenty-first century, it is still required from the architect a solid base on those aforementioned subjects to set the first constrains and to come up with viable solutions.

> *"The differentiation between architectural design and structural design has to be dissolved."*
>
> Heino Engel, 1967

Engel states that the essential function of the structure is to redirect forces, based on the system's characteristics of mechanical behavior, form/space geometry and design potential. In his work is ranked five types of mechanisms to deal with redirecting acting forces. Those types are shown on the table in the following page, extracted from Heino Engel's book.

These different types of mechanisms for load redirection are often seen in a hybrid way, showing a primary and secondary mechanism working together. The one to be researched is **Form-Active**.

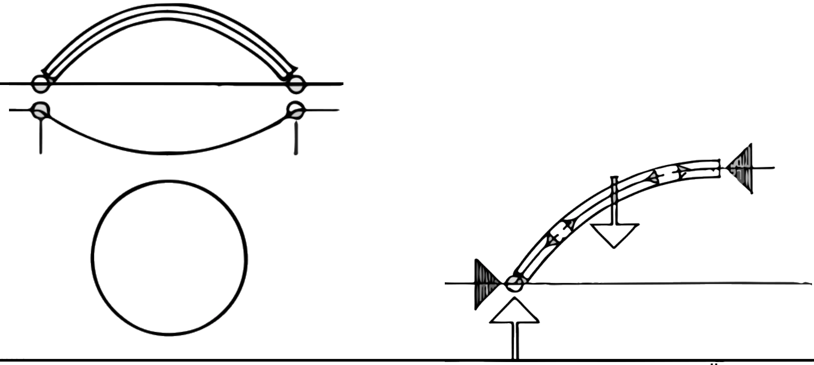
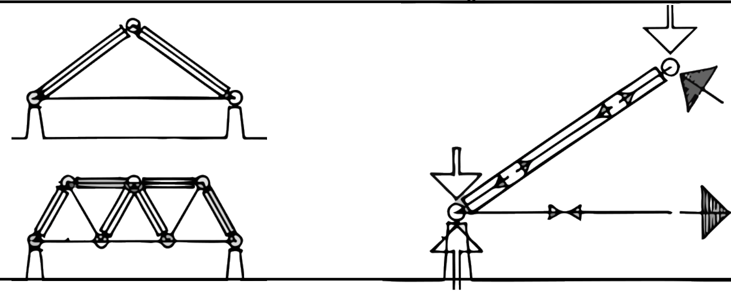
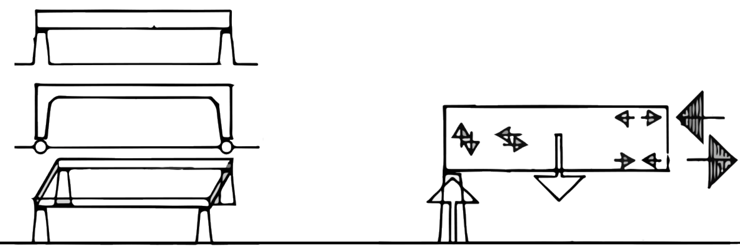
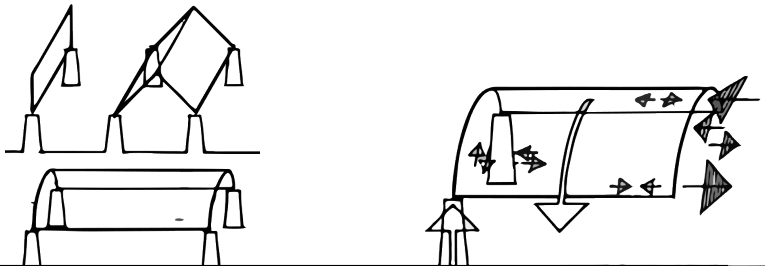
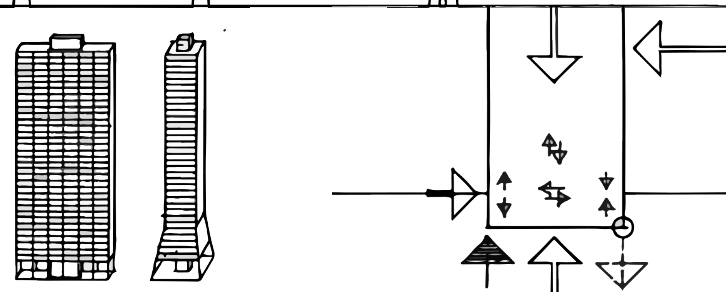
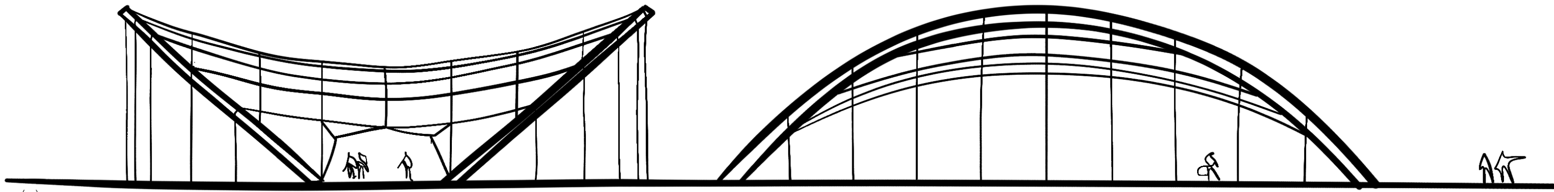
Structure Family	Definition	Structure Type	
Form-Active	Systems of flexible, non-rigid matter, in which the redirection of forces is affected by particular form design and characteristic form stabilization. (compression or tension only)	1.1 CABLE Structures 1.2 TENT Structures 1.3 PNEUMATIC Structures 1.4 ARCH Strucutes	
Vector-Active	Systems of short, solid, straight, lineal members (bars), in which the redirection of forces is effected by vector partition, by multi-directional splitting of single forces (compressive or tensile bars)	2.1 FLAT Trusses 2.2 TRANSMITTED Flat Trusses 2.3 CURVED Trusses 2.4 SPACE Trusses	
Section-Active	Systems of rigid, solid, linear elements - included their compacted form as slab-, in which the redirection of forces is effected by mobilization of sectional forces	3.1 BEAM Structures 3.2 FRAME Structures 3.3 BEAM GRID Structures 3.4 SLAB Structures	
Surface-Active	Systems of flexible, but otherwise rigid planes (resistant to compression, tension and shear), in which the redirection of forces is effected by Surface resistance and particular Surface Form	4.1 PLATE Structures 4.2 FOLDED PLATE Structures 4.3 SHELL Structures	
Height-Active	Systems in which the redirection of forces necessitated by height extension, i.e. collection and grounding of storey loads and wind loads, is effected by typical height-proof structures, Heighrises	5.1 BAY-TYPE Highrises 5.2 CASIN Highrises 5.3 CORE Highrises 5.4 BRIDGE Highrises	

Table and drawings extracted from the book “Structural Systems”- Heino Engel (1967)

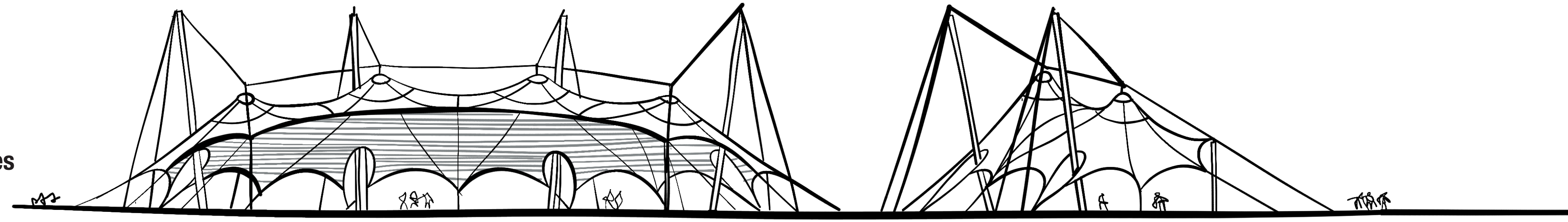
Form-Active

Cable Structures



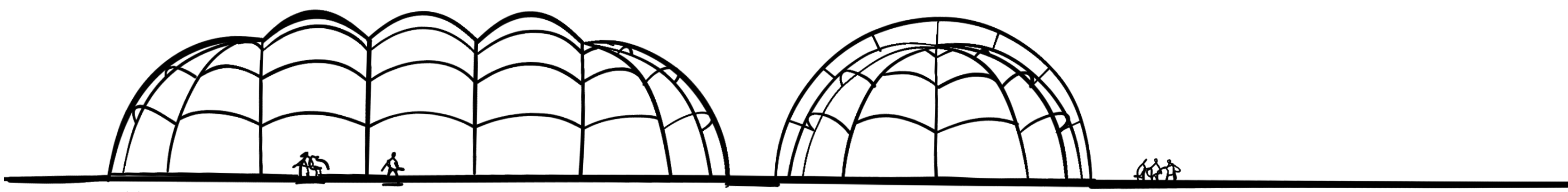
(a)

Tent Structures



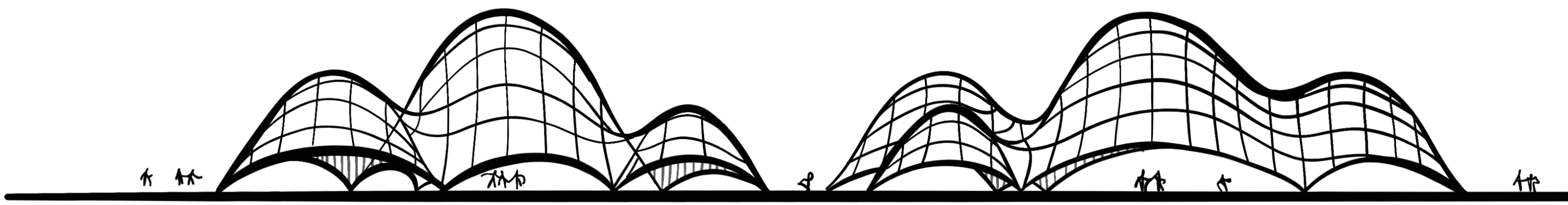
(b)

Pneumatic Structures



(c)

Arch Structures



(d)

Drawings (a, b, c and d) based on the images from the book “Structural Systems”- Heino Engel (1967)

Furthermore, Heino says that mathematical calculations are not fundamental in the structural conception, and are not necessary to "inspire the creative spirit for structural invention". Nowadays, with the virtual simulations, structural behavior can be apprehend in an interactive way in which the designer can understand its logic by inserting the initial parameters and observing its reaction.

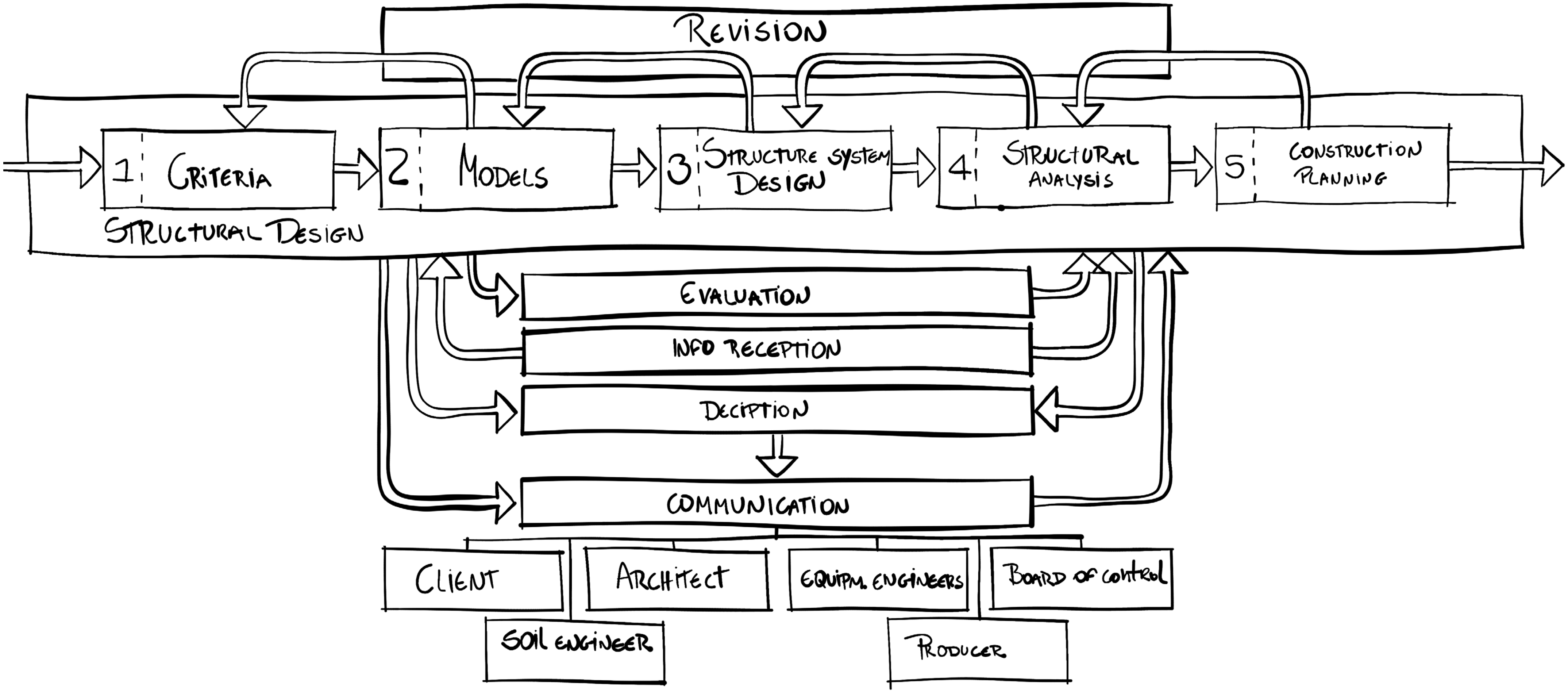
Engel describes a structural conception divided into interconnected phases, based on informed feedback among them, encompassing client, architect, engineers and producer. This conceptional method relies on constant reviews and information flows so, regarding it, communication is fundamental.

The starting data, which is the criteria definition, are the first parameters considered by the architect. The first constraints are analytical information extracted from objectives set, including the study of the site, size of the project, its social use, among others. In this first step, it can also be included the parameters to be reached in a performance-oriented approach.

After setting the first constrains, according to Engel, it follows separately, but yet connected by information flows, the model development, the structural system design and the structural analysis.

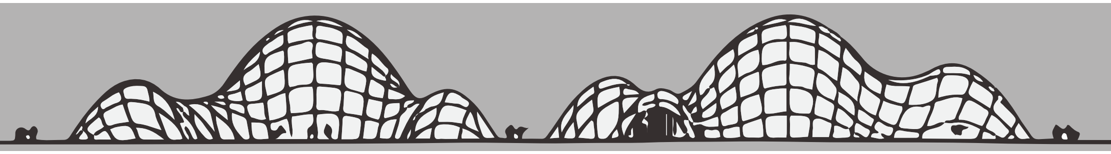
What is currently seen in a parametric approach is the dissolution of such steps into one, extensive and integrated step, based on the virtual conception of the model, from which all information is going to be placed and extracted. Such integration happens due to the incredible speed of information that is a reality now, and as a result, the virtual model is ruled by sets of information that are intrinsic it, and such parameters interact among them bringing together as output the expressional form, the structural conception and analysis.

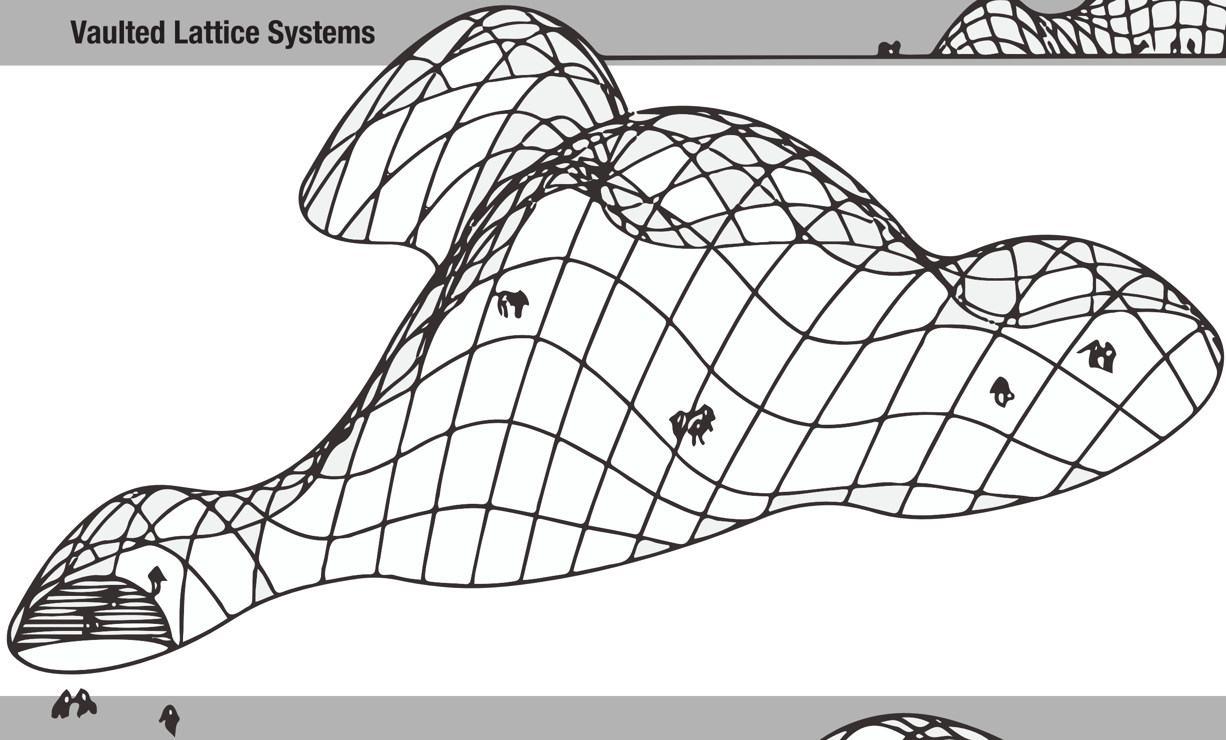
The model shifts from the first representational tool to a continuous flow of information, being a tool to visualize forces and holding the information necessary for its fabrication.

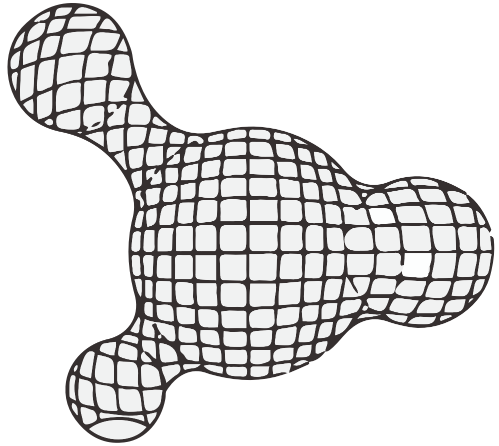


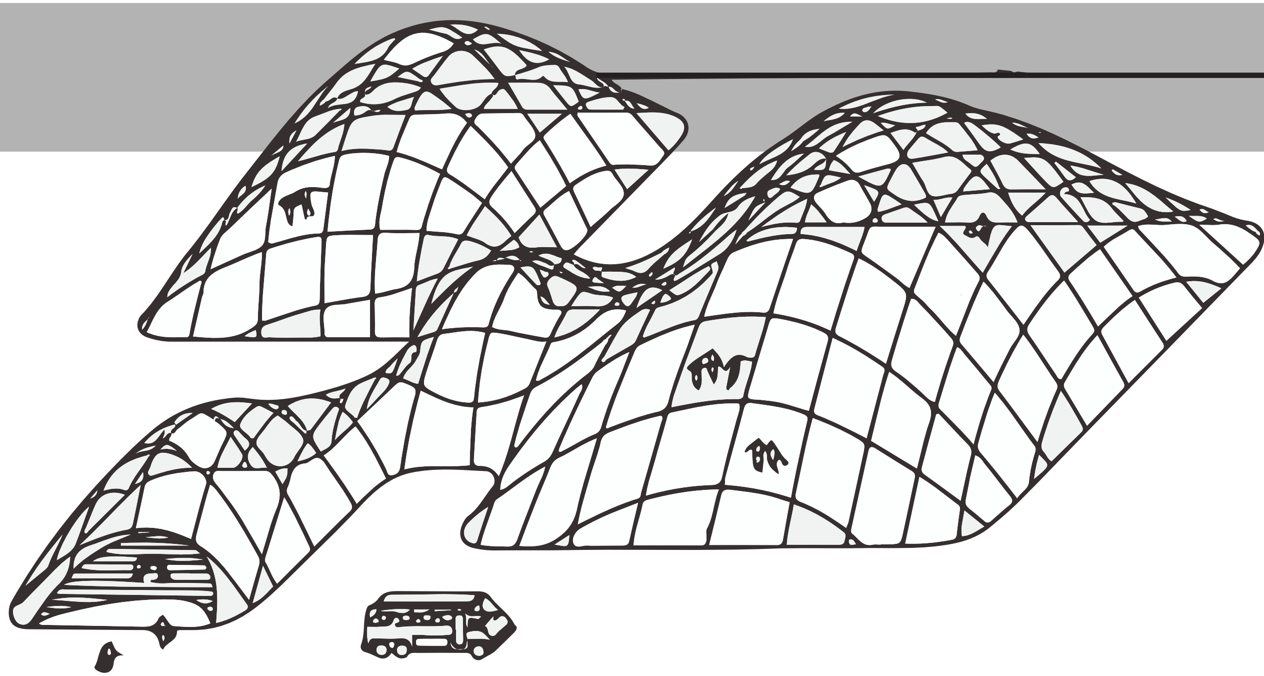
Routine functions accompanying the planning process - from “Structural Systems”- Heino Engel (1967)

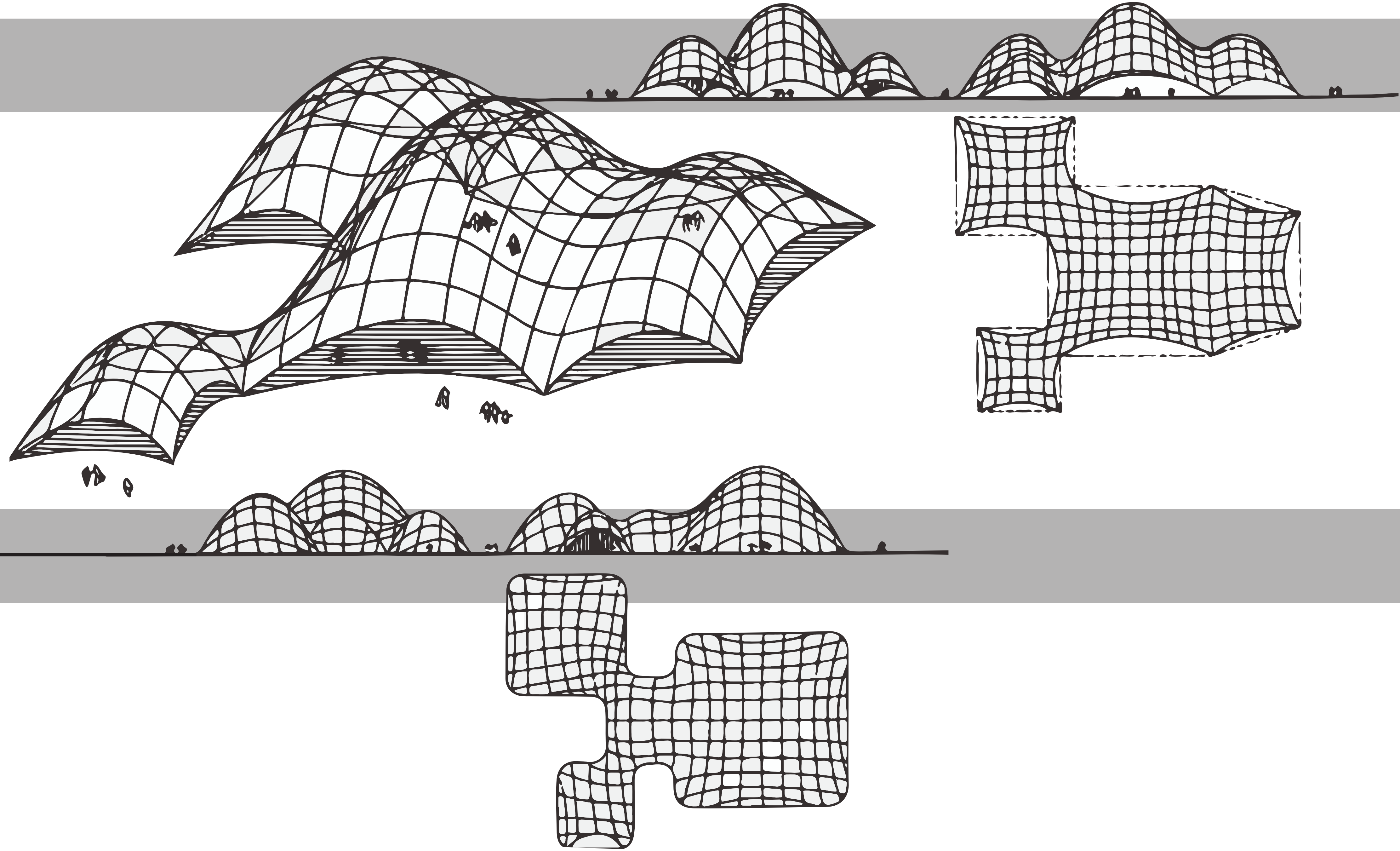
Form-Active
Arch Structures
Vaulted Lattice Systems





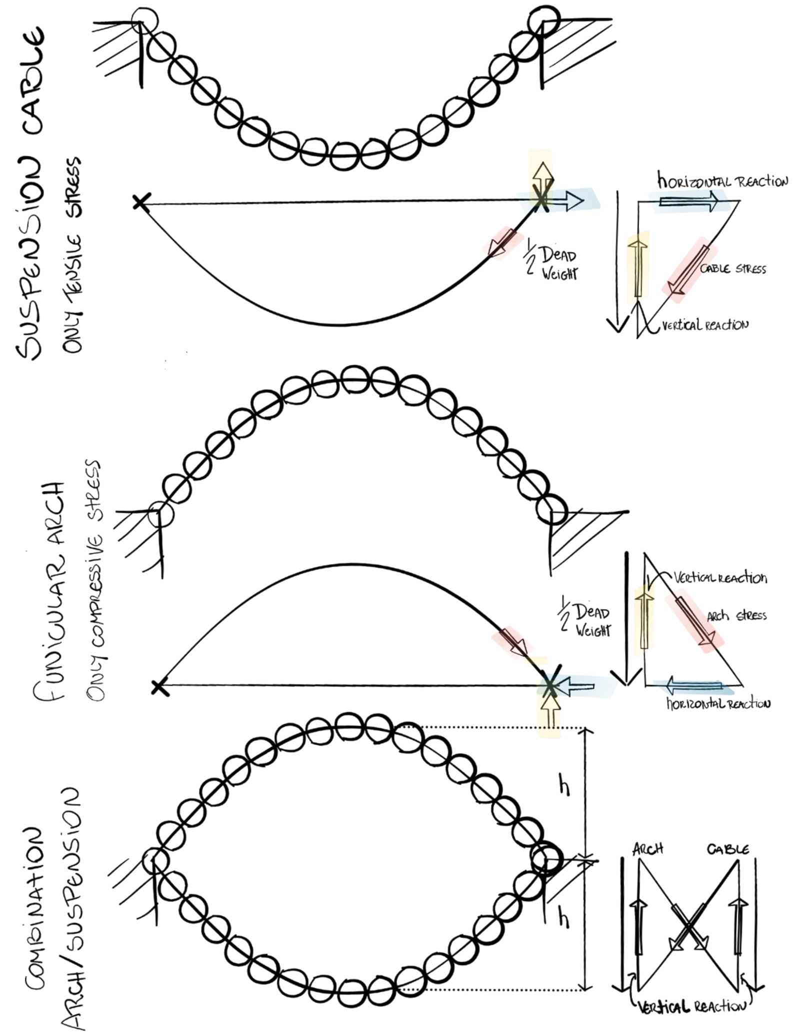






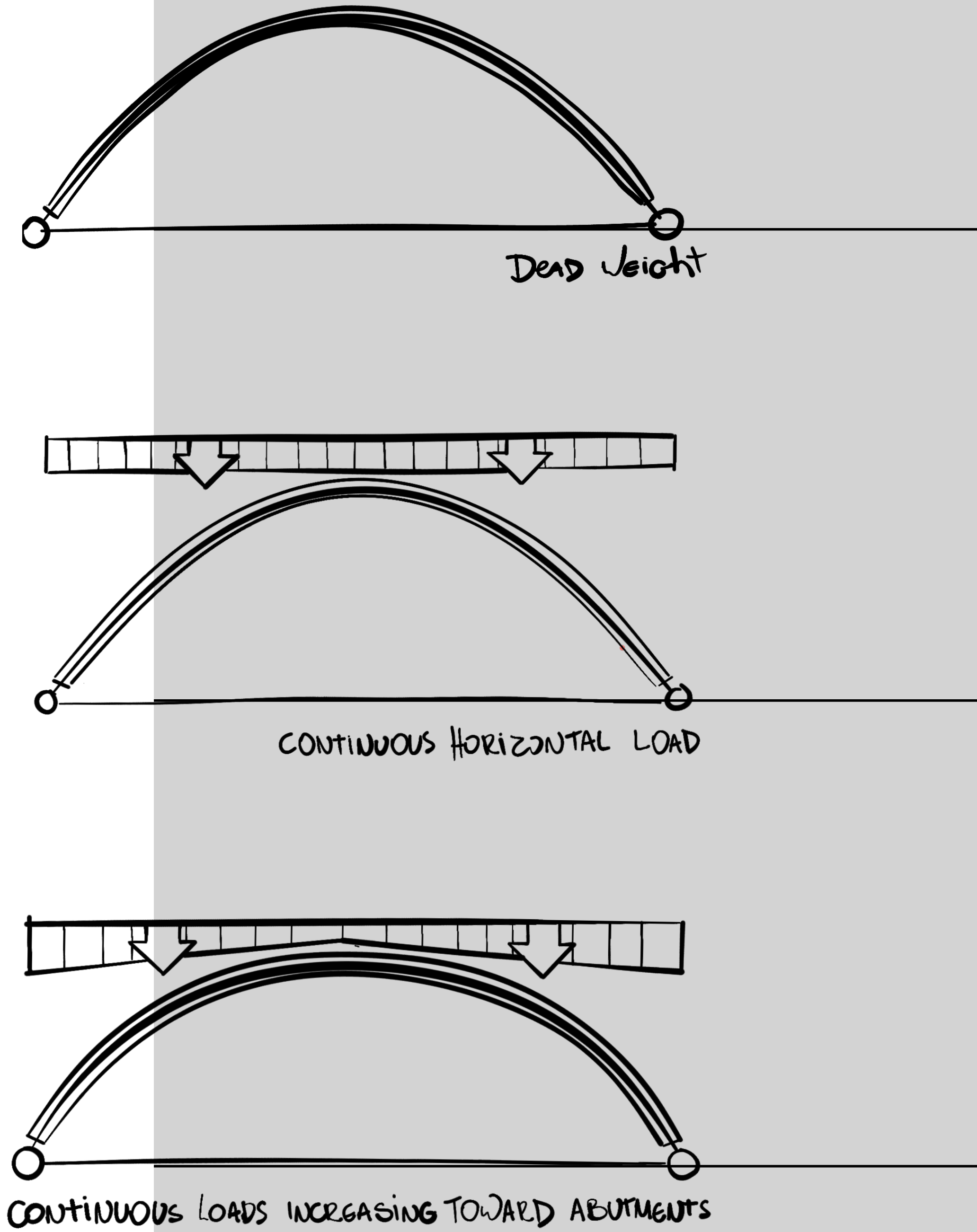
Drawings extracted from the book “Structural Systems”- Heino Engel (1967)

Engel defines a Form-active system of redirecting forces as a "non-rigid, flexible matter, shaped in a certain way and secured by fixed ends, capable of support itself and a span space". In this structural system, forces are transmitted by pure compression or tension. The geometrical shape is fundamental in the redirection of forces and should be precisely calculated, accordingly with the flow of the forces, meaning that any deviation from the optimal results in inefficiency.

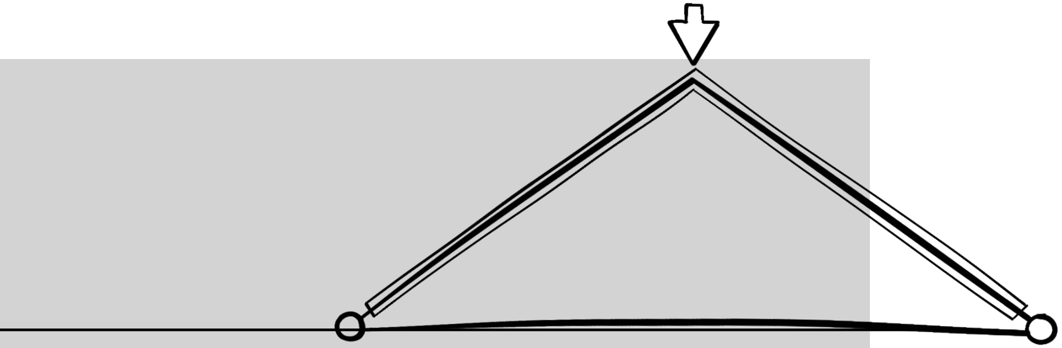


Spanning mechanism - drawing based on "Structural Systems"- Heino Engel (1967)

Geometry according to load distribution



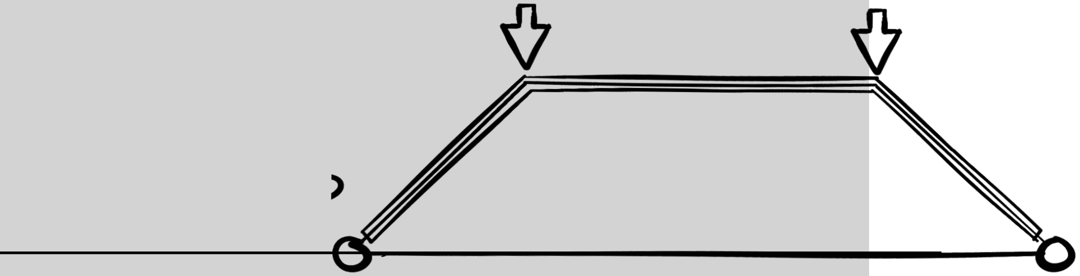
Geometrical forms - drawing based on "Structural Systems"- Heino Engel (1967)



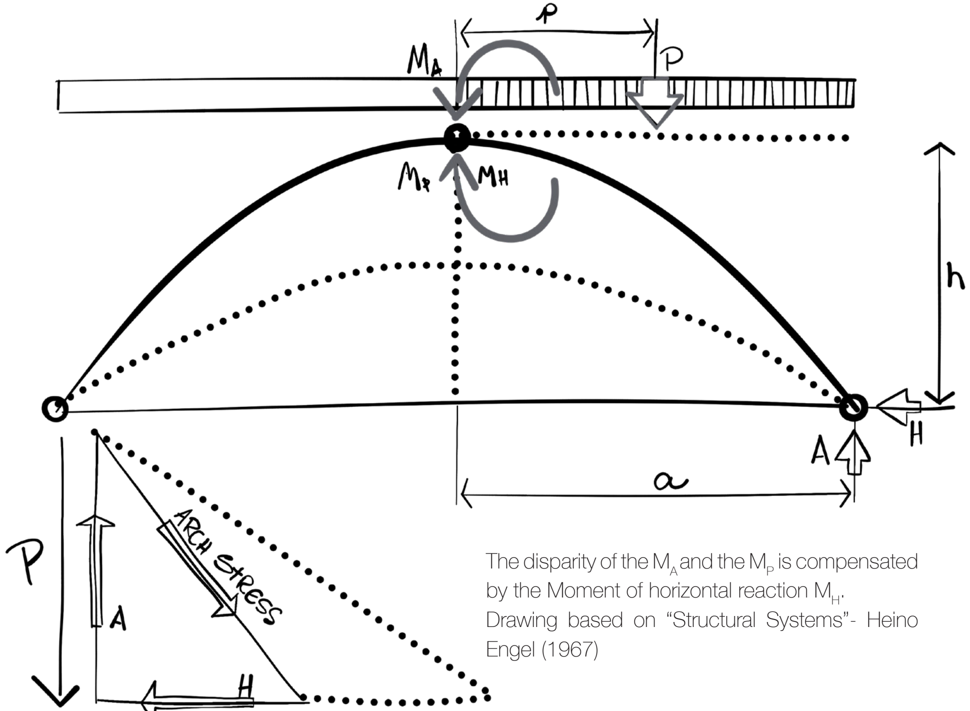
POINT LOAD IN CENTER

> *"Form-active structure systems, therefore, are the 'natural' path of forces expressed in matter."*
>
> *Heino Engel, 1963*

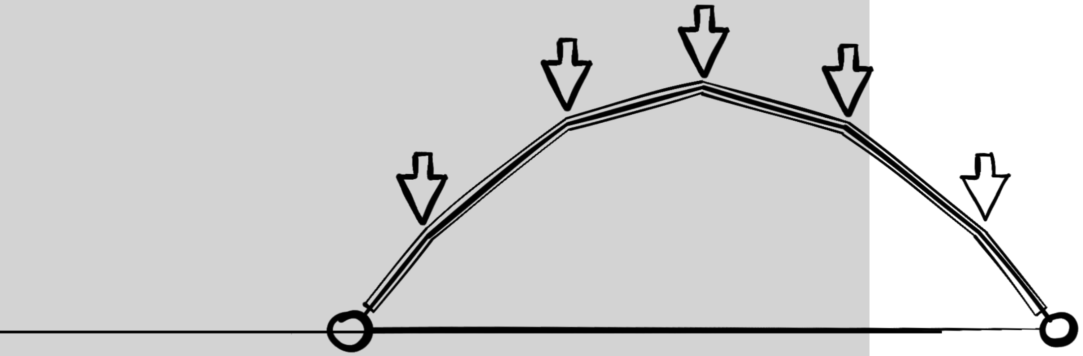
As the load distribution in this system is fundamental to set its flow of forces and consequently its shape, any changes in the force flows leads to deviations in the thrust line and assumes the need for extra stiffness. The shape cannot be an arbitrary free-form, but it needs to be a result of the initial topology combined with the anchor points and acting forces.



TWO POINT LOADS

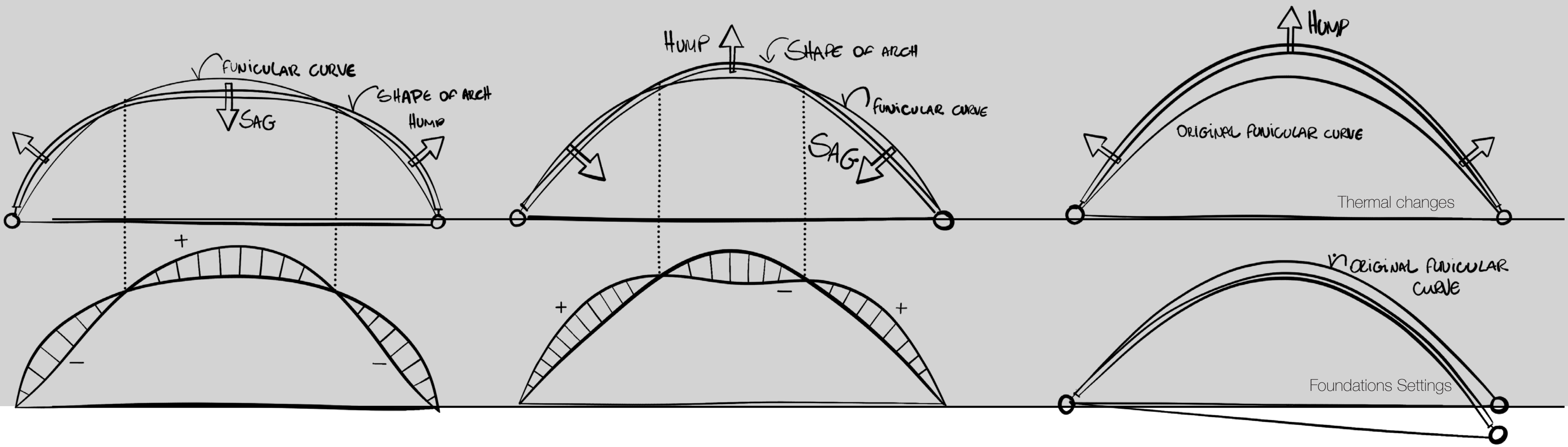


The disparity of the M_A and the M_P is compensated by the Moment of horizontal reaction M_H. Drawing based on "Structural Systems"- Heino Engel (1967)

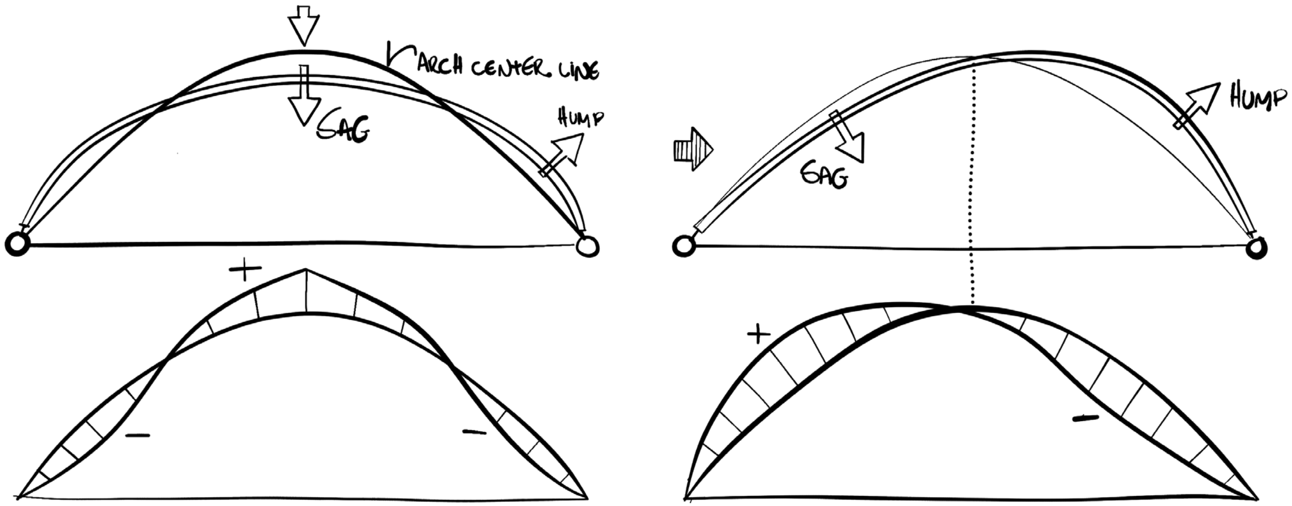


SYMMETRICAL POINT LOADS

Bending due to deviation of center line from funicular curve



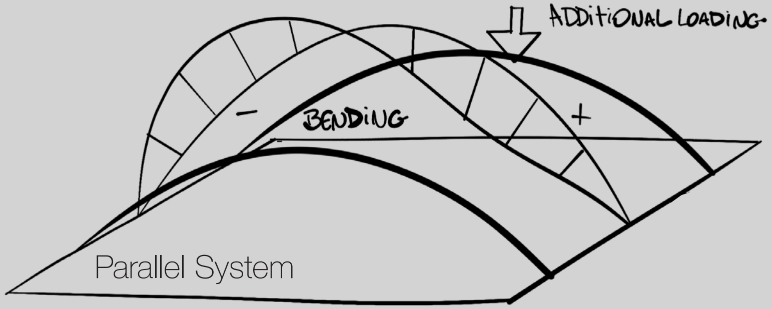
Bending due to additional vertical or horizontal loading

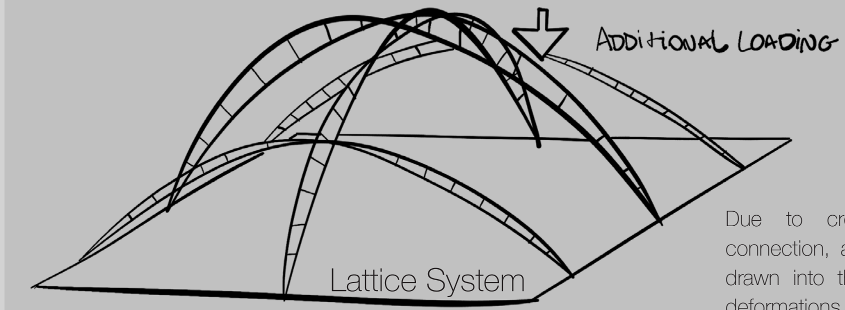


Due to the characteristic of assuming only pure compression or tension, the final output is an optimized structure, being able to win wide spans with minimal use of material. It is defined by a thickness much smaller than the other two dimensions. (Qingpeng Li, 2018)

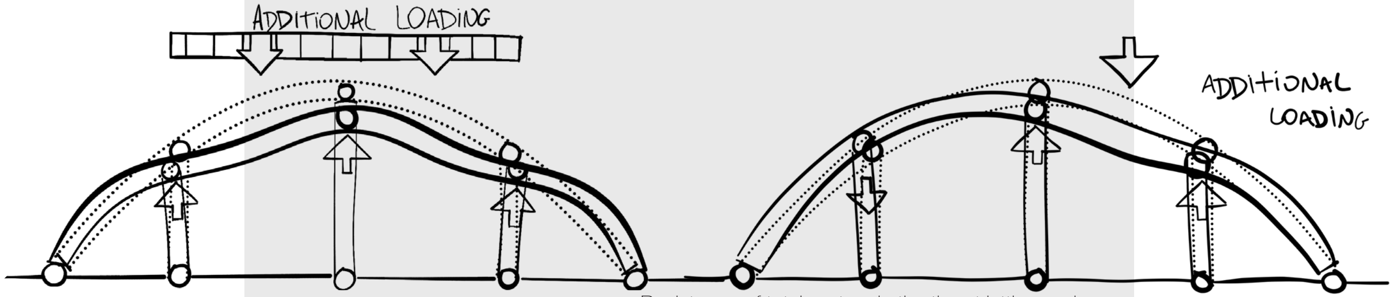
The Form-active principles can be applied to other structural systems, principally in the surface-active structure, adding strength to the whole structure. Engel considers that, due to the intrinsic system's optimal rapport between material and span, they have the "potential structural form for future building", in which the architects hold power upon the design and structural form.

Difference between parallel and lattice system under point loading



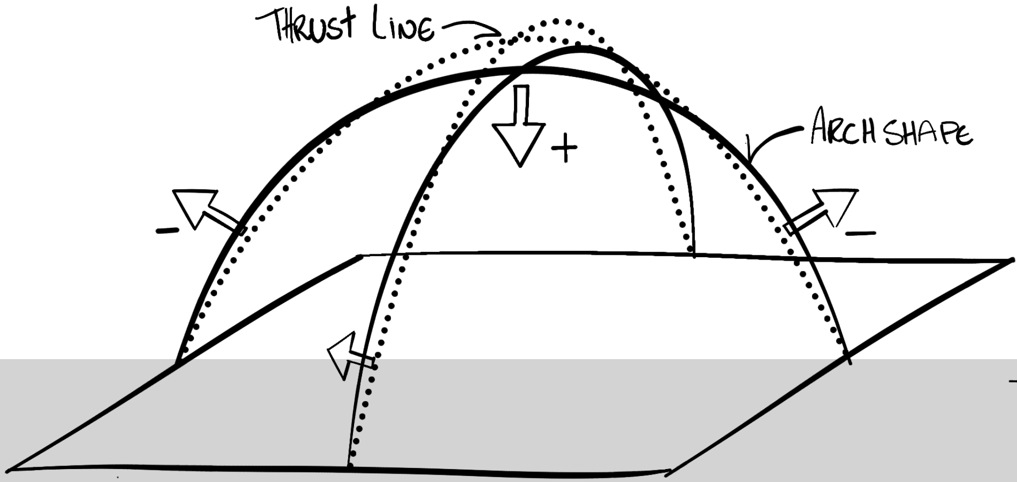


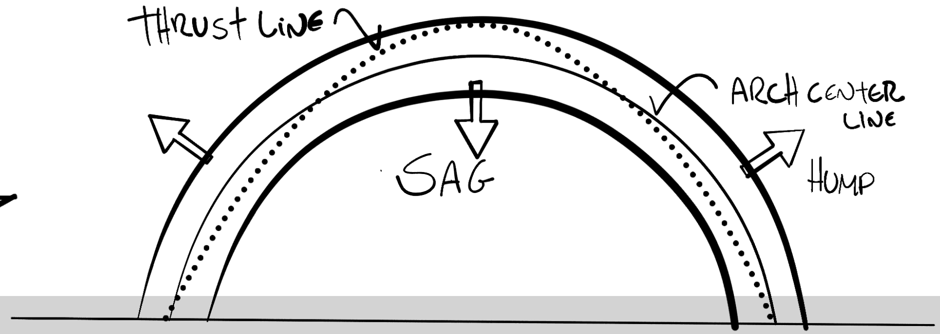
Due to crosswise interpretation and rigid connection, also the arches without loading are drawn into the resistance mechanisms against deformations.



Resistance of total system in the thrust lattice under additional loading

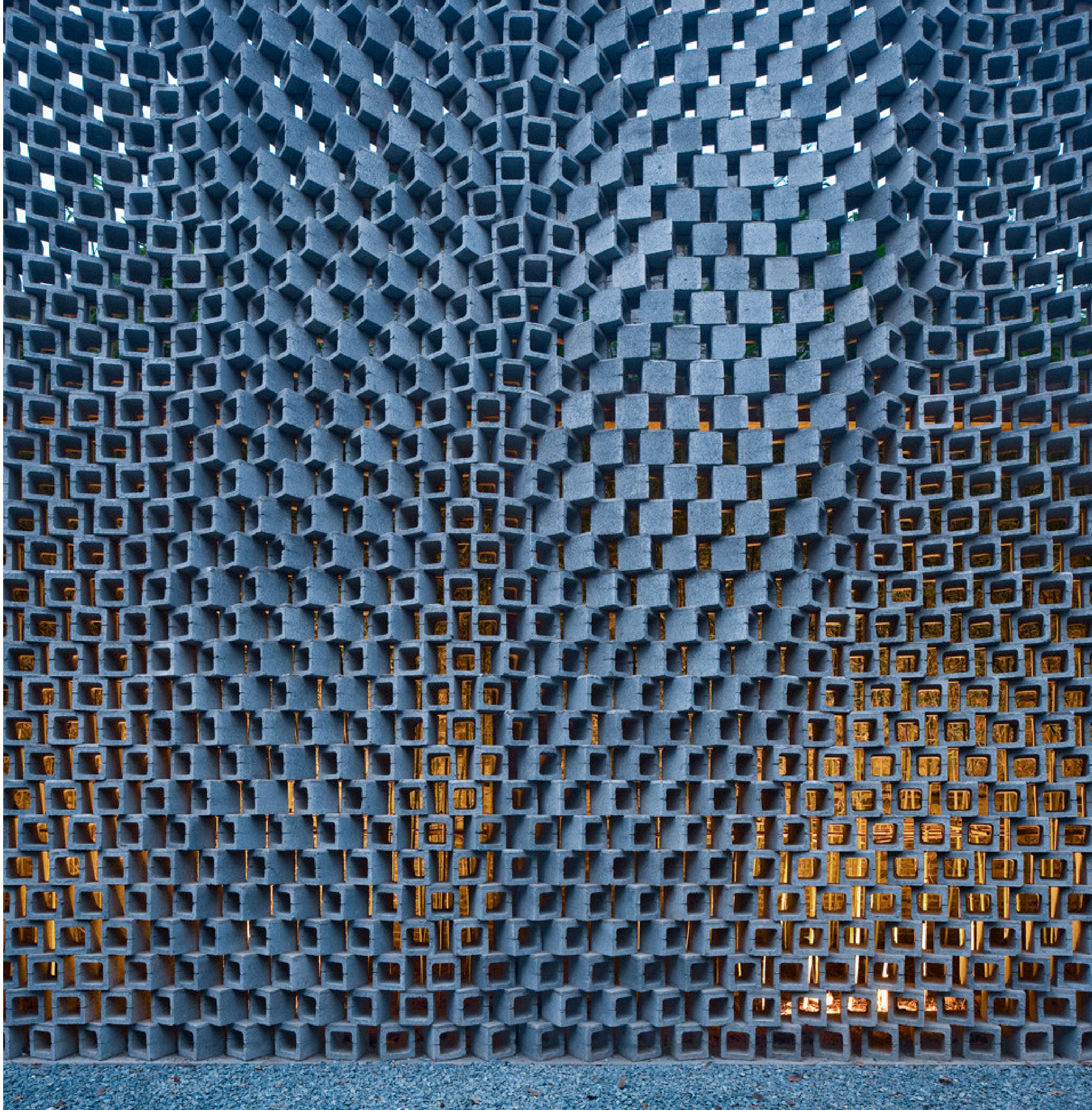
Bending stressing in the vaulted thrust line





All drawings were based on "Structural Systems"- Heino Engel (1967)

3. The Digital Turn

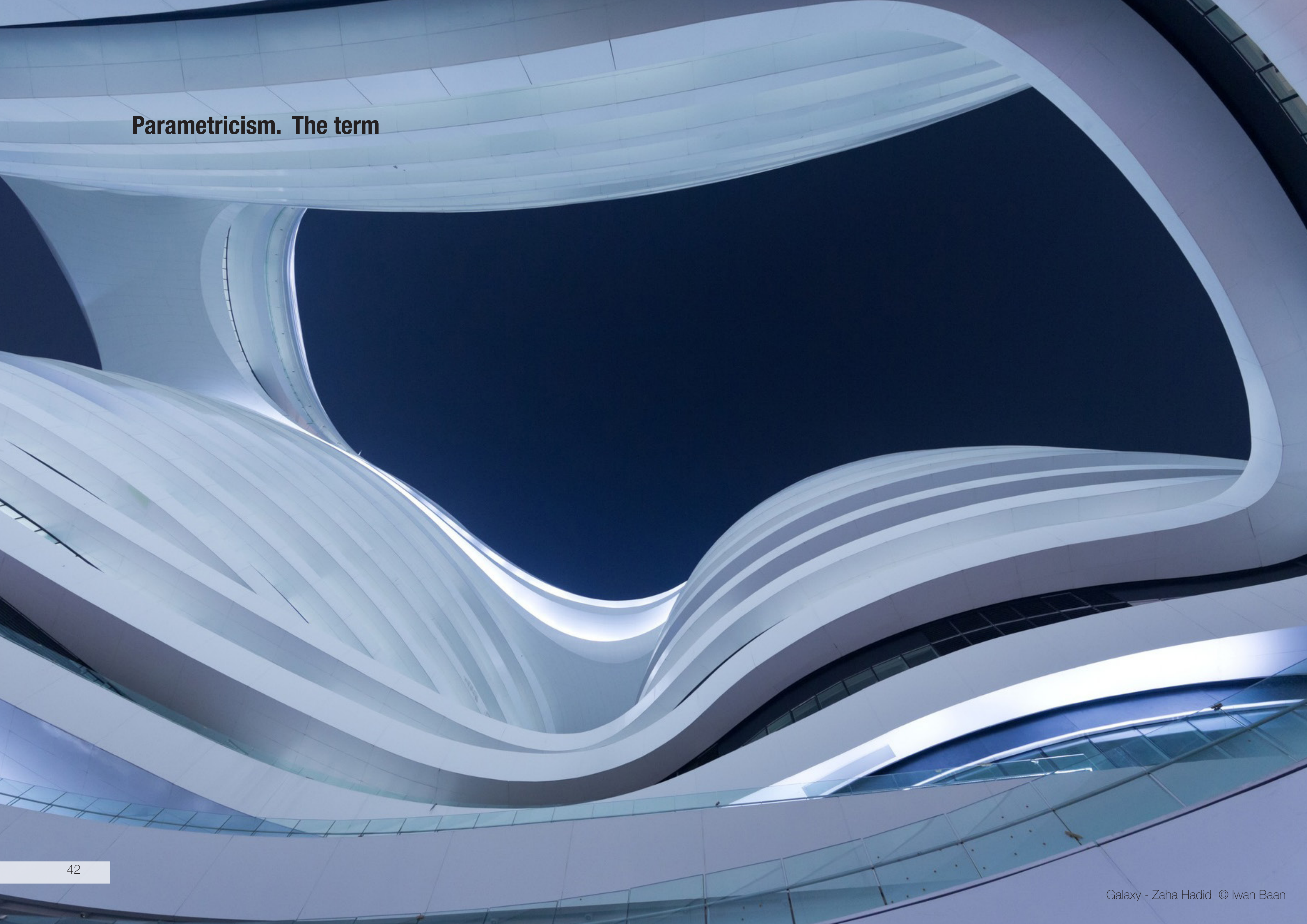


The Fouth Industrial Revolution

We are now facing the Fourth Industrial Revolution, and it is evolving at an exponential pace. The term "Fourth Industrial Revolution" was coined by the founder of the World Economic Forum, Professor Klaus Schwab. In his work he says that the First Industrial Revolution came with the use of water and steam to power machines, the Second used electricity for mass-production and the Third used electronics to an automatized industry. The Fourth Industrial Revolution "is characterized by a fusion of technologies that is blurring the lines between the physical, digital, and biological spheres", and what differs it from the Third one in its "velocity, scope and system impact". (Schwab, 2016)

> *"Engineers, designers, and architects are combining computational design, additive manufacturing, materials engineering, and synthetic biology to pioneer a symbiosis between microorganisms, our bodies, the products we consume, and even the buildings we inhabit."*
>
> *Klaus Schwab, 2016*

Parametricism. The term



Galaxy - Zaha Hadid © Iwan Baan

The term ‘Parametricism’ was coined by the architect and philosopher Patrick Schumacher. Through a manifesto called ‘Parametricism as Style - Parametricist Manifesto’ (2008), presented and discussed in the 11th Architecture Biennale in Venice 2008, he launched the term to refer to the ‘new architecture of the post-Fordist era’. He considered Parametricism to be the only style capable of dealing with the current ‘heterogeneous society of the multitude’, basing his ideas on the thoughts of the German philosopher Niklas Luhmann.

> *"Parametricism is the great new style after Modernism."*
>
> Patrick Schumacher
>
> The Autopoiesis of Architecture, Volume I

> *"It is a style rooted in digital animation techniques, its latest refinements based on advanced parametric design systems and scripting methods."*
>
> Patrick Schumacher
>
> Parametricism as Style - Parametricist Manifesto (2008)

He argues that Parametricism is an answer to the crises of Modernism, and an end to the ephemeral movements that characterized the postmodernity of the twentieth’s century’s second halfy. The accumulation of innovations generates cycles of style, shifting the whole society to other levels of needs. In such an heterogeneous society that we now live in, Parametricism is the only style that can organize, process and coordinate complexity, responding to current social needs.

> *"There is a strong, global convergence in recent Avant-garde architecture that justifies the enunciation of a new style: Parametricism. Its most conspicuous outward characteristic is a complex and dynamic curvilinearity accentuated by a swarm-like proliferation of continuously differentiated components."*
>
> Patrick Schumacher
>
> The Autopoiesis of Architecture, Volume II

The idea of a “continuous differentiation” is fundamental to understand the Parametricism proposed by Schumacher. Following Greg Lynn’s writing, The Folding (1993, 2004), the new architecture is based on a smoothness achieved by a continuous differentiation of its elements and their correlation. This differentiation refers to elements that heterogeneously compounds the complexity of the whole, in a bottom-up approach.

In 2016, Schumacher reviewed the Parametricism agenda and updated it to more accurate social and ecological architectural needs. Parametricism 2.0 is a self-critical review regarding the use of digital tools. This maturation of the Parametricism aims to shift the style beyond a mere ‘expression of artistic or technophilic exuberance’, reaching to optimize “social performance” and functional principles in what we can call Performance-Oriented Design. (Schumacher, 2016).

> *"Parametricism needs a real structural and engineering innovations to differentiate itself from purely image-driven architecture and to realize the full potential of complex curved geometry."*
>
> Phillip Block,
>
> AD Magazine - Parametricism 2.0 - 2016

The Use of Parameters to Generate Architecture

The project to be presented in the last chapter relies on digital tools throughout its conceptional process, until its materialization and fabrication. Beyond a simple representational tool, the use of software in the architectural generation gives instant visual feedback of the expressional form and structural behavior. Such speed of information shifts the architect's role to a broader spectrum, propitiating the exploration of areas such as biology, geometry, computer programming, material engineering, cinematic, mathematics and physics.

Robert Woodbury (2010, 2014) considers computers as mediums to do design, but instead of standards tools responding passively to the design desires, they play an active role in the design conception. It opens a vast field of exploration and, as a consequence, demanding from the designer the mastering of new skills.

> *"The architectural design medium is pencil and paper. More precisely: pencil, eraser and paper. The pencil adds and the paper subtracts. Add a few tools, like a T-square, triangle, compass and scale, and drawings can become accurate and precise models of a design idea. Designers are used to working in this mode; add marks and take them away, with conventions for relating marks together."*
>
> Robert Woodbury
>
> Elements of Parametric Design - 2010

Woodbury says that in parametric modeling, the above mentioned "marks" work as independent elements, arranged in an interdependent way, relating the parts of the design together, in a 'bottom-up approach'. What the designer must do is to establish the degree of connection desired among the parts and what kind of relationship it would develop.

In this kind of design process, the parts - variables - work under pre-determinate constraints. Setting relationships between the system parts is the designer's key challenge and it is fundamental to achieve a satisfactory output. That means that the architect should converge firstly to the logic wrapping the design, instead of a straight manipulation of the form.

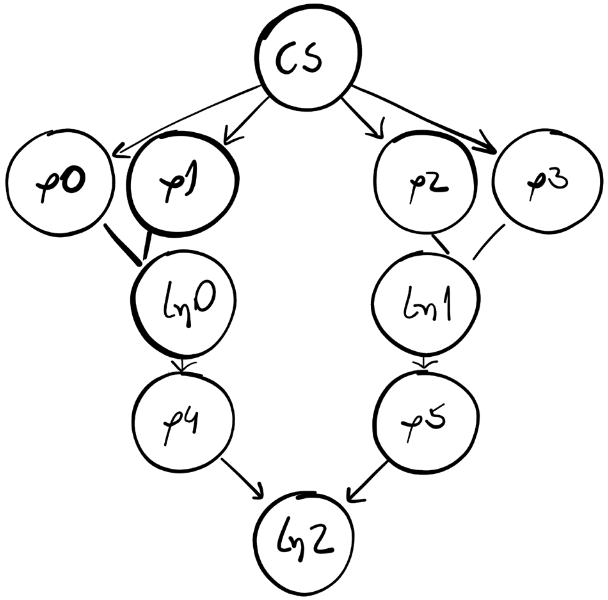
Parametric design is based on the manipulation of information inside an algorithm's code. The output generated by these procedures depends on base inputs, unfolding into a highly adaptive architecture as the final result. Larger the design is, more constraints may the algorithms have. This adaptability also implies that late changes in design are easily made, enabling the comparison between different possibilities of design options, relying on instantaneous form and performance feedback.

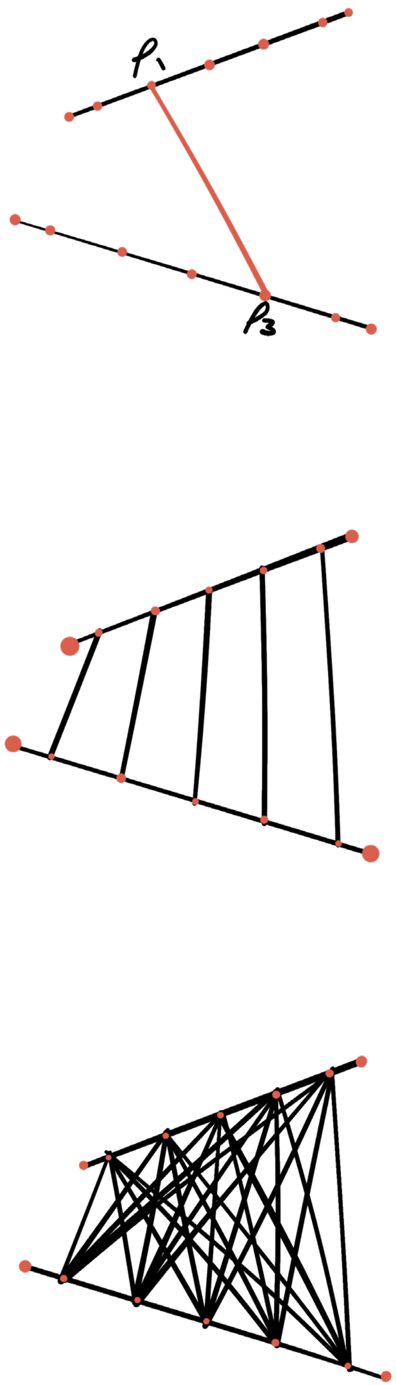
Another outcome of the adaptive characteristic of the parametric design is the possibility to use it as means towards more sustainable architecture. The input parameters can and should be thought to fit local parameters, such as eco-parameters, social constraints, legal constraints, among others. The possibility to accommodate the project to diverse scenarios is one of the points of the "mass-customization" principle attributed to a parameter-dependent design.

In the past, manufacturing was handcrafted in a slow customization mode. The Industrial Revolution and the modernity introduced new tools and technology that made mass-production not only possible but socially and economically desirable. Now we have a new paradigm, the mass-customization, and it was enabled only through significant technological improvements, fundamentally in the field of information management.

Although Schumacher (2008) firstly states in his Manifesto that the current architecture is defined by smoothness, Migayrou (2014) writes in his paper “The orders of the non-standard” that formation precedes form. He says that the output is a result of a set of rules pre-established by the designer, and the complex “free-form” is not mandatory but can be a possible result of the algorithm’s logic.

The use of parameters to generate architecture demands a broader knowledge, in an interdisciplinary procedure. Beyond the manipulation of software and algorithms, architecture also considers biochemical properties of materials together with fabrication methods. Computers are now a reliable tool to create an unprecedented design, emphasizing the architect’s authorship over the project. Due to the multidisciplinarity that characterizes the holistic procedures of the architecture in the Second Digital Turn, the authorship is not necessarily individual and often is a result of collective practices.

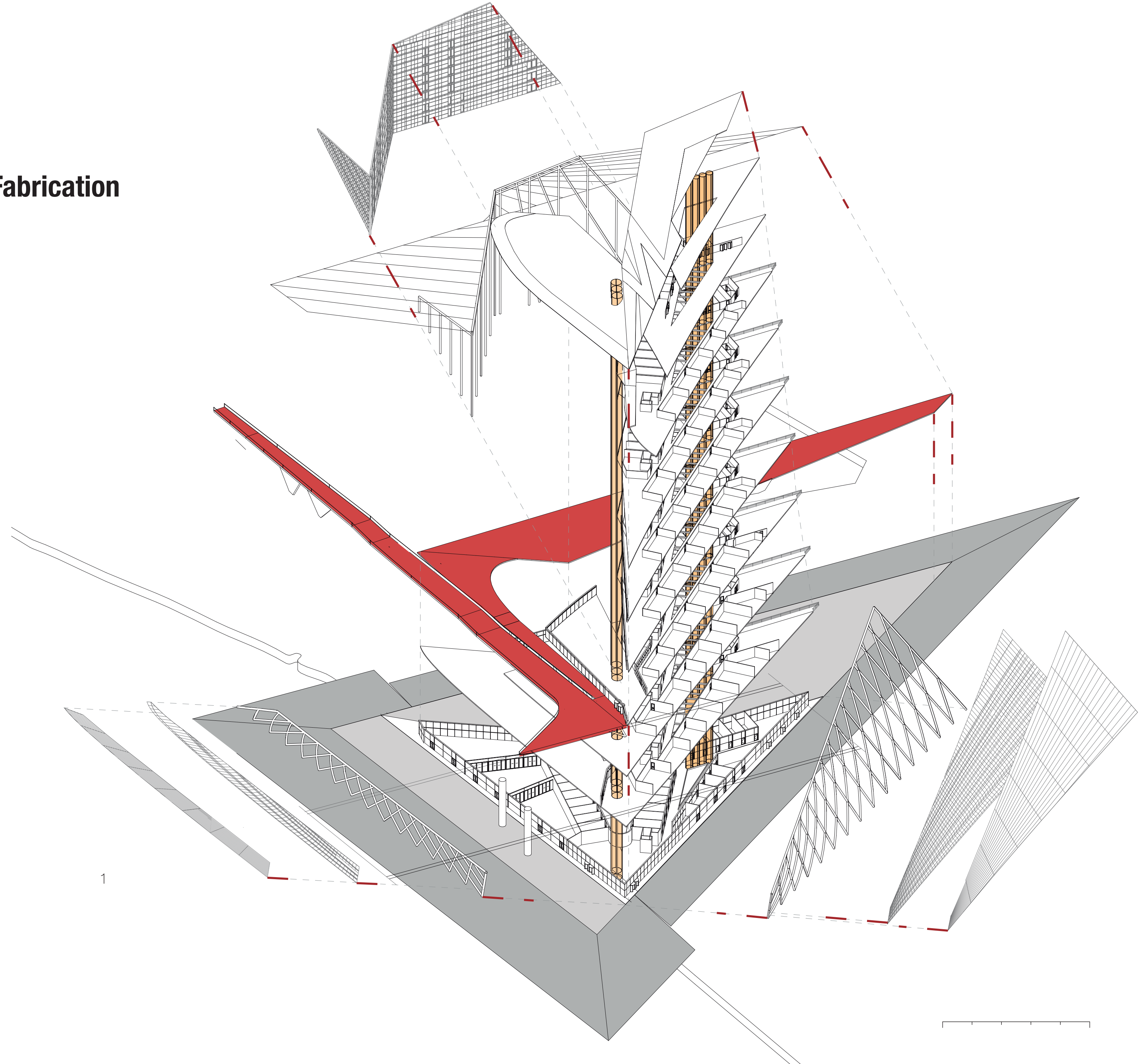




Drawing based on schematic figure from Robert Woodbury - Elements of Parametric Design (2010)

The Model

From Conception to Fabrication



1. Authoral project - The Ark - Fernanda Povoa
2. Scheme based on the Mario Carpo's work

2

The computer generates a virtual model. This virtual model can be used to represent architecture by image, as well as it can be used to build it in the physical world, breaking the historical position of the architect as an 'agent of notation' and adds him also the role of 'agent of fabrication', blending the bounders between thinkers and makers. With computer, the same tool is used to think, draw and make, in other words, notate, represent and fabricate (Carpo, 2017).

As architecture deals with a large scale, there is still the need for all layers of technical separation. This fact makes the digital fabrication more complicated in architecture than in other fields of knowledge, as for an example in medicine, dentistry and also design. At the same time, in the architectural field, as it deals with a larger scale, robotic is assuming the role of fabrication and assembling, reducing the degree of separation of components and systems.

In this context, much is said about the role of Artificial Intelligence in the model's design process. Artificial intelligence plays a crucial role in decision-making, meaning that AI assumes the role of quantifying and comparing results, providing an optimal outcome based on a numerical approach. The architect is still in charge of the creation, but by delegating to the computer the role to find an informed decision assures a performance-oriented architecture.

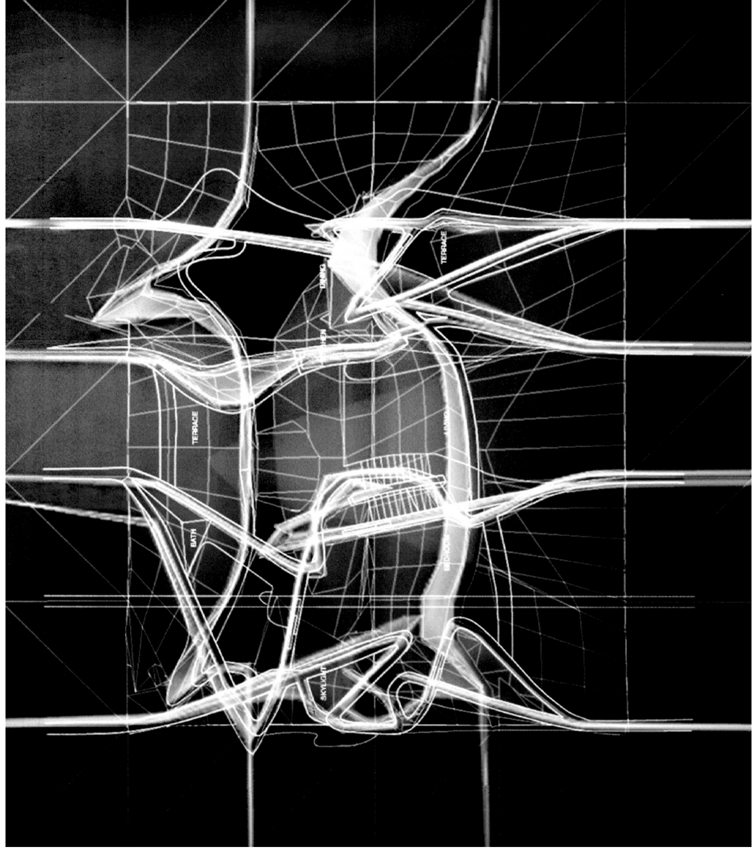
Mario Carpo (2017) separates the Digital Turn in two different phases. The first one was the rise of the first machines that could fabricate architectural elements based on digital models in a subtractive manner (CNC, milling machines), fading the separation between designing and making for the first time in history. The second one was marked by the rise of artificial intelligence, in which the machines were no longer a simple machine for making but was also a tool for thinking.

Carpo also points out how those fabricating tools have influenced the architectural conception, backwardly. The milling machines, risen in the 90s, worked on a smooth and continuous curve, a spline, in a subtractive pattern. As a result, the architecture aimed to embrace this smoothness and reflect it in a broader visual conception as we can see in the work done by Peter Eisenman in that decade.

With the emergence of 3d printers also came the exploration of the discrete elements in architecture. 3d printers work with the addition of material, voxel by voxel, considering their nature of discrete elements. This logic of infinitesimal deposition of voxels is impossible to conceive with only human ability, whereas it is pretty feasible and fast using machines. Said so, it is valid also to consider the scale of resolution desired using such addition methods os fabrication. Its use can be applied to a microscopical level of material granularity, taking into consideration the digital-informed structural behavior of each element (Carpo, 2016). As consequence of such precision, as in preliminary informed simulations as in fabrication, it is possible to save a massive amount of material and resources.

Mass-Customization

The concept of mass-customization is based on the adaptability of new digital fabrication tools. Due to the development of information management, and consequently, the rise of man-machine communication through software manipulation, the production line of construction can be adjusted easily and quickly, according to manufacturing demands.



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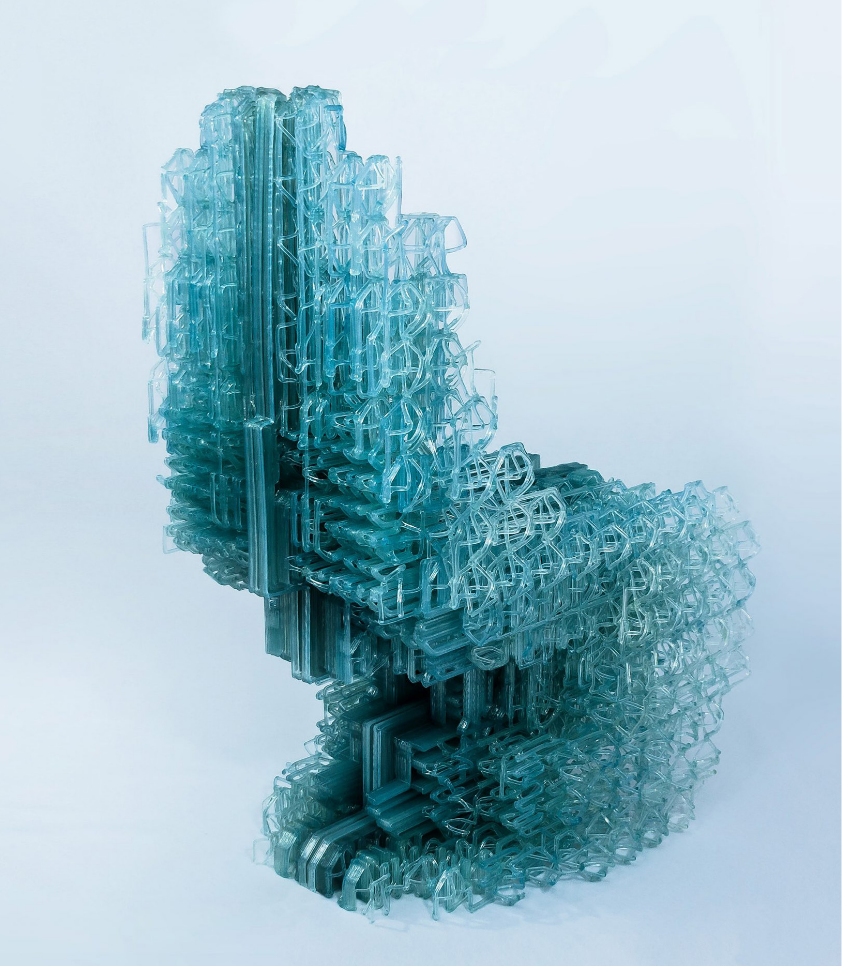
1. Virtual House - Peter Eisenman - 1997; Source https://eisenmanarchitects.com/Virtual-House-1997
2. VOXEL CHAIR V1.0; Bartlett's Design Computation Lab (DCL)
3. VOXEL CHAIR V1.0; Close-up; Bartlett's Design Computation Lab (DCL)



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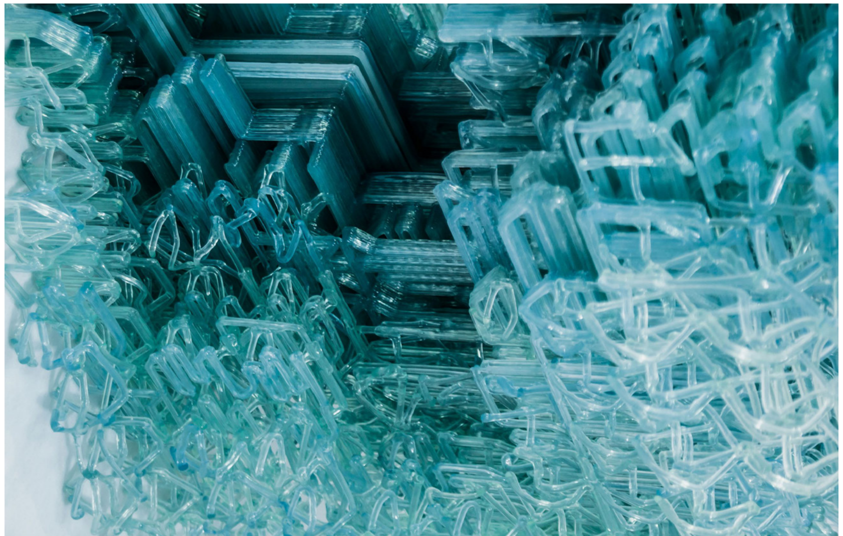

Architects and Engineers

New digital tools have changed the dynamics in the roles of architects and engineers. They had empowered architects with a whole new field of knowledge that before was not easily accessible, but still, the roles among different professionals remain under different domains. The past reality was the architect relying on his abstracts desires of expression and composition, leaving to the engineer to do a posterior rationalization. Now the procedure is quite different, by manipulation of algorithms and parameters with real-time feedback, the architect can come up with different rationalized and informed options of design. While the architect explores different techniques in a vast design space, engineering seeks precision and determinability. Through simulation, engineers arrive at a defined model and its constitutional properties, establishing clear and defined boundaries. Architecture is an anticipation, an exploration seeking expression while engineering is about material simulation and feasibility of the proposal. The fields are not competitive but complementary. (Menges, 2017; Belogolovsky, 2019)

Roots of Parametric Architecture

Mario Carpo (2016) writes about the early use of parametric descriptions in architecture. He says that the first use of sets of rules to describe procedural steps to build architecture, at least of what is known, dates back to classical antiquity. With limited technological press improvements, spread building proportion rules was only possible by describing them by a set of rules and parameters, hand-written, instead of images. Considering the proportions observed in the standard classical columns, parametric relationships define the proportion between its variables such as base, capital, entablature and height. (Frazer, 2016)

Vitruvius's manuscripts described, procedurally, the proportion and arrangement of different elements in a system without giving any visual example of it. His rules were quite complex and included the use of conditionals (if-then) clauses, what we could see today as a 'procedural algorithm' (Carpo, 2016).

Also in the Middle Ages, parametric procedures are observed. Almost all medieval building's parts were described as sets of verbal rules, explaining how to handcraft each component and how to assemble it to the whole. The outcomes of such a method of constructing are series of objects similar, as they belong to the same class, but seldom identical. Taking into account that information, such as building procedures and proportions, was disseminated by verbal rules due to technological limitations. Technological improvements also implied a shift in the informational spread. With the advent of the press and the possibility of printed images brought with the Renaissance, the image replace this proto-scripting procedure. (Carpo, 2017)

In the mid-twentieth century emerged another example of architecture based on described constraints. In the 1940s, the Italian architect Luigi Moretti coined the therm 'Architettura Parametrica', being the first person to do architecture using parametric equations using digital tools. In 1960, at the XII Triennale di Milano, he presented computer models of the "Progetti di strutture per il sport e lo spettacolo", a stadia designed parametrically with the aid of a 620 IBM computer. In his work he set nineteen different parameters like dimensions, costs and view angles to generate the form. (Davis, 2013)

Parametricism, as we know today, emerged rooted in Leibniz's modern differential calculus (Migayrou, 2014). The infinitesimal differentiation to find a finite outcome was the base on which the French philosopher Gilles Deleuze worked in his book "The Fold, Leibniz and the Baroque" that later served as support to architectural theories about the Digital discourse and "Differentiated Smoothness" developed Greg Lynn (1993).

> *"Smoothing does not eradicate differences but incorporates free intensities through fluid tactics of mixing and blending. Smooth mixtures are not homogeneous and therefore cannot be reduced. Deleuze describes smoothness as 'the continuous variation' and the 'continuous development of form'."*
>
> *"Folding became the method by which the surface of a large homogeneous volume could be differentiated while remaining continuous. This tactic acknowledges that the existing fabric and the developer tower are essentially of different species by placing their differences in a mixture, rather than contradiction, through the manipulation of a pliant skin. "*
>
> Greg Lynn
>
> The Folding, 1993; 2004

Architects and engineers in the nineteenth and twentieth century have used a process known as form-finding to derive shapes using physical models. By using gravity force and material properties as main parameters, catenary curves were generated directly in physical models instead of using parametric equations from the catenary curve. This process will be further discussed in the next chapter.

1. The plans for stadium version M and N showing the "equi-desirability" curves (Bucci and Mulazzani 2000, 114). https://www.danieldavis.com/a-history-of-parametric/
2. A model of stadium N by Luigi Moretti. Exhibited at the 1960 Parametric Architecture exhibition at the Twelfth Milan Triennial. The stadium derives from a parametric model consisting of nineteen parameters (Bucci and Mulazzani 2000, 114). https://www.danieldavis.com/a-history-of-parametric/

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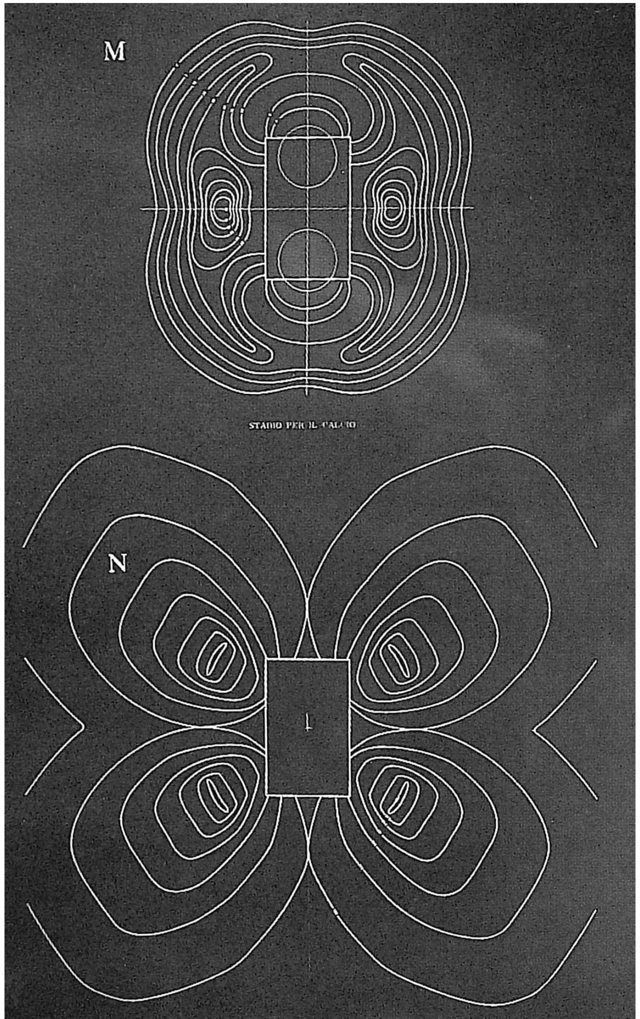

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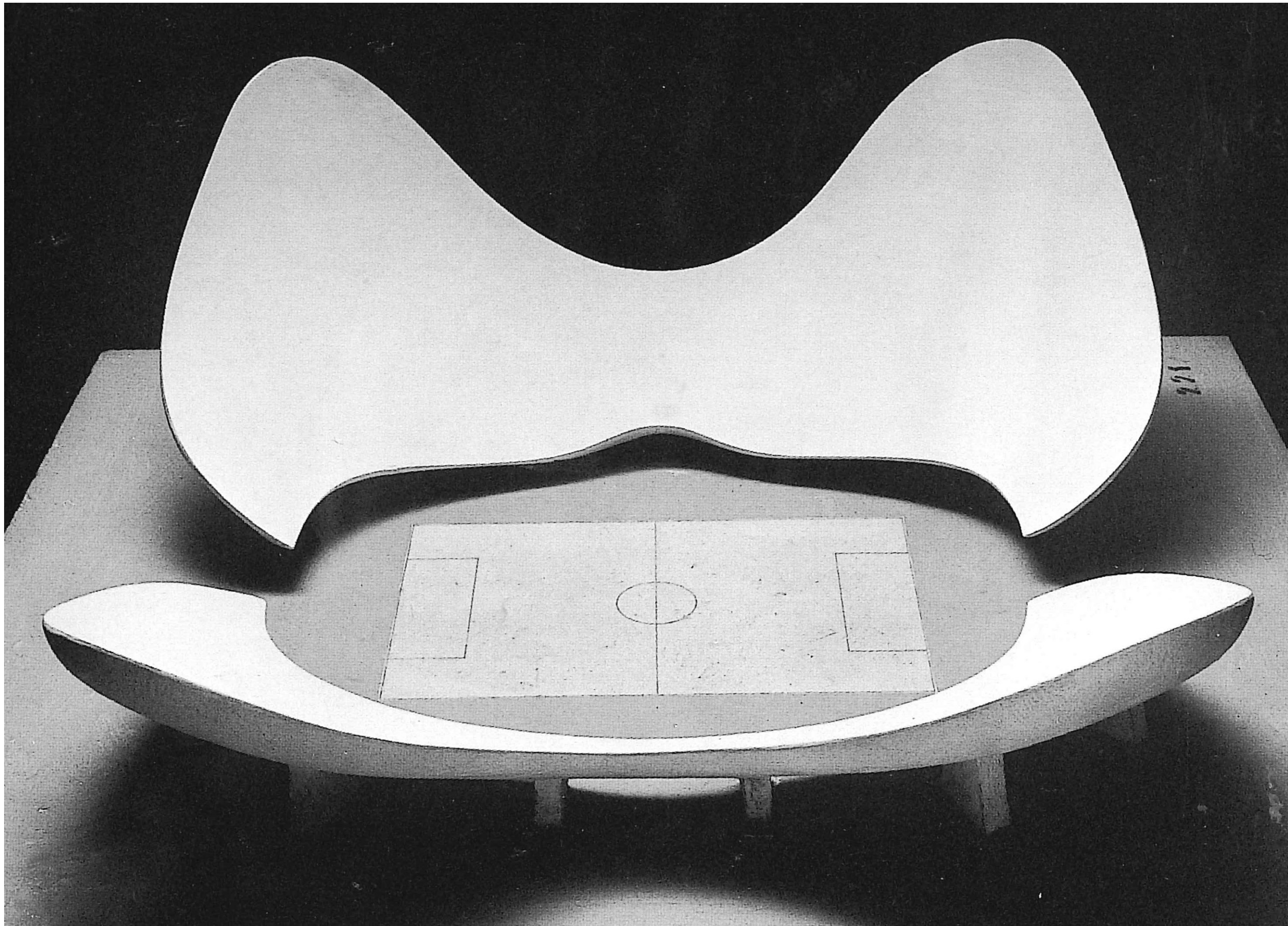
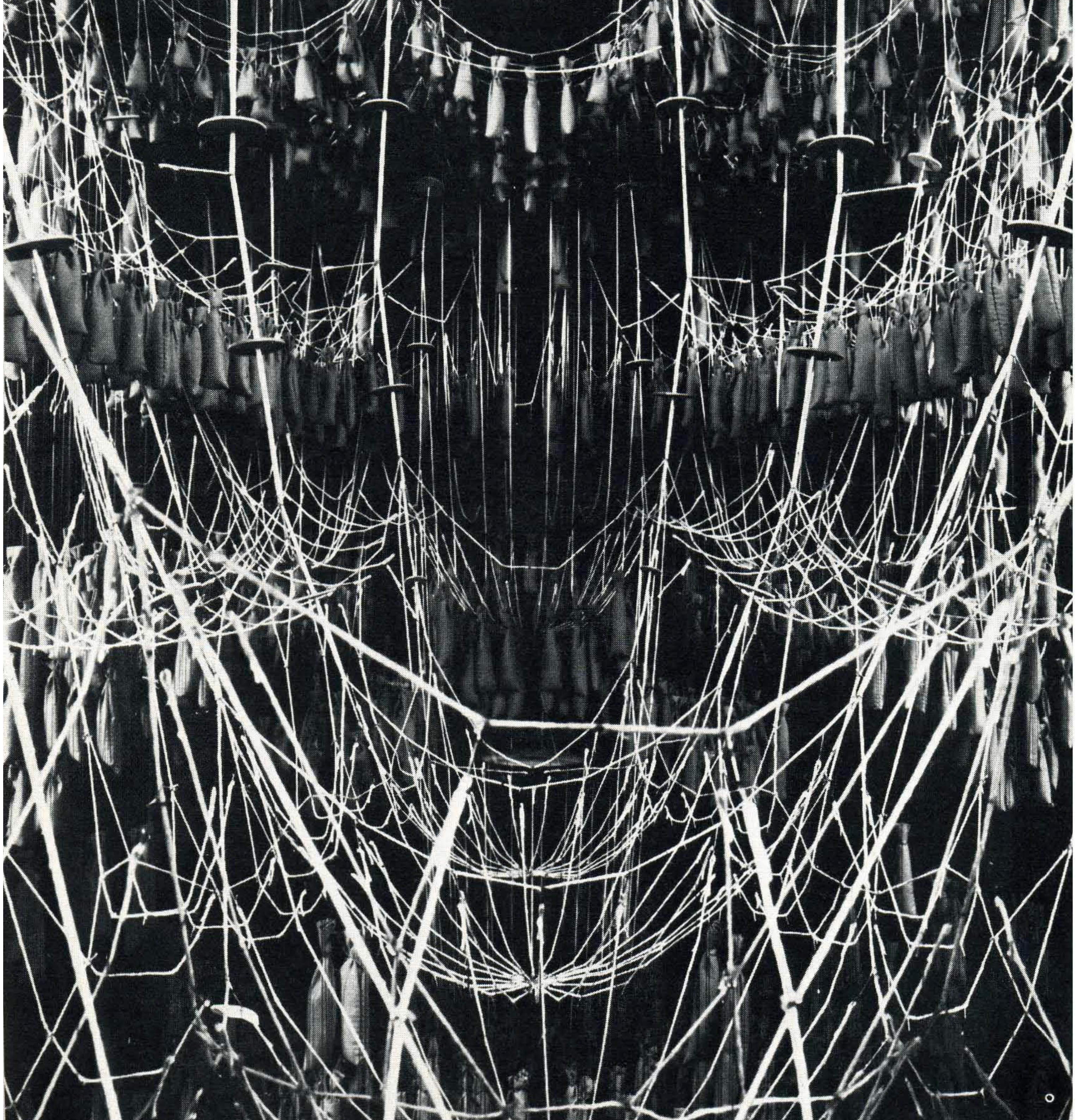
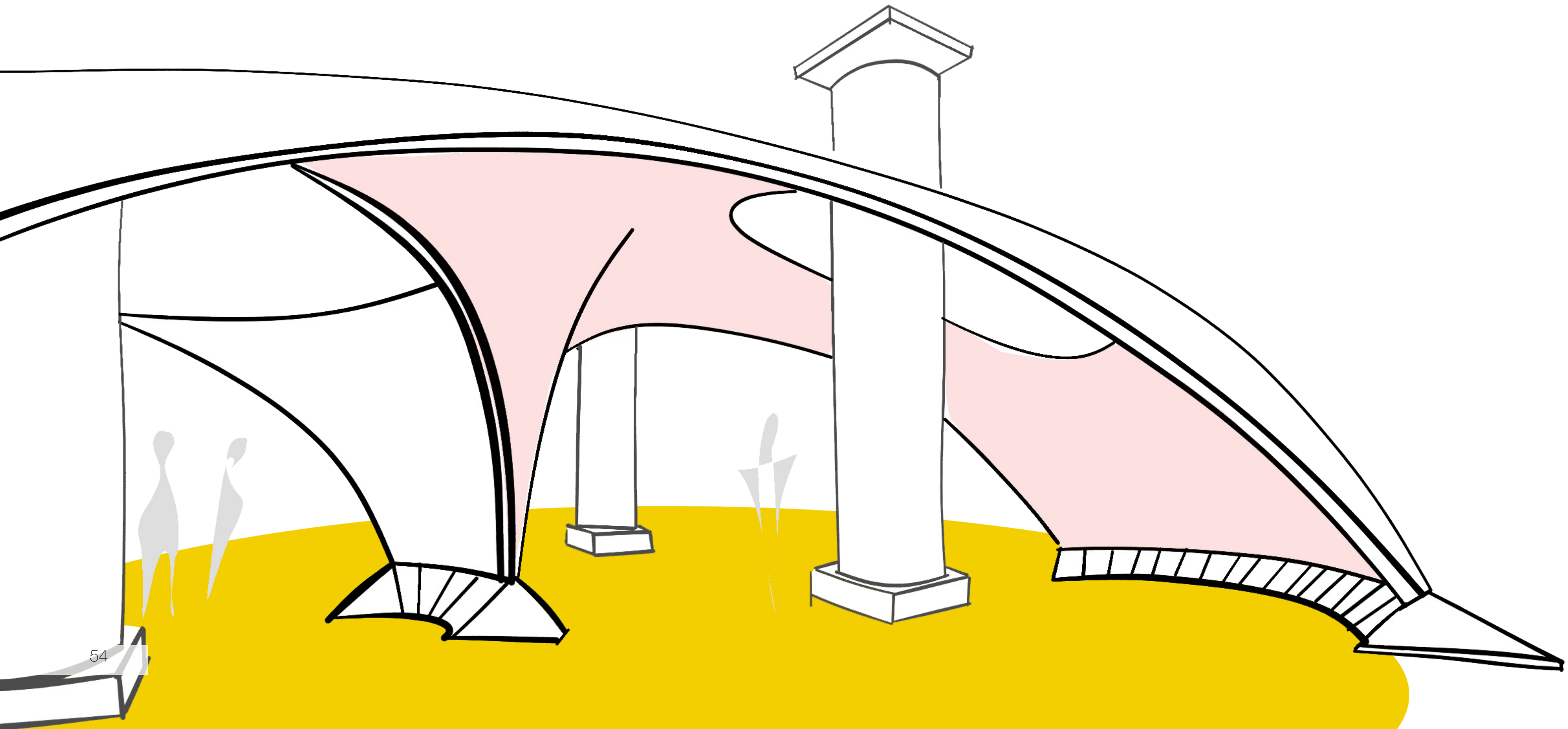


4. Form-Finding



Inside Gaudí's hanging model for the Colònia Güell. source: https://www.danieldavis.com/a-history-of-parametric/

Form-Finding Process



Authoral Drawing based on the work of Bloch Research Group - Armadillo Vault, Venice, Italy, 2016

The use of digital tools to achieve a performance-oriented design is undoubtedly one great answer for a sustainable architecture. The information generated by such methods delivers instantaneous feedback, enabling designers to visualize the optimized output in every single step of the design process. The kind of information to be regarded in order to drive any project can be various, such as bioclimatic, structural responsiveness, the ratio of built spaces, among others. Also, that information can be combined, creating a 'pool' of possible outcomes based on the input data constrains, orienting the process of decision-making in a data-informed approach.

Free-forms have been, throughout the history of architecture, a source of fascination and expressional impact. The apparent lack of stability, together with the wonderments of such geometry's constructibility triggers enchantment upon people and even turns it into obsession among professionals (Picon, 2014). Before the development of interactive software, mathematically describable geometry, such as spheres, toroids, cones, ellipsoids and paraboloids, has been often preferred because their behavior and dimensions could be easily calculated through known equations (Addis, 2014). To obtain a low environmental impact, it is mandatory, when building such fluid forms, an integral view of the architectural project and structural project as one, since the first stage of design. Besides leading to considerable savings in material resources, the outcome inherent an elegance based on structural efficiency.

In some cases of complex architectural shapes, the structure is not conceived in parallel with the formal expression. In order to assure the feasibility of such projects, a post-rationalization of the structure is usually done. In this approach, simplification and abstraction of the whole complex form are done in other to assure it to stand still at the lowest cost (Ripmann, 2016). As already discussed in the second chapter, the funicular shape is shown to be the optimal shape for a shell structure, resulting in optimized use of material. Different load cases must be taken into consideration and, regarding it, an ideal funicular shape is not suitable for full-scale structures, as they must resist to accidental loads that, if not taken into consideration in the design phase, can result in a poorly designed structure (Addis, 2014). In order to simulate real materials and load cases, small scale models have been valuable tools to find optimal forms.

The digital form-finding process for compression-only structures has its roots in the same methods as pre-digital methods. That means that the constraints imposed by nature are still the principal parameters to be considered to generate form. Among these constraints, mechanical properties of the material to be used needs to be one of the main drivers in the project's conception. (DeLanda, 2004)

> *"And we may now be in a position to think about the origin of form and structure, not as something imposed from the outside on an inert matter, not as a hierarchical command from above as in an assembly line, but as something that may come from within the materials, a form that we tease out of those materials as we allow them to have their say in the structures we create."*
>
> Manuel DeLanda, 2004

Before introducing digital methods for finding structural equilibrium for vaulted structures is vital to set a background of the pre-digital methods. Based on the research of Rippmann (2016) in his Ph.D. work, the following paragraphs will briefly discuss the method of Graphic Statics, Hanging Models and Soap Bubbles as precursors of the current digital form-finding methods.

Pre-digital Form-Finding

Technological advances greatly stimulated structural explorations during the twentieth century. Physical models played a significant role in the development of new complex shapes in architectural and engineering fields. From those physical models, geometric information was extracted in a process known as Form-Finding. In such an analogous process, three-dimensional compressive and tensile forces were understood as intrinsic behavior derived from form and material. For the use of such empiric method, we can point-out three principal figures: Antonio Gaudí, Frei Otto and Heinz Isler. Those will be discussed later in this work.

Different methods of prototyping were used, being the most known Hanging Models and Soap Films. The first one, hanging models, derive from the exploration of the catenary's physical properties. In order to better understand this kind of physical form-finding process, the second chapter of this thesis gave essential information about the catenary curve and its physical behavior.

There are many reasons to use small scale models in this kind of design process. According to Bill

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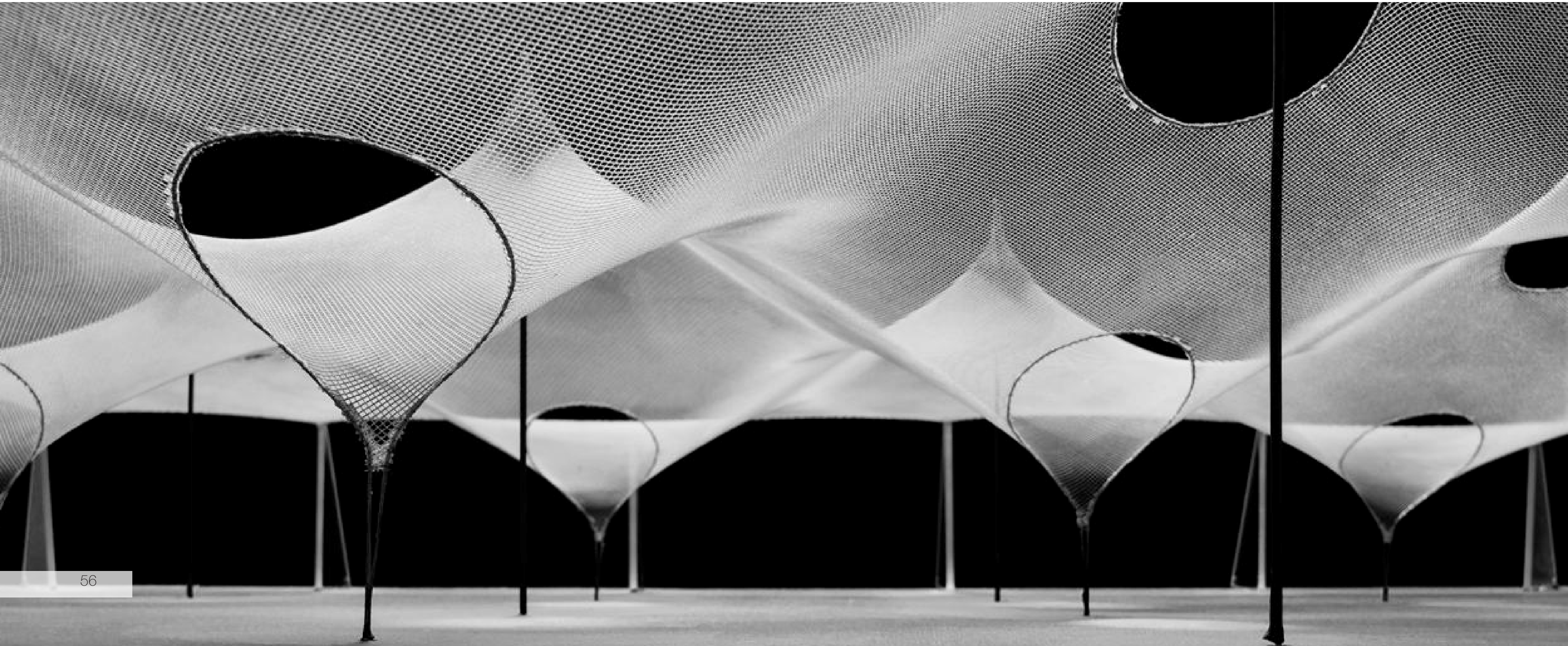


Addis (2014), the main reasons are:

- Calculation methods are complicated and time-consuming;
- The costs of building full-sized prototypes are high;
- Regular structural analysis was thought not to be reliable in those kinds of structures;
- Lack of built precedents in those kinds of structures.

Another reason regards the possibility to scale up a model still providing reliable structural information. In those structures, the scale does not interfere in its structural behavior, and by scaling up the model up to twenty times, it still presents the same load-bearing behavior. The structures that present a physical response not dependable from scale are systems working under pure compression, such as arches, domes and vaults. (Addis, 2014)

Although the reality now is virtual, and in this context, computational form-finding methods are hegemonic, physical models can still be a reliable source of information. As digital methods can show programming errors, as well as structural misinterpretation from the part of the user when inserting the essential inputs, it can lead to an unstable output. That said, small scale prototypes can serve as a validation technique that would check up the stability of the designed system.

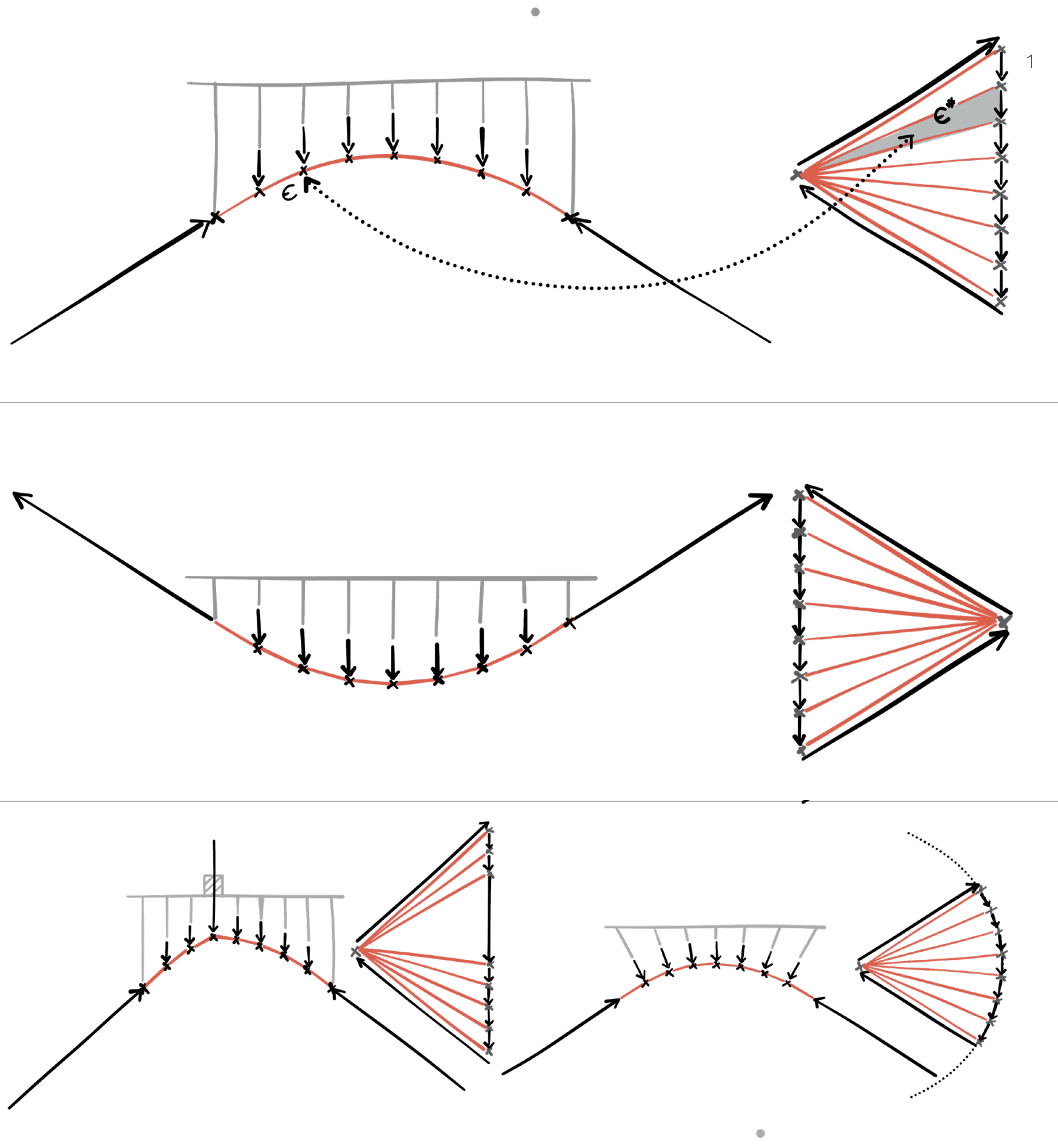
1. Model Frei Otto; source: Book "Thinking by Modeling"
2. Ice sculptures Heinz Isler; Souce: https://www.vice.com

2

Graphic Statics

This method provides a two-dimensional representation connecting a form diagram with the force diagram, being those magnitudes reciprocal (Maxwell, 1864). Form and force diagrams are reciprocal having the same number of edges. Each edge in one diagram always has a parallel one in the reciprocal diagram, and their dimensions are equal in the magnitude of axial force at a chosen scale, giving them the characteristic of being dually corresponding in both diagrams. Each node in one diagram represents a closed polygon in the other diagram. These properties of reciprocal relationships establish the internal equilibrium of the system by drafting and analyzing simple vectors.

Because of the reciprocity characteristic of the dual diagrams, the forces can establish the form the same way that the form can set the forces, and by controlling both diagrams, it is possible to pursue an informed design exploration. (Block, Lachauer and Rippmann, 2014)



1. Drawing based on the work of Rippmann “Funicular Shell Design”: *"The reciprocal relationship between the (a) form and (b) force diagram for a uniformly loaded funicular polygon in compression. The same funicular polygon (c) inverted in tension, (d) with an additional point load applied, and (e) a funicular polygon with constant axial force. "*
2. Funicular polygons by Varignon (1725)

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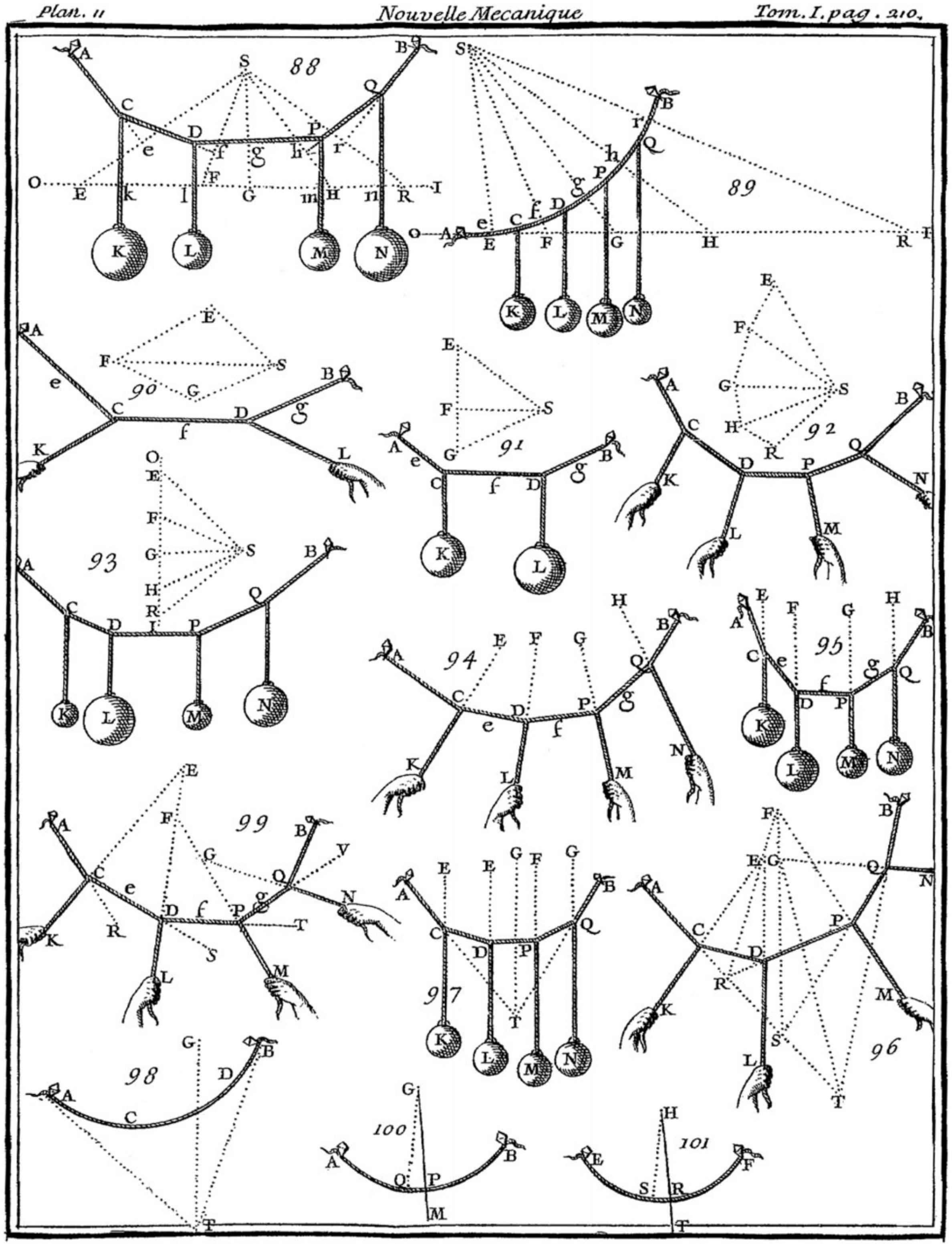

Hanging models

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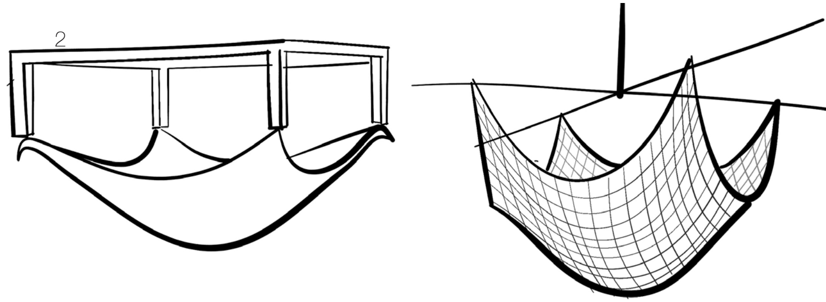
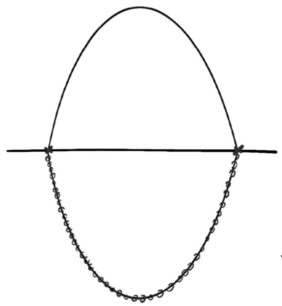




"Ut pendet continuum flexile,

sic stabit contiguum rigidum inversum.

As hangs the flexible line,

so but inverted will stand the rigid arch."

Hooke's law

1. Reproduction of Gaudí's hanging model for the crypt of Colònia Güell, Barcelona

2. Authoral drawing based on Isler's Hanging Models

This tree-dimensional method to obtain shapes that work in pure-compression has been used over centuries. The first one to use such method, exploring shapes by mechanical properties of the catenary, was Robert Hooke (1635-1703). (Rippmann, 2016). Firstly, it is worth giving the formal definition of the curve known by 'catenary', and its physical behavior.

Wolfram defines a catenary as being "The curve a hanging flexible wire or chain assumes when supported at its ends and acted upon by a uniform gravitational force. The word catenary is derived from the Latin word for 'chain'(catena).". The catenary, when its load is equally distributed along its path, approximates its curve to a parabola.

Hooke's Law that states:

> *"Ut pendet continuum flexile, sic stabit contiguum rigidum inversum.*
> *As hangs the flexible line, so but inverted will stand the rigid arch."*

That means that a hanging shape, working under pure tension, without bending moments, when inverted would work in pure compression, also free from bending. The shape of the catenary changes as the loads applied differs, and that is the starting point from any form-finding process.

By exploring the behavior of flexible lines responding to gravity, in pure tension, he came up with the conclusion of the equilibrium of funicular arches. St Paul's Cathedral in London is known as the first architectural use of Hooke's theory. The architect in charge, Christopher Wren, came up with the shape of the Dome's interior cupola by using hanging chains heavily loaded in its middle portion, as proposed by Robert Hooke.

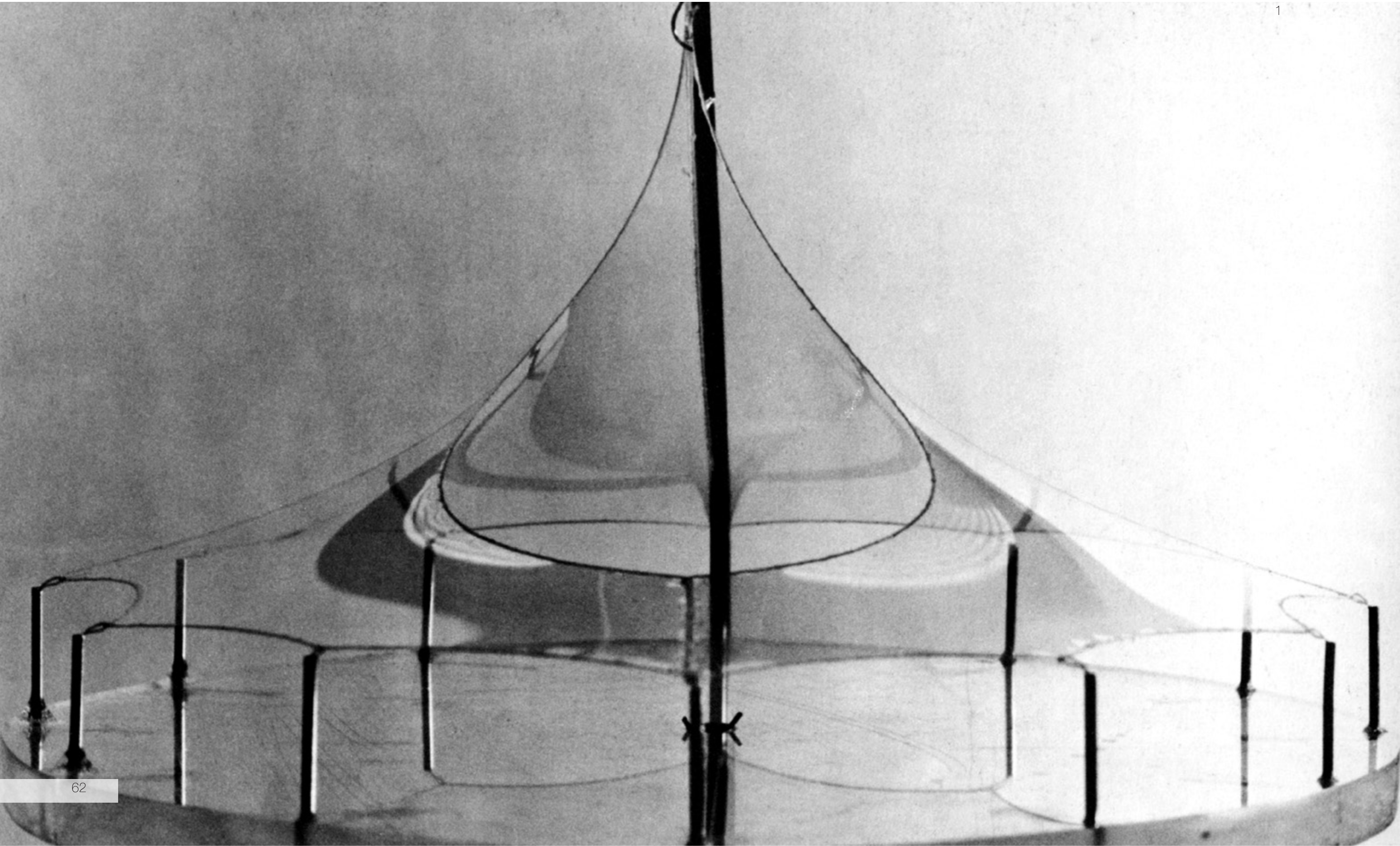
Antoni Gaudí was fundamental in the process of spreading such techniques. To come up with his creations, he explored complex three-dimensional hanging models, composed of interconnected strings and weights, in what can see today as a pre-digital parametric process. Playing with the placement and length of the strings, combined with loading, he was able to define the surface's topology and final shape of the whole building. In this process, the first string is the most susceptible to deformations, since it served as anchor points to the following. (Spuybroek, 2014)

In the twentieth century, two figures are worth mentioning regarding their form-finding creative process in the pre-digital age: Heinz Isler and Frei Otto. The first, Heinz Isler, has mastered structural art relying mainly on his models of hanging cloth, coated with plaster, resulting in a geometry derived from the natural funicular shape of pure tension. Those models, when dried and turned upside down, worked as optimized compression shells. Frei Otto, head of the Institute of Lightweight Structures in Stuttgart, also used such method of form-finding. Kwon by his work of thinking through models, he worked vastly with membranes, under tension and compression, and has always searched inspiration by observing and interpreting Nature's principles in order to optimize the use of materials. (Meissner and Möller, 2017).

Generally, the suspension method of form-finding, in order to create a vaulted structure free from tensile moments, a net with a defined topology is fixed by pre-established anchor points to a supporting structure. In the case of using cloths, after positioning these anchor points, plaster or any glue-like material is applied to the first net, and it is let to dry, reaching structural stability. By letting the whole structure dry and flipping it upside down, a shell-like form is created, structurally optimized, free from bending. In such method, the model shifts from a small scale miniature of a top-down process of design to an active generator of forms and structures. (Spuybroek, 2014).

This process is fundamentally a material-oriented approach in which material properties, their anisotropy orientation and the cutting pattern (topology) of the membranes used drives the output of the form-finding process. These material constraints imply that it is very hard to compare results between different experiments and such peculiarities of the material used in the prototype should be considered in the built structure. (Bletzinger and Ramm, 2014)

Soap Film and Bubble Minimal Surfaces



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Frei Otto played a significant role in exploring new complex forms. Inspired by nature, he started his experimentations by soap bubbles, minimum surfaces and fluid forms, and those experiments led to a wide range of possibilities due to their infinite forms (Otto, 2010). He also analyzed animal's bodies and their cells and bones, plants stems and stalks, unicellular organisms as diatoms and spider webs.

> *"The form of the building develops from a process of intense study and investigation. The more detailed this study and the freer it is from the preconceived ideas of the architect, the more chance there is finding a form of supremely sculptural quality and thus of symbolic expressiveness."*
>
> Frei Otto, 1958, 2014.

Experiments with soap bubbles and soap films illustrates physically minimal surface. Influenced by the biological text "On Growth of Form", written in 1917 by D'Arcy Thompson, these experiments with soap were fundamental visualization tools for tensile the work of Frei Otto. Even before Otto and D'Arcy Thompson, the Belgium physicist Joseph Plateau (1801-1883) first made experimentations with soap bubbles creating minimal surfaces.

The method consisted of wireframes being dipped into soapy solutions and resulting in surfaces with a minimum surface area and minimized surface tension. In such anticlastic surfaces, the mean curvature in each point is constant and equal to zero, meaning a consistently equal surface tension. (Otto, 2014) Otto affirms that such experiments delivered only 'parts of minimal surfaces', which in theory could be extended infinitely from all edges and mathematicians are still trying to reach those 'complete' minimal surfaces.

1, 2, 3 and 4 Frei Otto's soap films and bubble experiments.
source: Book "Form Follows Nature"

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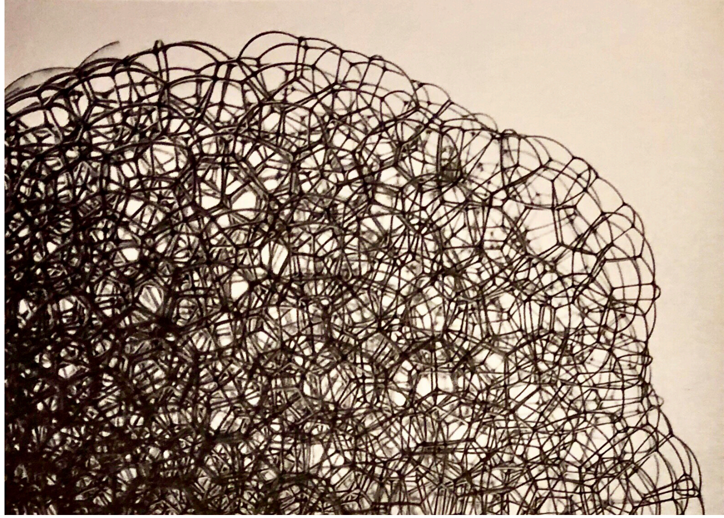

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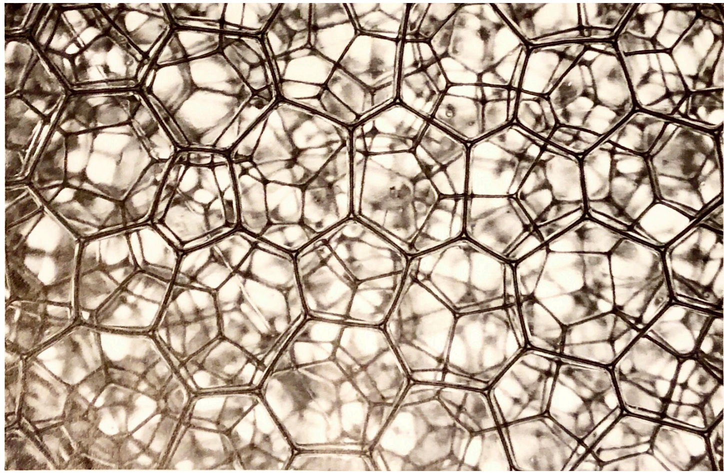

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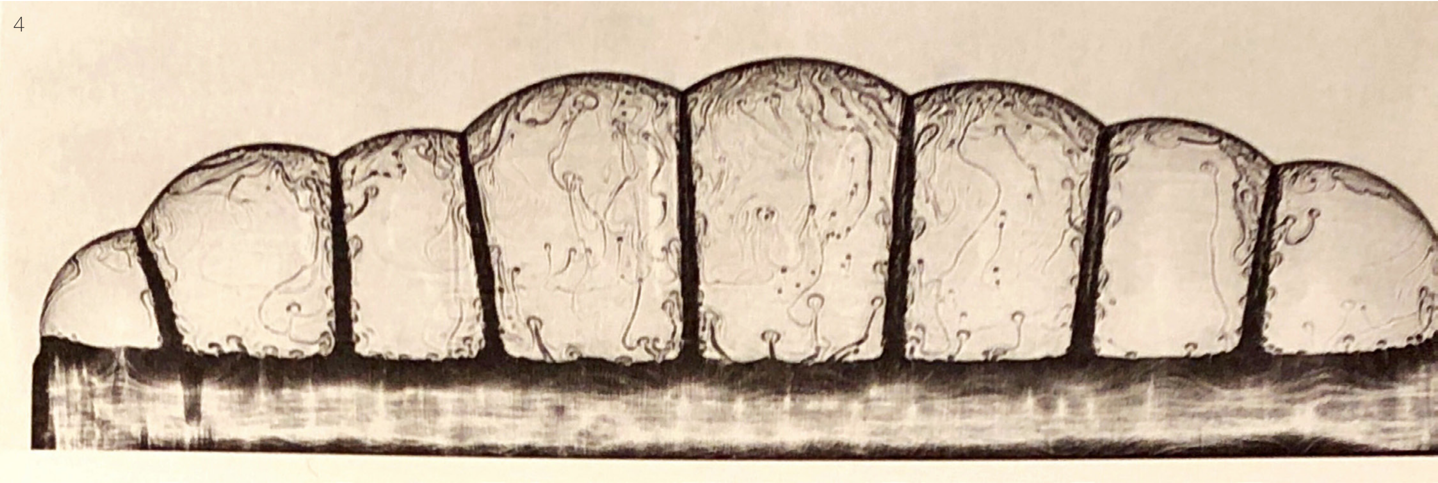


Pre-Digital Form-Finding Architects

Antoni Gaudí (1852-1926)

"Nothing is art if it does not come from Nature."

Antoni Gaudí

Born in Catalonia, Spain, and strongly influenced by a catholic context, Gaudí's legacy is still a source of inspiration for the contemporary architecture of the twenty-first century. The fascinating impact that his work promotes upon its spectators is the result of an extraordinarily complex and detailed architecture that links together structural and expressional form. His work turned out to be taken as an integral part of Barcelona's urban culture.

Nature was one of the most significant sources of imaginative inspiration for the Catalan architect, and by assimilation of its principles, he translated it to human-made form. He, by observation, realized that in nature structure and ornament is attached, that the natural forms were "statically perfect and extremely beautiful" (Roe, 2012), always performing perfectly under constraints imposed by the physical world. Antoni Gaudí understood structural design deeply integrated and inseparable from architectural design. Known by his sinuous shapes, he preferred working with parabolic arcs rather than the traditional roman arc derived from a circle. Structurally, Gaudí based his works on Hooke's Laws, establishing as an optimal form for compression efficiency the catenary derived from emblematic hanging models. (Huerta, 2006)

Besides his works with catenaries due to their mechanical performance, he also explored ruled surfaces, such as hyperbolic paraboloid and revolving hyperboloid. Those forces act in a surface-active mechanical performance, giving more stability than plane surfaces.

His most iconic building is the unfinished church in Barcelona, La Sagrada Familia. The project started in 1877 and the first stone laid in 1882, but in the year of Gaudí's death, 1925, only a small part of the church was yet done. Nowadays the project follows under the supervision of Mark Burry and relies genuinely on high tech digital tools to be able to carry on the project, in the most reliable way as possible, according to the original idea.

1

Images extracted from the website archdaily.com

1. The Passion Facade © Expiatory Temple of the Sagrada Família

2. Organic Columns La Sagrada Familia © Expiatory Temple of the Sagrada Família

Gaudí - La Sagrada Familia

Considered to be one of the most astonishing works of the Catalan architect Antoni Gaudí, the church of La Sagrada Familia started to be designed in 1877, planned to lay on the heart of Barcelona. The first architect in charge of its design was not Gaudí and its original design style was Neo-gothic. In 1882 the first stone was laid and only in 1884 Gaudí was named the official architect responsible for the church's design, changing the course of the design to his acclaimed "modernista" style.

In the design's conception, Gaudí relied on models of hanging chains in order to find optimized shapes. The chains were hang upside down, interconnected, with small weights hang attached to them.

By the time of Gaudí's death, the church was still far from done and still today is under construction.

The team in charge of the conclusion of the project is lead by the architect Mark Burry and relies on cutting edge digital tools in order to follow with Gaudí's design.

Frei Otto (1925-2015)

The German architect Frei Otto was a pioneer in the exploration of lightweight structures in the second half of the twentieth century. Deeply inspired by Nature and its physical generation principles, he developed a wide range of structures, based on different structural systems, integrating material and form. Such complexity present in his work led him to win the Pritzker Prize the year following his death.

Looking for optimized ways to do architecture, he motivated his research based on material and energy efficiency. From his variated experiments, we can highlight his explorations with cable nets structures, gridshells, branching structures, pneumatics structures and even wool-thread machines to search for minimal paths and apply it into urbanism. (Spuybroek, 2014)

> *"'Less is more' is something that fascinates me: use fewer houses, consume less material, less concrete, less energy, but build in a humane way using what is available: earth, water, air. Build in harmony with Nature and make a lot out of little, observe and think critically from the very first line of drawing. Better not to build at all than build too much! These are old and new goals."*
>
> Frei Otto, 1996

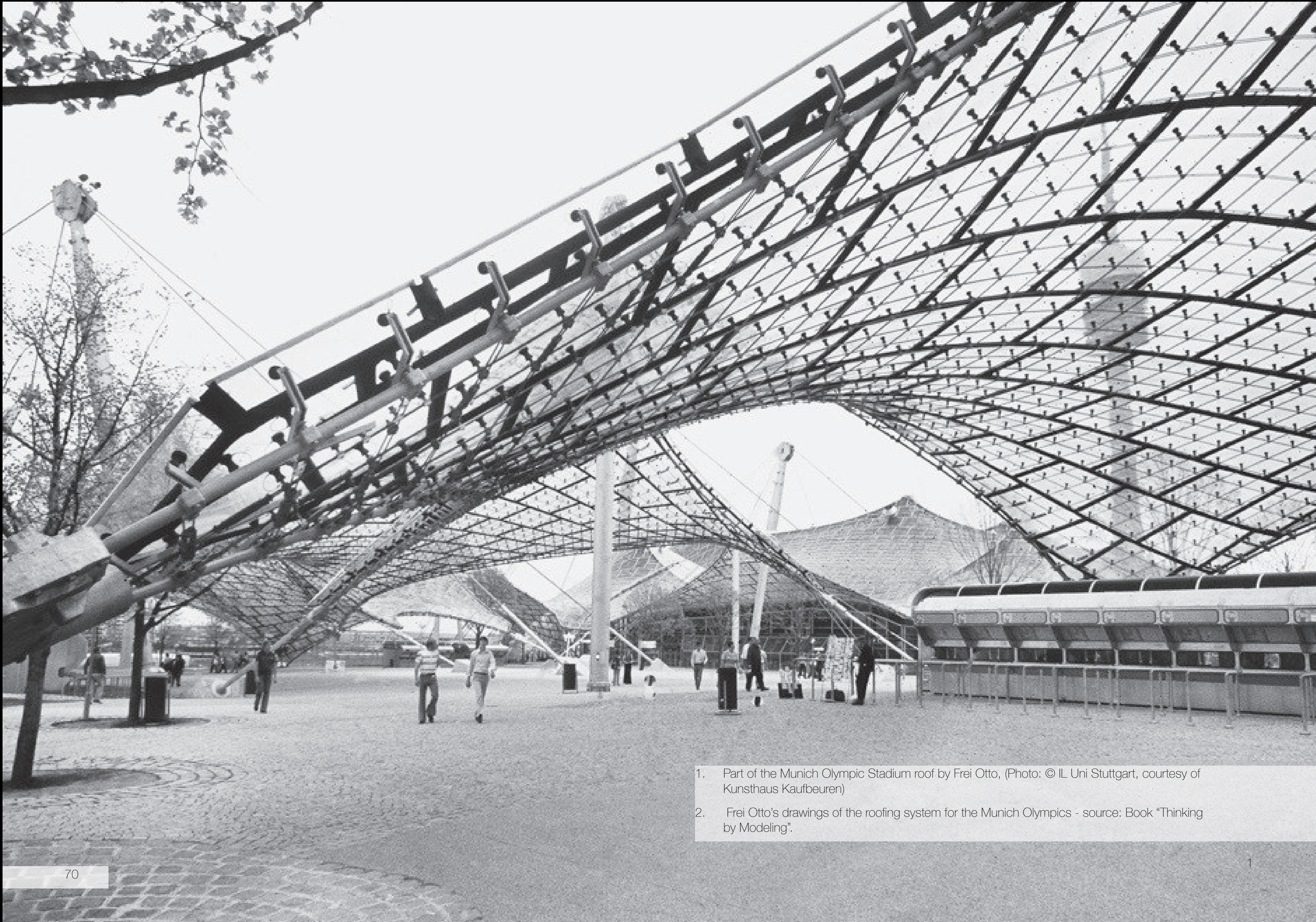
By observing Nature, and trying to understand it, he called himself a 'form-finder'. In order to carry on his research on Lightweight structures, Otto founded in Berlin in 1958 the Institute for Development of Lightweight Structures and in 1964 he became the head of the new Institute for Lightweight Structures in Stuttgart. (Meissner, 2015)

In the 1960s he finished his studies with air/water tensioned membranes and joined a research group called "Biologie und Bauen (Biology and Building)" in the Technical University of Berlin, the group was composed of biologists, paleontologists and architects. (Otto, 1996)

.

> *"A new world opened to us, an entirely new perception of Nature. Our work now became more important to me than building houses. We wanted to do pure basic research. We wanted to know how the world of animate and inanimate Nature came to exist, how its form developed and which constrains holds this forms together or modify them. We wanted to know whether our bold assertion 'in the beginning was the pneu' was really true and if this lightest of all lightweight structures did indeed lead to a preliminary stage of life and finally to the algae and bacteria and everything that followed. We wanted to learn about Nature and understand its creation a little more."*
>
> Frei Otto, 2015

In this context, the lightweight structures played a role much more significant than its optimal behavior and turned into an aesthetic grinding principle for Otto's Form-finding



1. Part of the Munich Olympic Stadium roof by Frei Otto, (Photo: © IL Uni Stuttgart, courtesy of Kunsthaus Kaufbeuren)

2. Frei Otto's drawings of the roofing system for the Munich Olympics - source: Book "Thinking by Modeling".

1

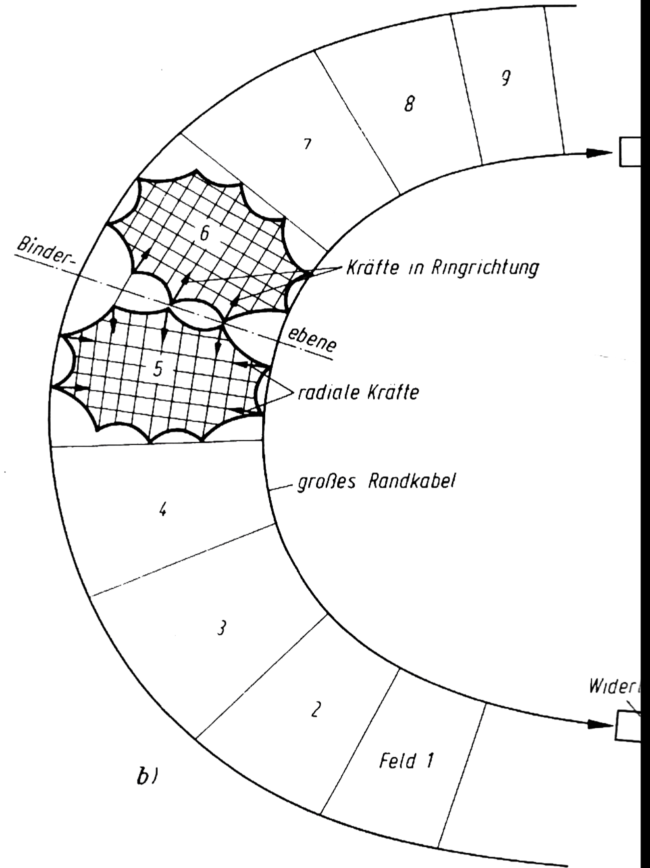
'72 Munich Olympics

Frei Otto and Leonhardt + Andrä

Frei Otto is well known by his pioneering work with new materials, arriving at forms though processes of form-finding. Through modeling, he mastered the mechanical manipulation Cable Nets structures, which worked similarly to membrane structures but could achieve larger spans due to the cables reinforcement. His first work with this kind of structure was the German Pavilion at the Expo 1967 in Montreal, although his most famous work with Cable Nets was the Roofing of the Olympiapark Munich, concluded in 1972.

Actually, there was a competition for the Olympic project in which Frei Otto did not take part. The winner was the architectural firm Behnish & Partner, but due to the architect's lack of knowledge in dealing with a large cabled structure and their feasibility, Frei Otto and the engineering office Leonhardt + Andrä were invited to lead the project's design, calculation and execution. The project's total area was about 72,000 m², counting with the main stadium, the sports arena, the swimming pool and a large roof connecting the arena and the pool.

Numerous models made out of tulle were used to establish the structural supporting system, the number, the type and the position of the masts. Further models were also used to extract scaled information regarding the topology of the final mesh, and through the method of "stereophotogrammetry", spatial coordinates were extracted for the prefabrication of the cable net. Cutting planes were created with the aid of computer programs developed just for this project. Also, a prototype 30x30 was created so it would be possible to test different kinds of materials to cover the roof.



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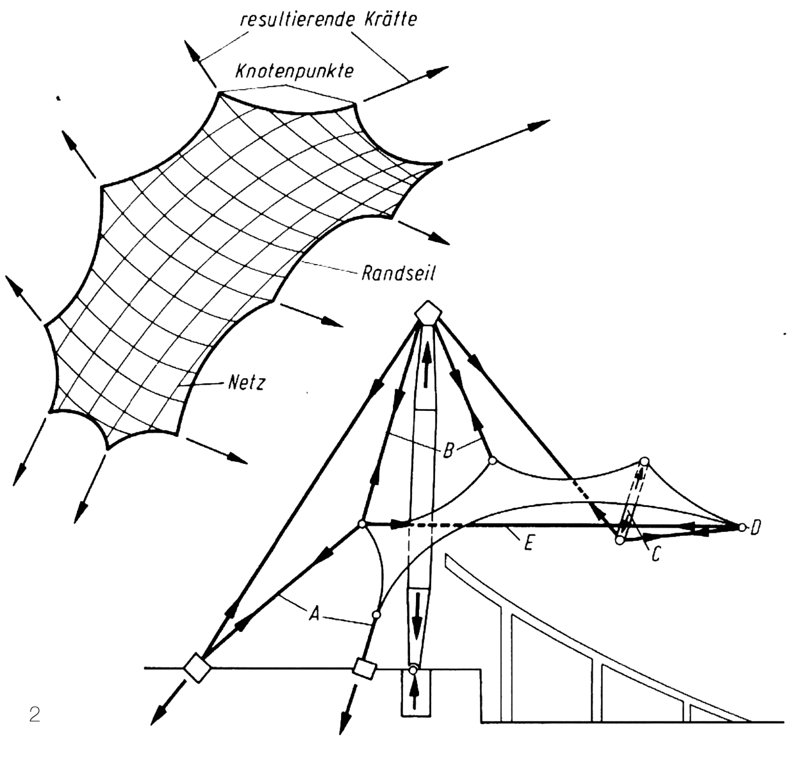

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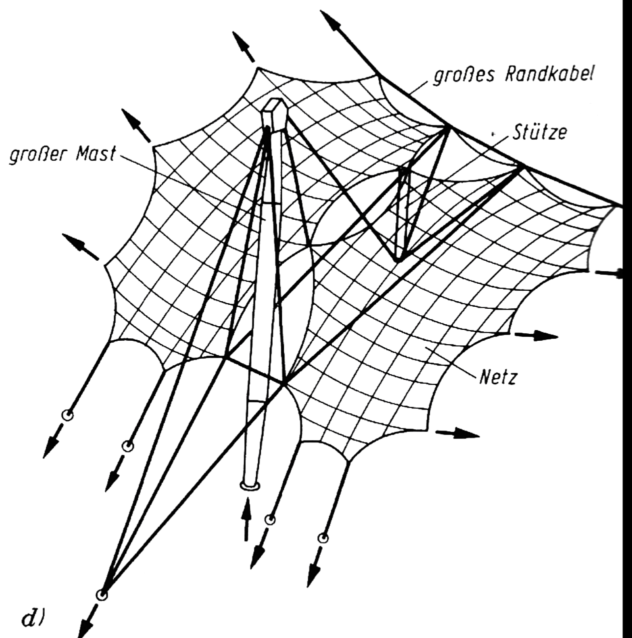

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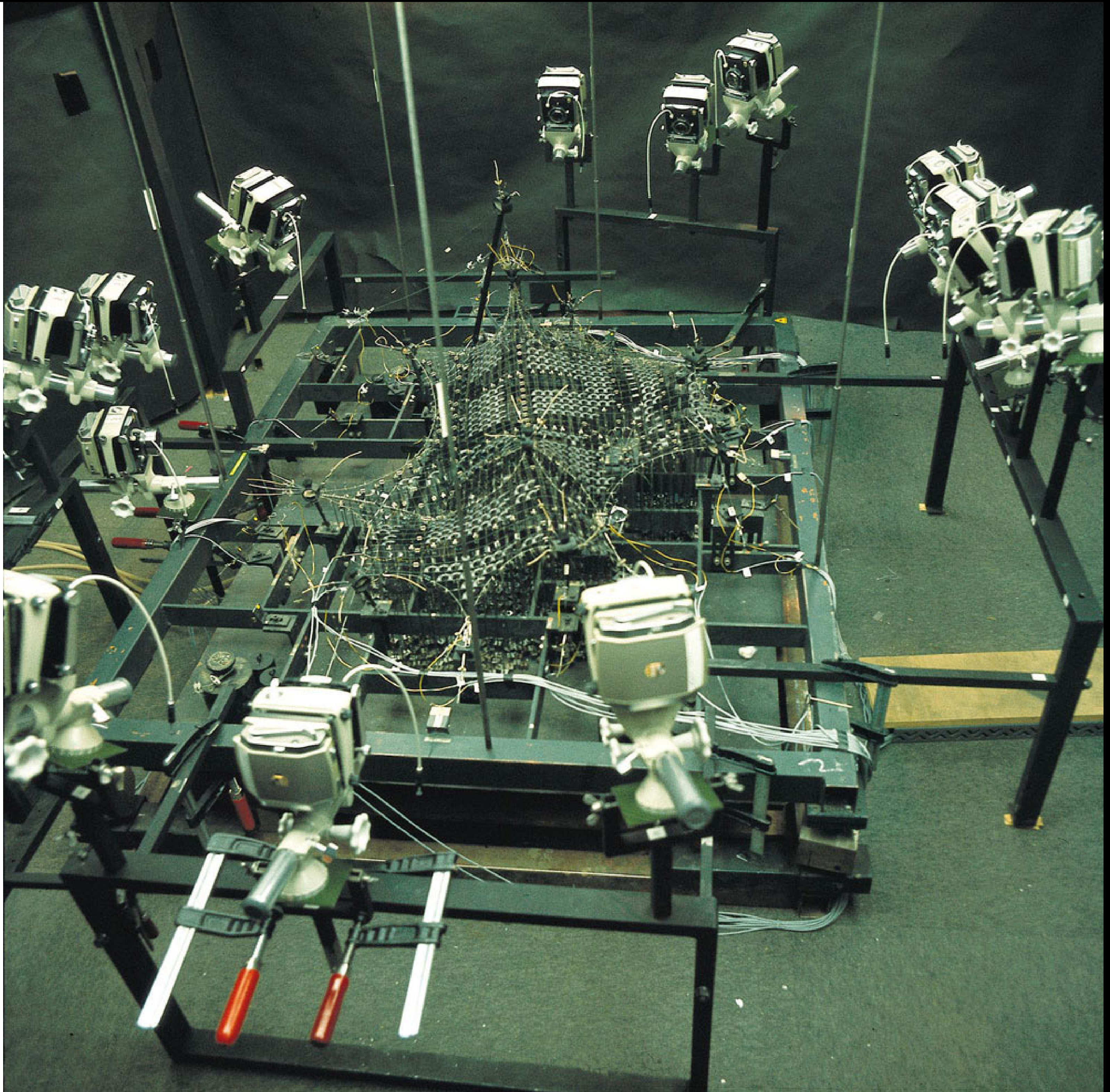

1. Model, roofs for the Olympic Stadium Munich, 1972 (co-operation with Behnisch & Partner, Leonhardt and Andrä). photograph: Atelier Frei Otto Warmbronn

2. Roofing for main sports facilities in the Munich Olympic Park for the 1972 Summer Olympics. Image © Atelier Frei Otto Warmbronn

1

Frei otto's gridshell - Bundesgartenschau Multihalle Mannheim

Ove Arup & Partners and Frei Otto

Based on the form-finding method of hanging chains subjected to photogrammetric analysis, Frei Otto has developed a series of gridshells. The Multihalle project, placed in the city of Mannheim - Germany, was built to attend the German Federal Garden Exhibition in 1975. The structure had a total area of 7,400m^2 and was made by 5x5 cm wooden laths laid crosswise layered in 2 or 4 laths. It had a maximum transversal span of 60 m and a longitudinal span of 85m, within a high of 20m above the floor. (Williams, 2014)

In this construction, the grid was first assembled as a planar surface, with the intersections lose. Afterward, a crane gradually lifted-up the system and the edges and nodes were stiffened in place, guarantying structural stability to the shell. Steel cables give extra stability to the grid, that receives a PVC-coated membrane as a roofing system.

2

1. Aerial view of the multifunctional hall in Mann heim, 1975 (co-operation with Carlfried Mutschler, Joachim Langner). photograph: Atelier Frei Otto Warmbronn
2. Inside the Gridshell, roof of the Multihalle, Mannheim, 1975 (with Carlfried Mutschler, Joachim Langner), Photo: Atelier Frei Otto Warmbronn
3. Hanging model, Multihalle's roofing, Mannheim, 1975 (mit Carlfried Mutschler, Joachim Langner), Foto: Atelier Frei Otto Warmbronn
4. Diagrams showing assembly of the grid shell - source: Book "Thinking by Modeling".

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Hanging model, Multihalle's roofing, Mannheim, 1975 (mit Carlfried Mutschler, Joachim Langner), Foto: Atelier Frei Otto Warmbronn

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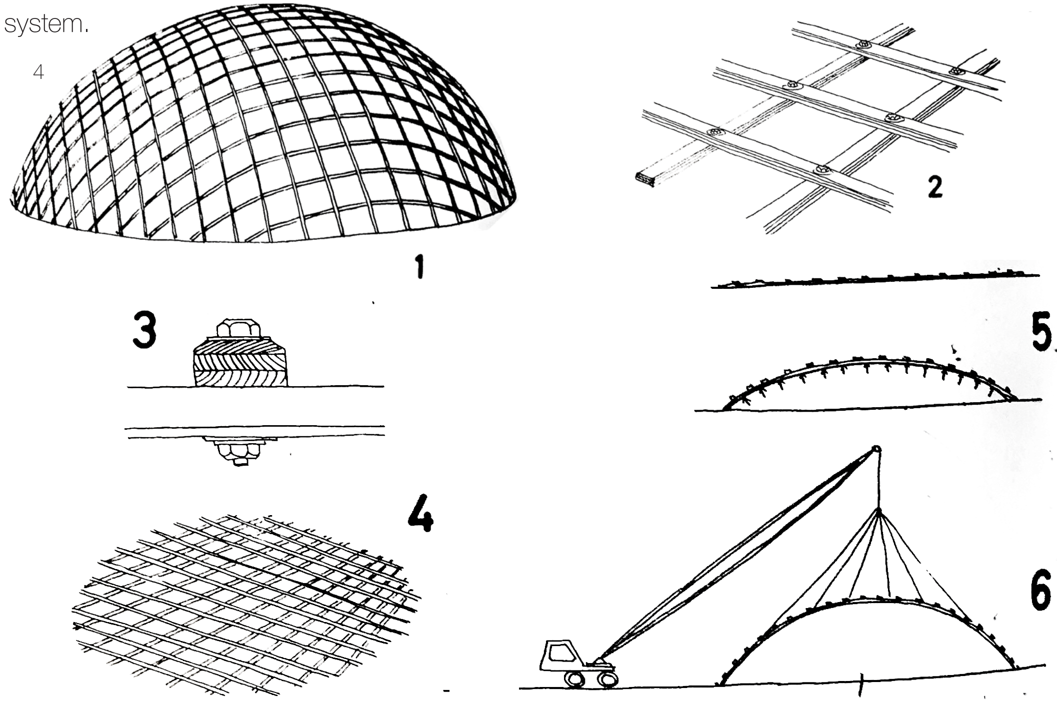
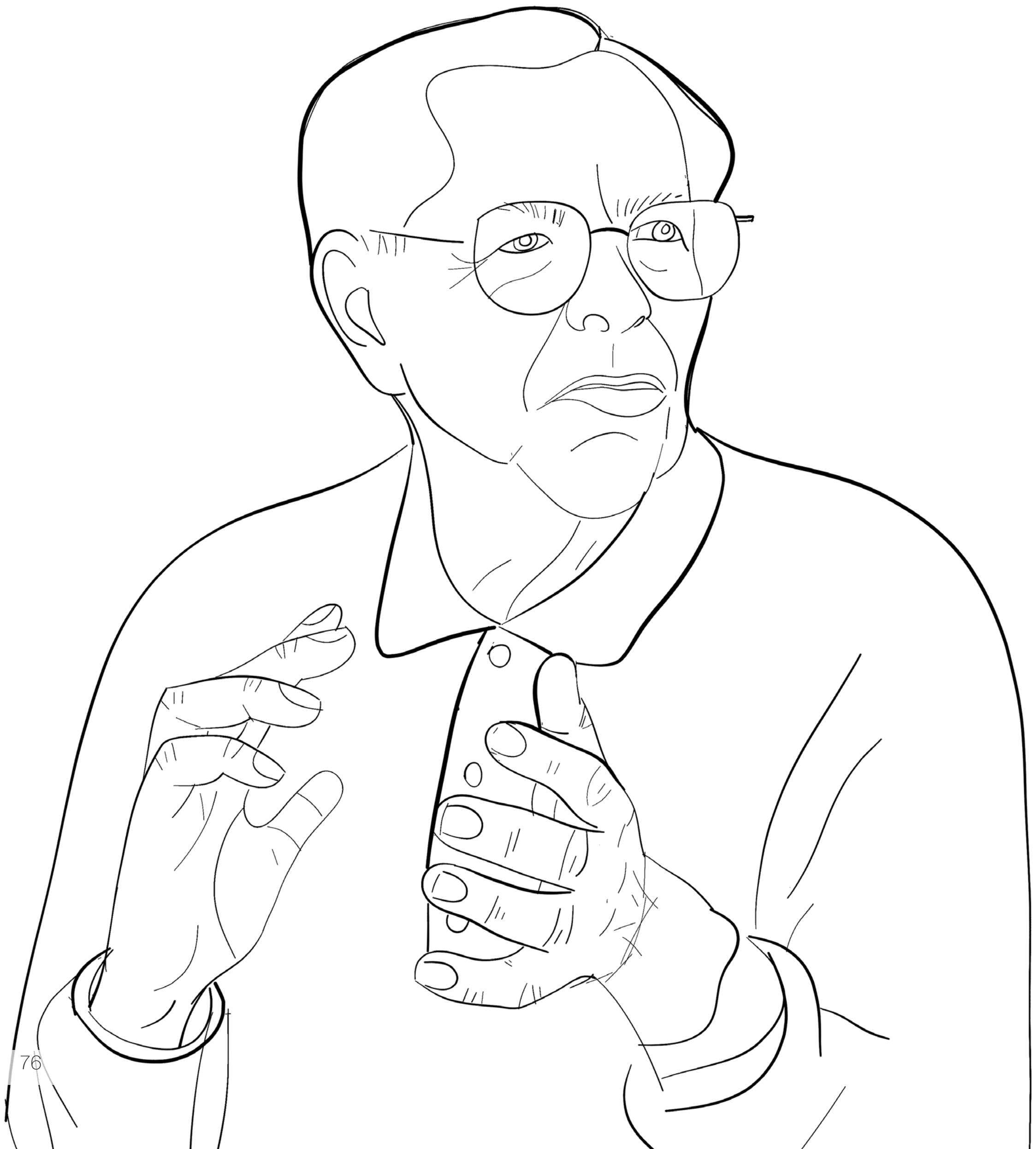
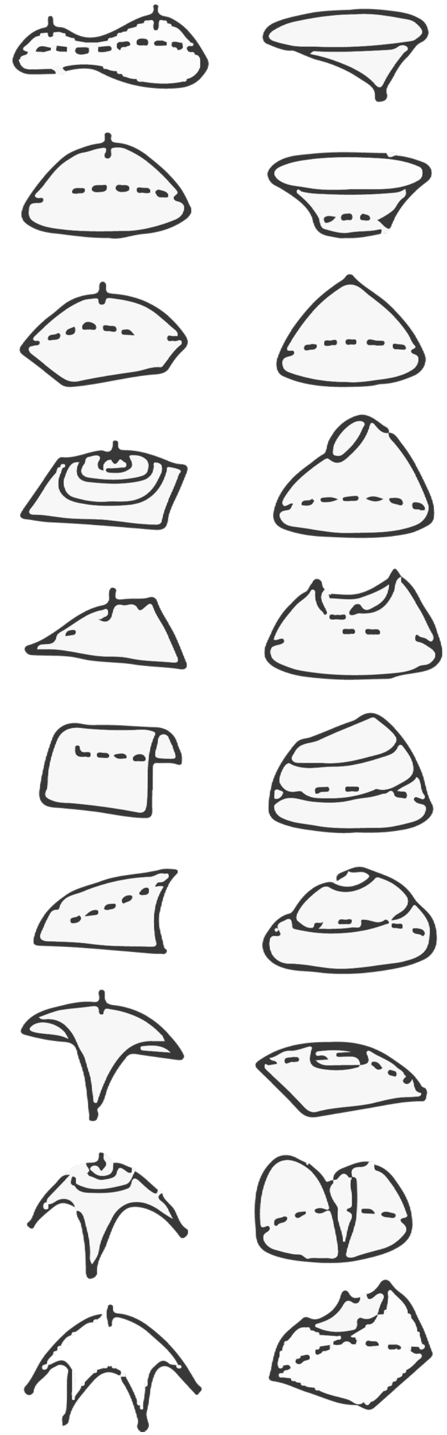
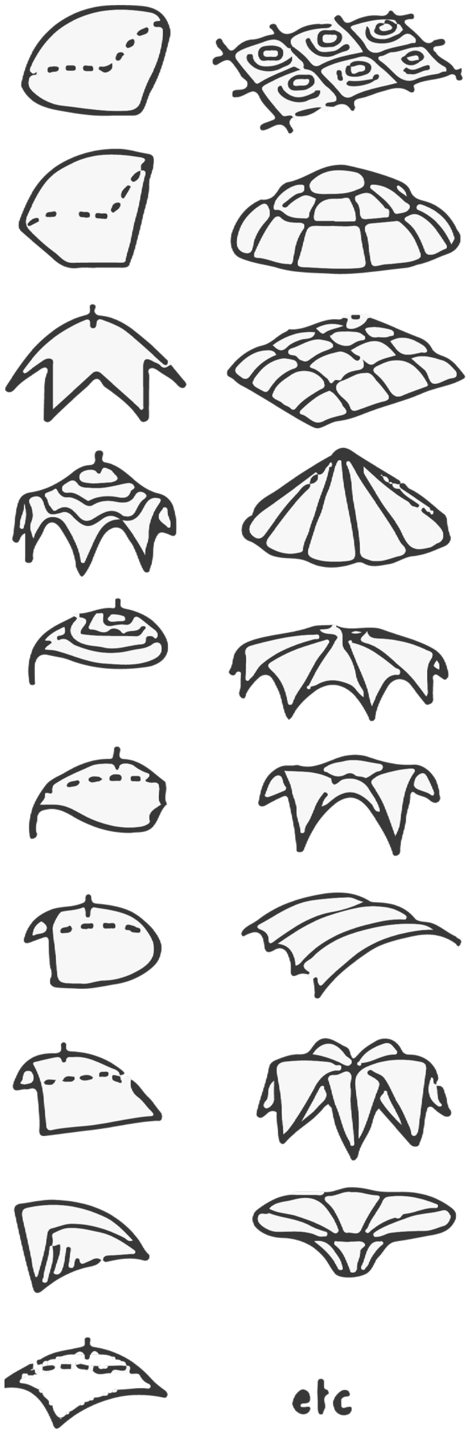


Heinz Isler (1926- 2009)







Proposition of possible compression shells
Heiz Isler

Born in Switzerland, the engineer Heinz Isler is one of the leading figures in form-finding in the pre-digital era, being responsible for the construction of around 1400 shell structures in 50 years of career, from 1954. Known for the development of his entrepreneurial methods of form-finding relying on physical models of shell structures, he used a wide range of techniques and materials (Chilton and Chuang, 2017),

In the pre-computational era, the only way to make these kinds of shell structures was through prototyping in different scales. By loading the empiric models, it was possible to extract data such as strain and stress. In 1961 he published a paper called “New shapes of Shells” in which he briefly explained his form-finding methods. In this paper he also reported three techniques to construct shells as a free-form, as a pneumatic structure or as a hanging membrane (Garlock and Billington, 2014).

One of his most exciting methods of form-finding consisted of the inflation of a rubber membrane attached to a test rig, forming a shape similar to ‘pillow’, with a double-curved geometry. After inflating the membrane, he would cover it with plaster and let it dry, so he could, afterward, extract its surface accurately translated into cartesian coordinates and curvature. With this extracted information, he plotted it as guiding profiles to further materialization in full scale. The bubble-like shape was widely used in his work, principally in his industrial projects (Silver et al., 2013).

A similar procedure was also applied to the form-finding method of hanging membranes. In this process, instead of inflating the membrane, Isler hangs it, extracting the funicular shape by casting it with plaster and carefully measuring its coordinates. Load tests on such structures were also made. (Chilton, 2010)

He also used ice in his form-finding experiments. As a result, he obtained astonishing ice sculptures, some of them even self-supporting. He managed to do such experiments with ice using only fabric and water under the cold Swiss winter. Such innovative methods he used to find form, including hanging, inflation, expansion and even freezing of thin membranes, gave him the recognition of being a “structural artist”.

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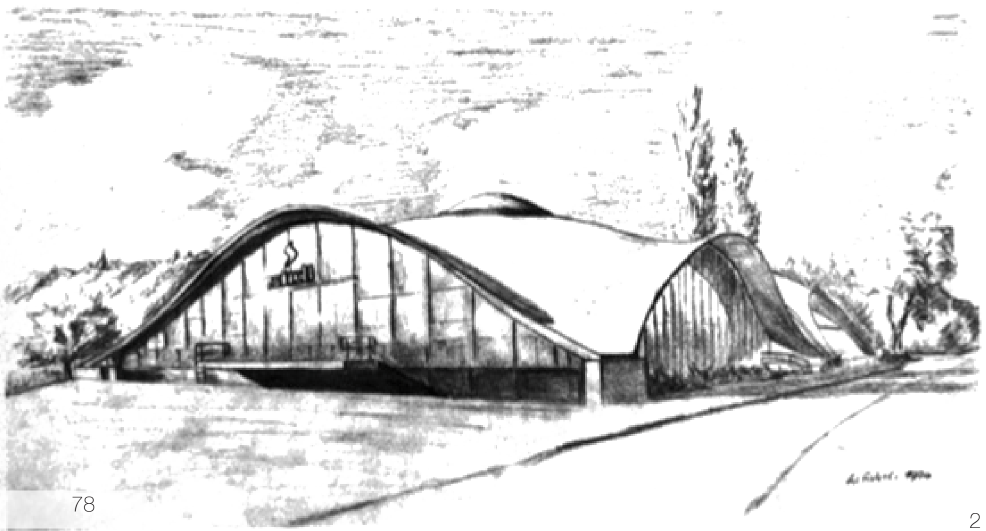

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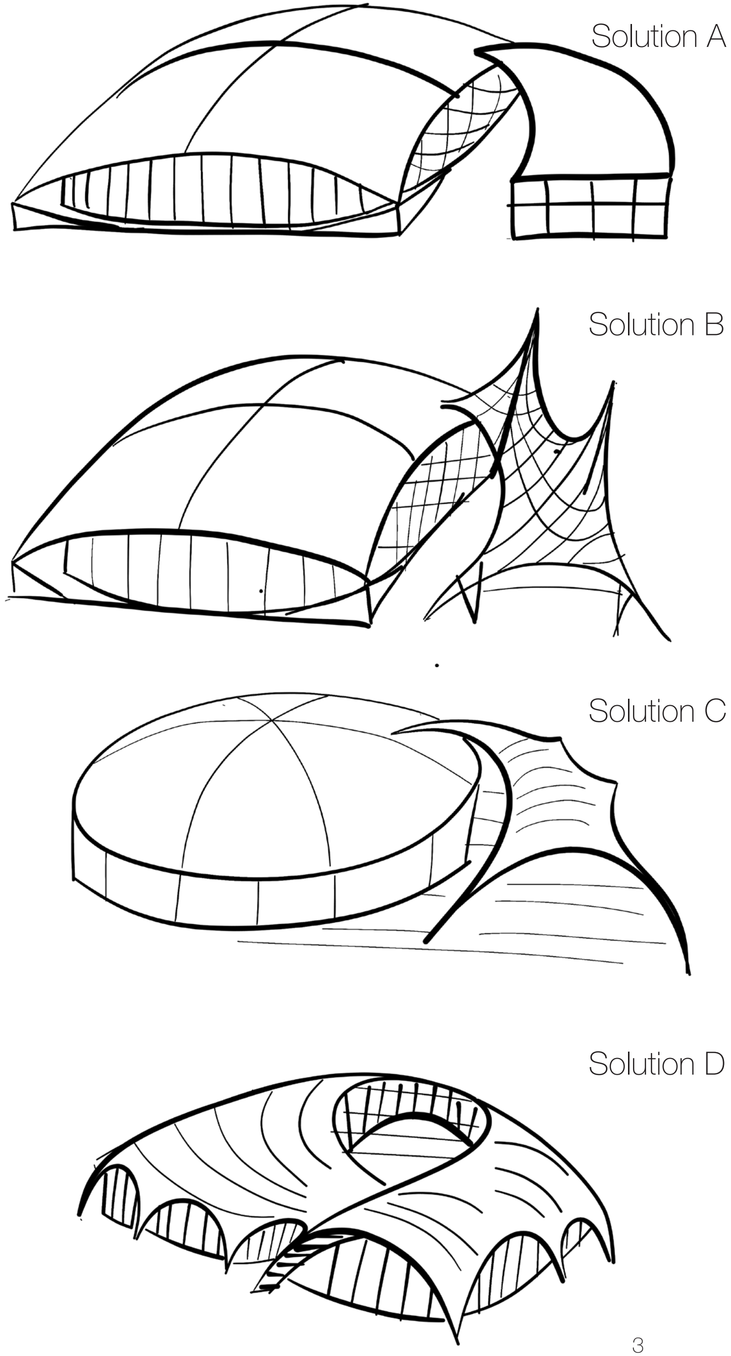

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Sicli SA Factory - Geneva

Constantin Hilberer and Heinz Isler

In collaboration with the architect Constantin Hilberer, the Sicli SA Factory was built in Geneva, Switzerland between the years of 1968 and 1969. Its roof is a shell working in compression, designed with the pre-digital form-finding method of hanging clothes. The structure has a span of about 33 x 53.5 m with a maximum high of 8.75 m and. The double-curved system was built in two layers, one concrete structural layer with a thickness of 90 mm and a 50mm layer of insulation that was also used as permanent formwork.

Isler has presented four initial design proposals. In the first one, the factory was developed under a squared shape shell while the office area was under a flat roof. The second one was similar to the first one regarding the factory area, but a tent roof covered the offices. The third solution was a rounded shell covering the factory and a conical shell curving the office area. The final solution was quite distinct from the first three ones. In this proposal, all functions were merged under one single spiral shell with fourteen anchor points (Chilton and Chuang, 2016).

The chosen design was based on elements from all four previous proposals. It merged all functions under an asymmetrical structure, dividing this way the different use purposes.

1. Sicli SA Factor, Geneva
2. Sketch of Sicli shell by Heinz Isler (© gta archives/ETH Zurich (Holding Heinz Isler). Photo: Chu-Chun Chuang)
3. Drawings based on Isler's sketches of (a) Solutions A, B, C and (b) Solution D (© gta Archives / ETH Zurich (Holding Heinz Isler)
4. Sicli SA Factory shell under construction, Geneva (ETH Zurich (Holding Heinz Isler), Photo: Chu- Chun Chuang)
5. Sicli SA Factory shell under construction, Geneva (ETH Zurich (Holding Heinz Isler), Photo: Chu- Chun Chuang)

Digital Form-Finding

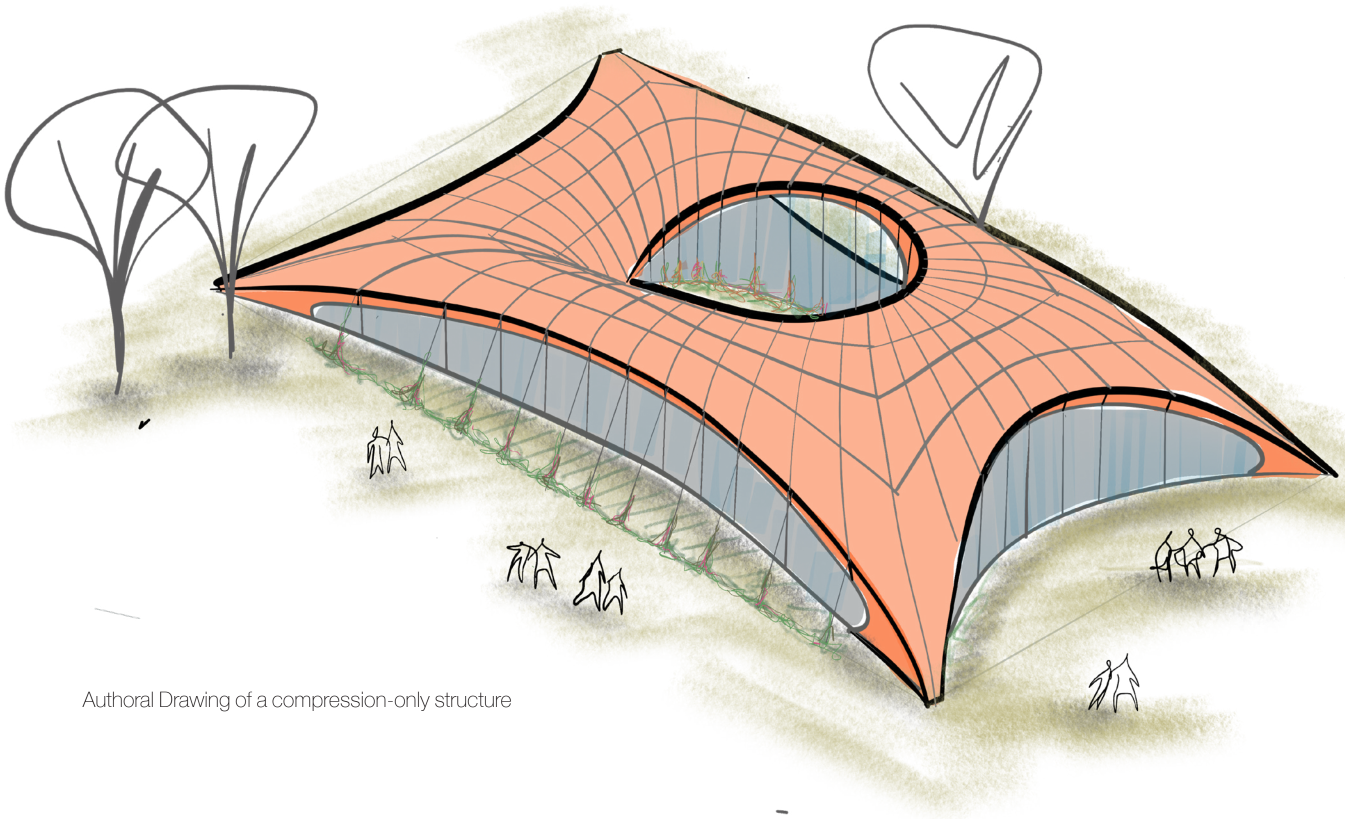
Compression-only Structures

Computational form-finding methods can be used as drivers to many performance-oriented designs. With the instant feedback that digital simulation offers, the use of such tools can be applied since the first steps of the project and can be based on infinite types of information, such as data from wind tunnel testing, bioclimatic parameters and acoustic simulations. The present work is about structural performance data, obtained from the natural behavior of compression-only systems.

Digital form-finding methods were born out of the need for more accuracy and speed in calculating complex structures. The analog process of modeling using gravity as an ally wasn't accurate enough to analyze precisely the forces flow, and due to such intrinsic complexity of funicular behavior, only computational tools would be able to analyze their mechanical performance in an integral approach. In response to this contemporary need, the first computational method of Form-finding was created by the engineer Klaus Linkwitz, based on the Force Density Method. (Rippmann, 2016)

The main challenge in form-finding is conciliating different criteria under one optimized structure. The architectural program and goals should come together with a structure that is designed to work under a dominant load case, which could be either tension or compression, so that makes the constraints regarding geometry more restrictive.

The main advantages of computational form-finding are regarding its fast speed, flexibility, adaptability and intuitiveness from the early design phase, in order to explore new structural geometries. That is mainly because of the possibility of controlling all constraints and parameters digitally, in a few clicks.



Authoral Drawing of a compression-only structure

RhinoVAULT

In the computational form-finding to be used and explained in the project is RhinoVaults, developed by the Ph.D. Matthias Rippmann, Lorenz Lachauer and Philippe Block (2012). This tool is a plugin to the Rhinoceros® software in which explores an interactive three-dimensional approach of form-finding method based on techniques such as Graphic Statics. Using RhinoVaults, the user should insert as input parameters the boundary conditions, the present design loads and the defined stress state. (Rippmann, 2016).

The equilibrium methods used in the software are the Thrust Network Analysis, The Dynamic Relaxation Method and Particle/Spring (PS) simulation and Force Density Method.

Besides being the first computational Form-finding method, the Force Density Method (FDM) is also one of the most used methods to project optimized tension/compression structures. Frei Otto, together with the architect Günther Behnisch, were pioneers by using such tools when designing in 1972 the pre-stressed cable net roofs of the Olympic Stadium in Munich, Germany. This method takes systems of non-linear equations, transforming them into linear equations so to find the static equilibrium of an initial data of forces, lengths and ratios. An advantage of using such method is that information about the material is not regarded when generating form, and it is taken into consideration only as a second step, not changing the original shape (Linkwitz, 2014).

The simulation methods, Dynamic Relaxation Method (DR) and particle-spring (PS) systems, work visually like the physical form-finding methods of hanging chains and soap bubble experiments. They achieve it by working with the elastic behavior of a network of linear elements, oscillating until finding the equilibrium state through a series of instant updates.

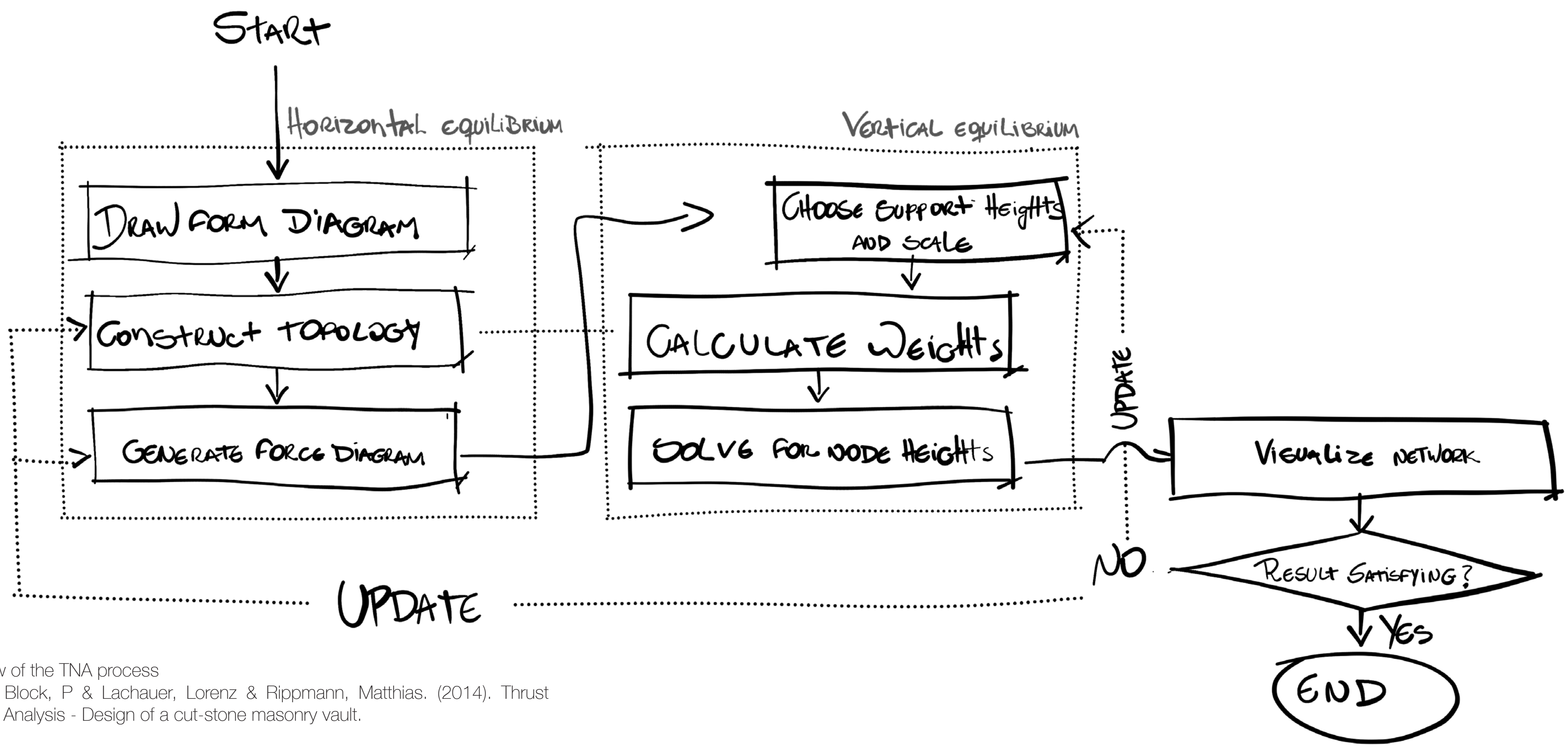
The core of the plugin RhinoVaults is based on the technique of Thrust Network Analysis (TNA). This method, developed by Philippe Block, has its grounds on the reciprocal form and force diagrams from Graphic Statics, so to apply to the FDM. The form diagram, as a horizontal projection, is the starting point from which the plan geometry is going to be defined, together with the force diagram, showcasing the horizontal trusts. After reaching the horizontal equilibrium, the software calculates the vertical equilibrium accordingly with the vertical loads. It is a tree dimensional version of the analysis of the thrust line, turning it into a spatial thrust network.

The interactiveness and the reciprocal graphics of form and force that the plugin presents are crucial to the form-finding process. This approach helps to build up structural knowledge and intuition even to designers with almost no structural background because it shows in parallel how technically the force and form are related to each other, given a robust educational character to the software.

The method is based on three key concepts: vertical loads constraints, reciprocal diagrams, statically indeterminate networks.(Block, Lachauer and Rippmann, 2014). The equilibrium of the horizontal thrust is based on the already mentioned method of Graphic Statics, in which the form and force diagrams work in reciprocity. The horizontal equilibrium is independent from the the vertical equilibrium, that makes the process if form-finding to be done in different steps. Firstly horizontal equilibrium need to be found and afterward, the vertical equilibrium. The first step, reaching horizontal equilibrium, consists of the manipulation of the horizontal projection of the thrust network aiming to find equilibrium with the force diagram, like the Graphic Statics method does, independently of vertical loads. The second step is about solving the vertical equilibrium based on the horizontal projection of the thrust network and the force diagram found in the first step, considering external vertical loads, nodes and anchor points positioning and hights. By reaching the vertical equilibrium under a predetermined load, the volumetric thrust network is set.

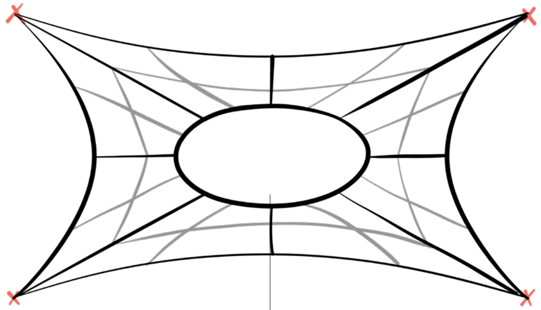
Several different thrust networks can be defined by different form and force diagrams and that is what is called “Static Indeterminacy of Networks”. There are a wide range of possibilities to reach a horizontal equilibrium for a predeterminated form diagram, that means that there is not a unique solution to form and force diagrams working with parallel edges, and each possibility reflects on different three dimensional solution . (Block, Lachauer and Rippmann, 2014).

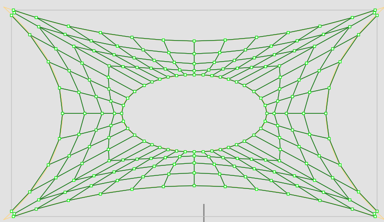
This dual process of finding horizontal and vertical equilibrium through two different steps enables us to interact effectively with the final output. The manipulations that can be made are the modification of the topology and geometry of the model, the redistribution of horizontal forces creating new forces paths, the overall height of the three-dimensional network and also defining and positioning the model’s anchor points.



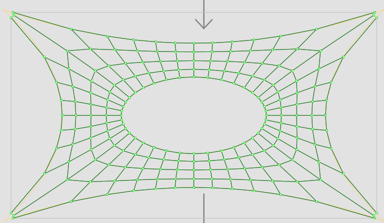
Overview of the TNA process
Source: Block, P & Lachauer, Lorenz & Rippmann, Matthias. (2014). Thrust Network Analysis - Design of a cut-stone masonry vault.

User's input - a polysurface with a topology already containing the implicit idea of force flow.

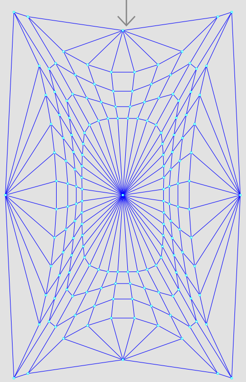




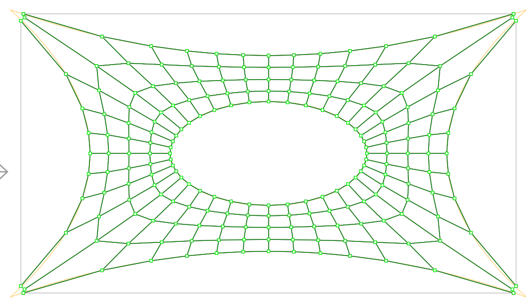
Primary form diagram generated by RhinoVault



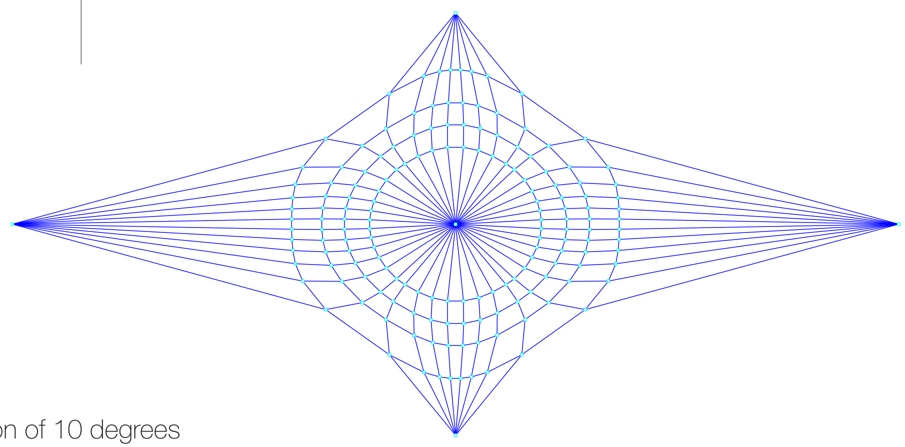
Form diagram after relaxation process

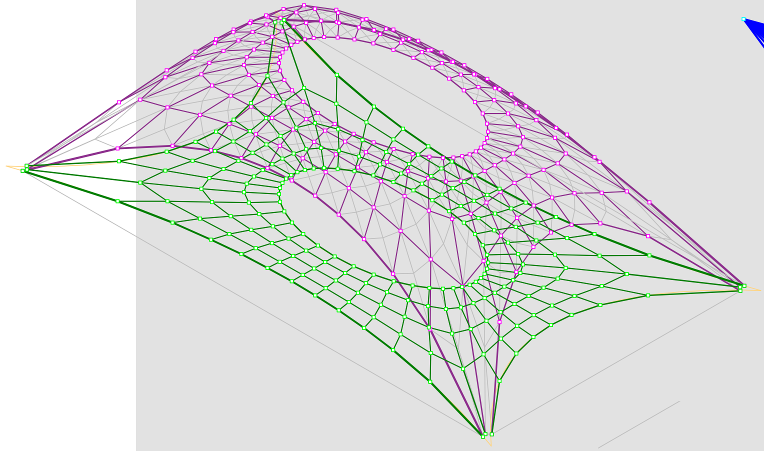


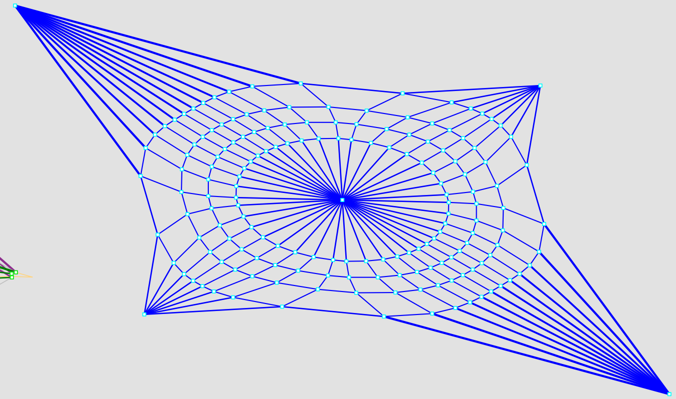
Force diagram generated by the form diagram

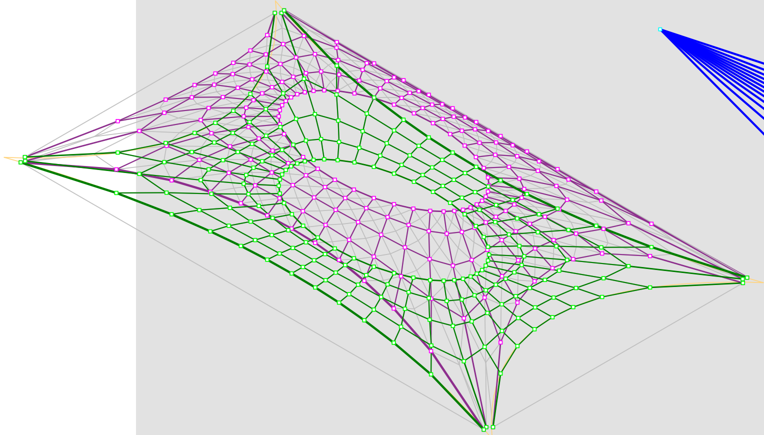


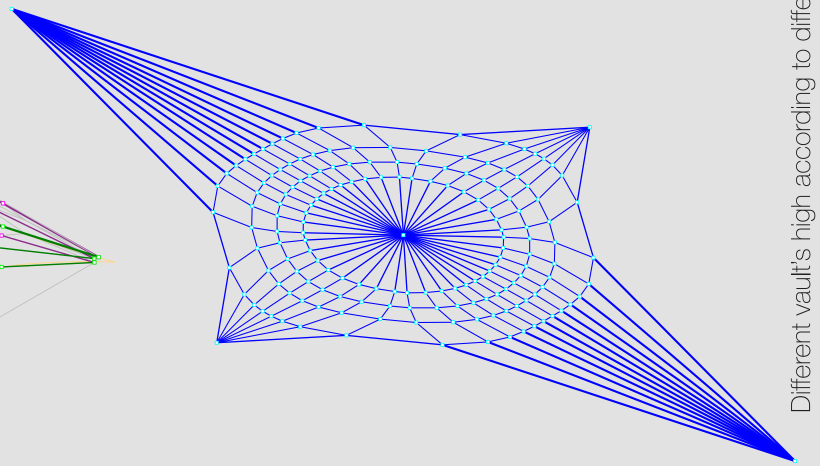
Horizontal equilibrium found with a maximum deviation of 10 degrees





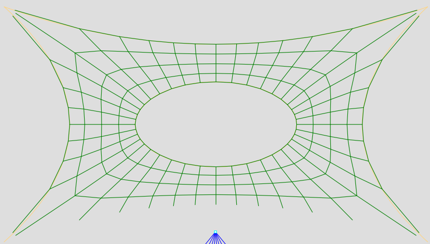


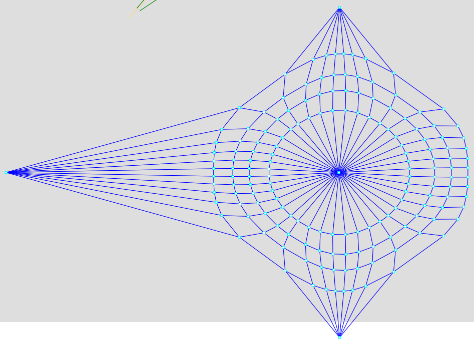


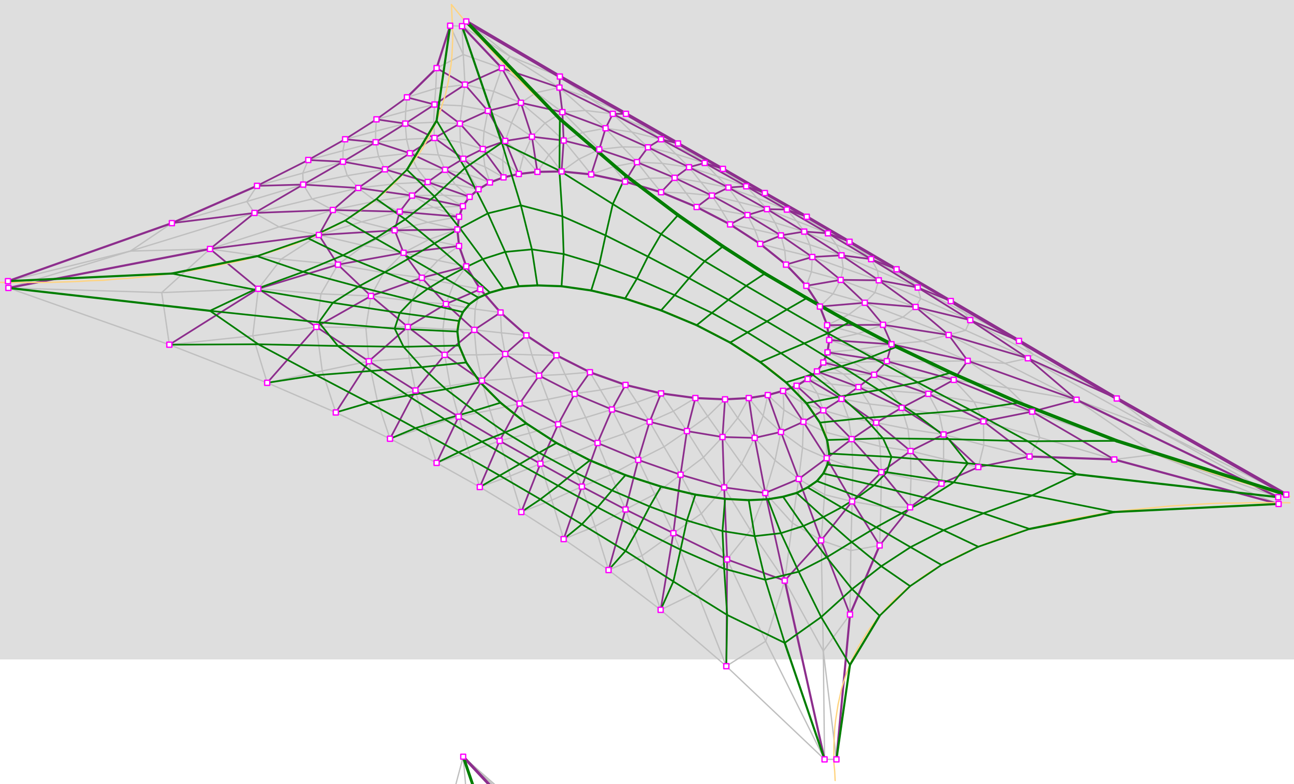


Different vault's high according to different scales established by the user

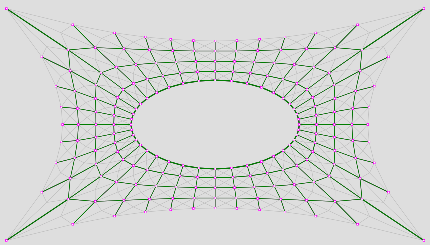
One edge changed to act as supporting edge

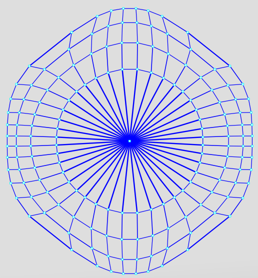


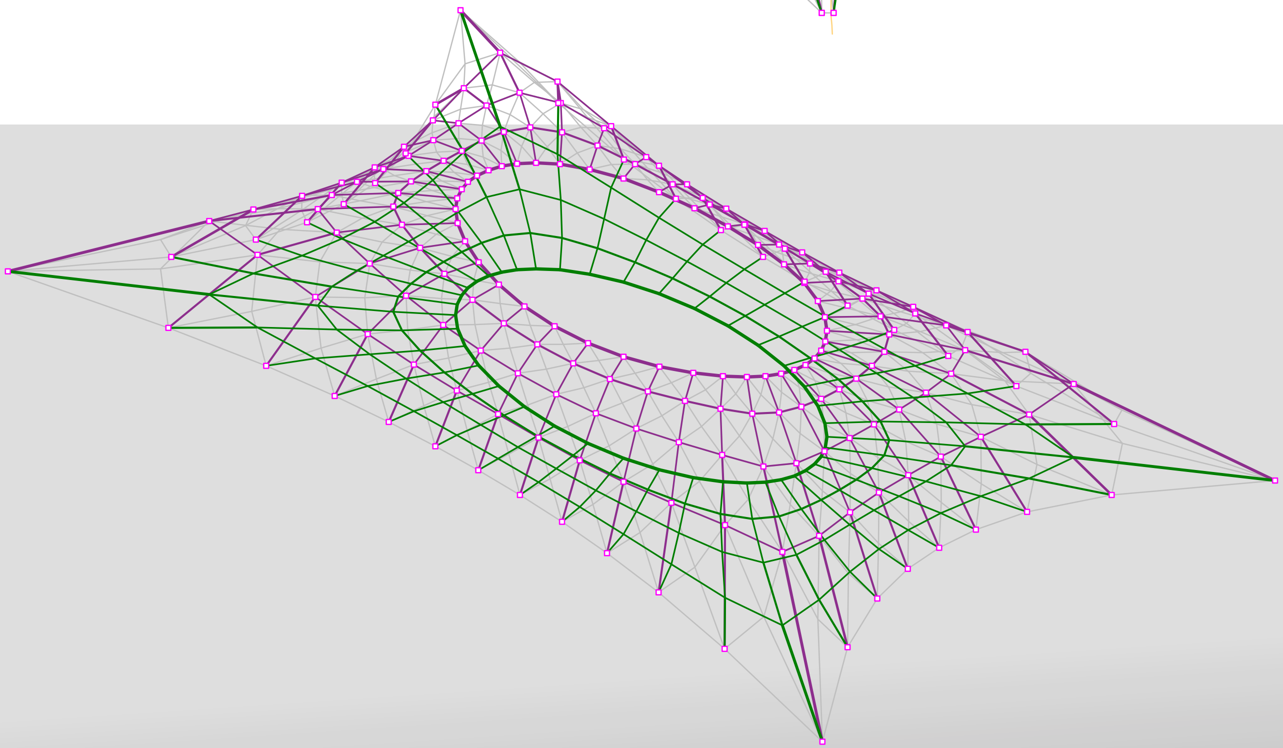




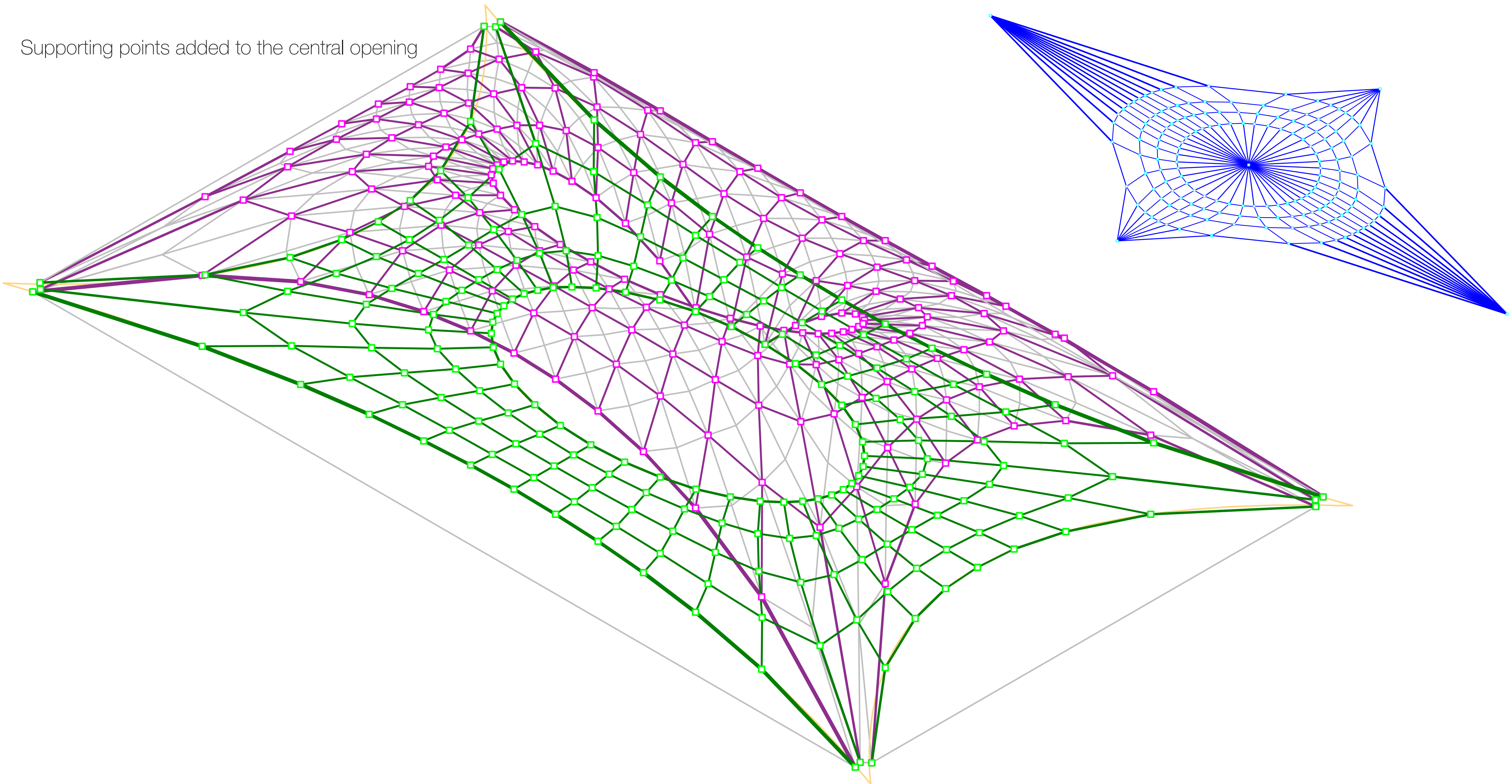
Four edges changed to act as supporting edges

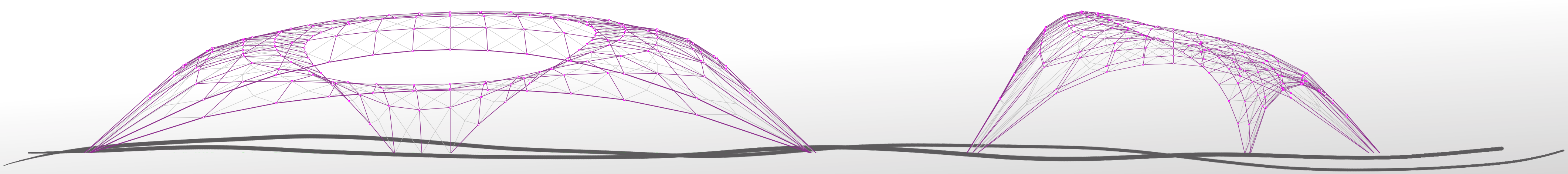






Supporting points added to the central opening





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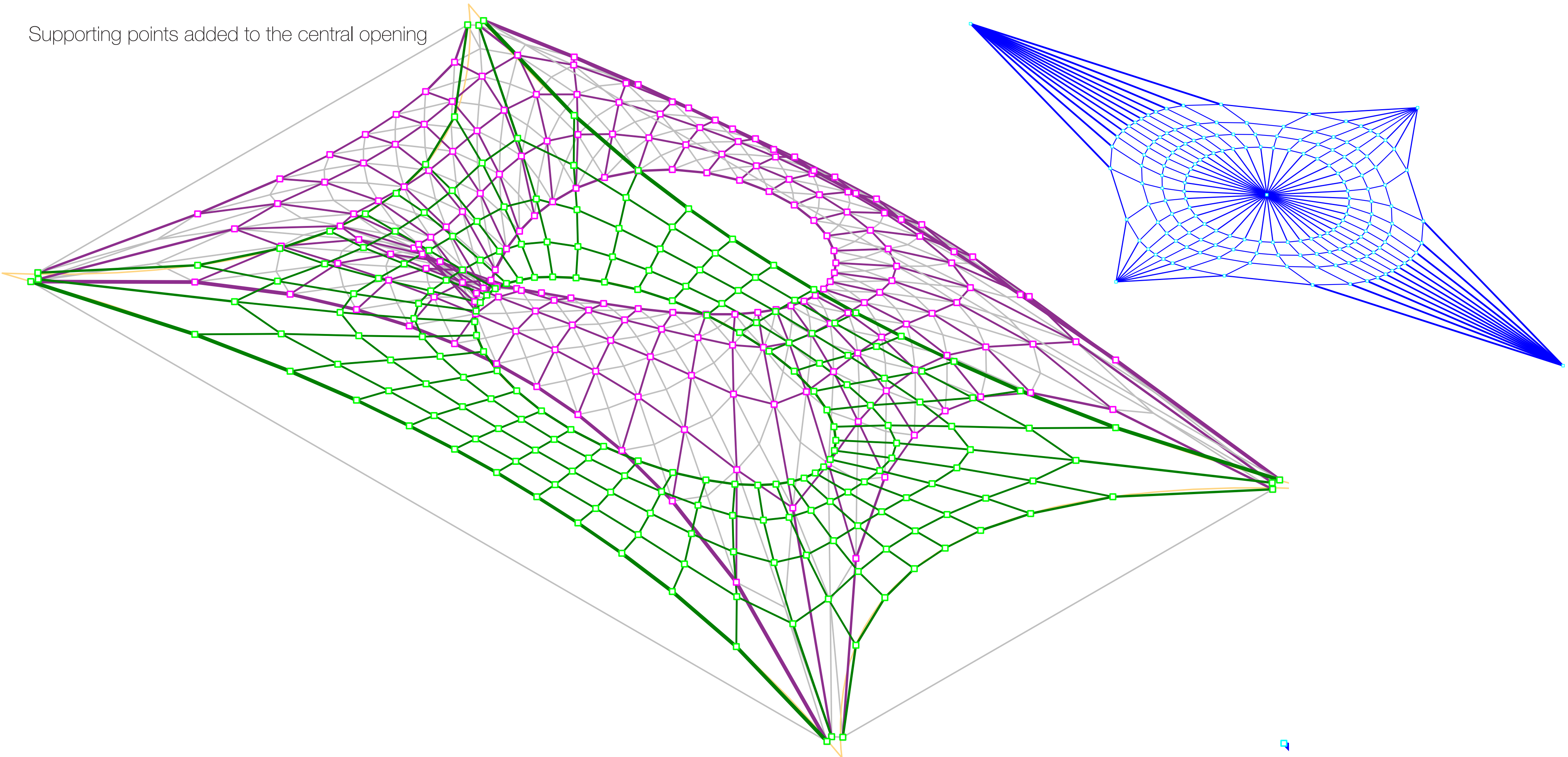
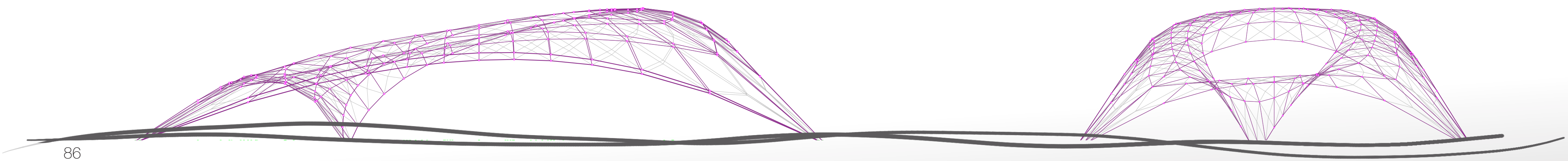
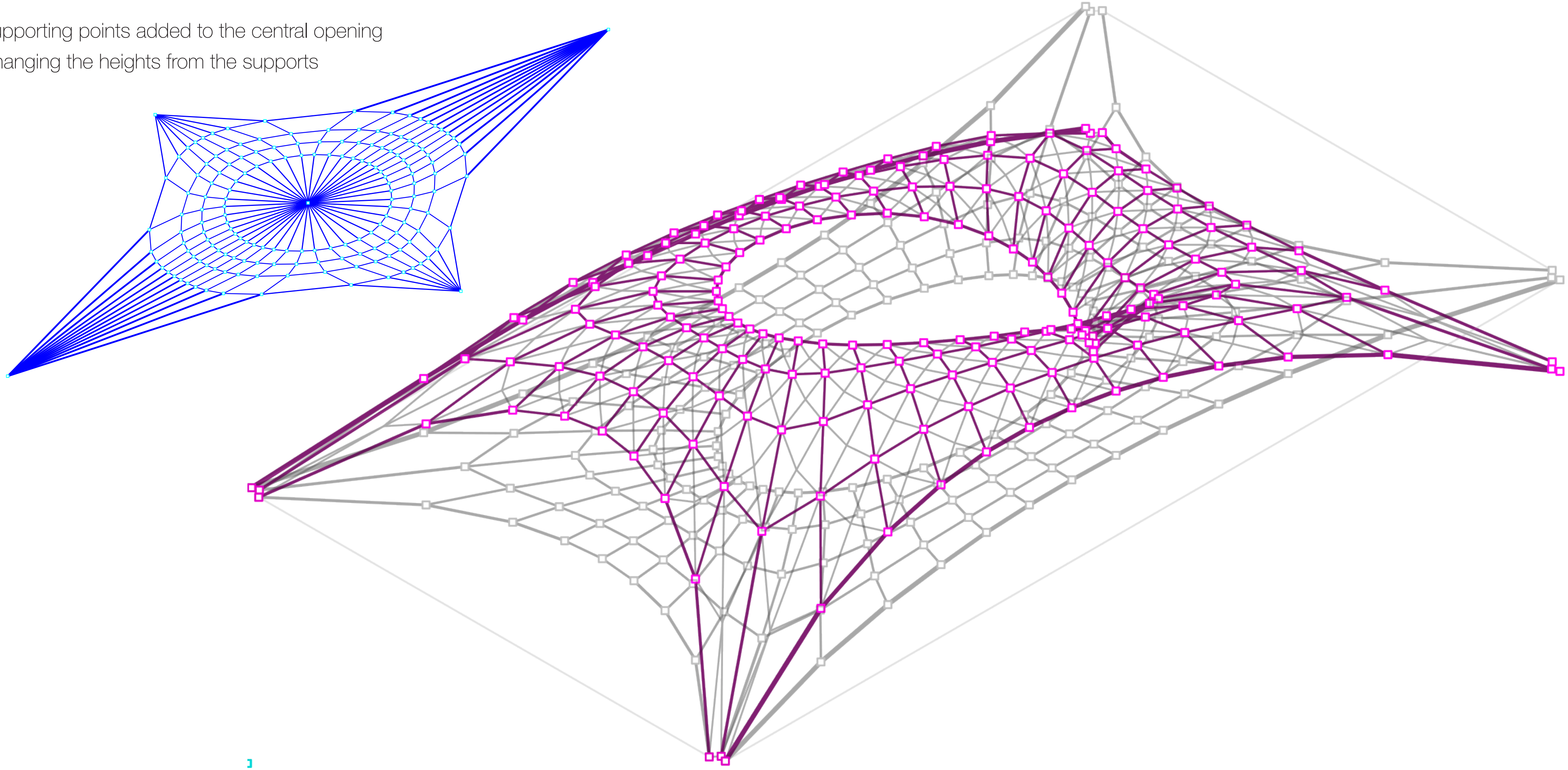
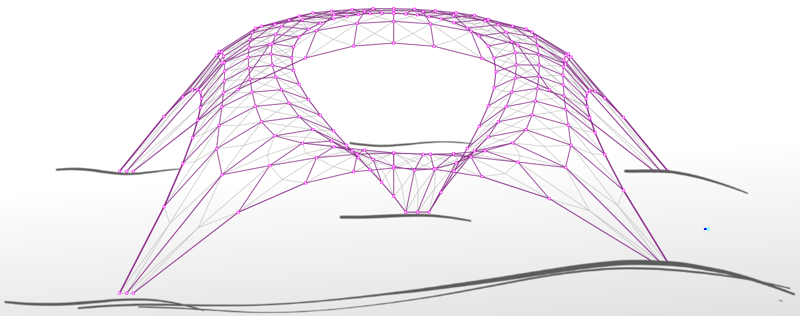


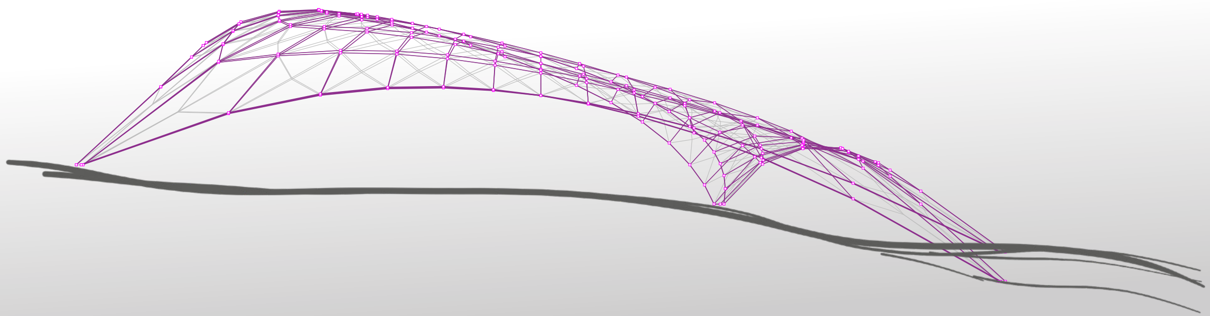


Supporting points added to the central opening

Changing the heights from the supports







Example Built Project Using RhinoVAULT

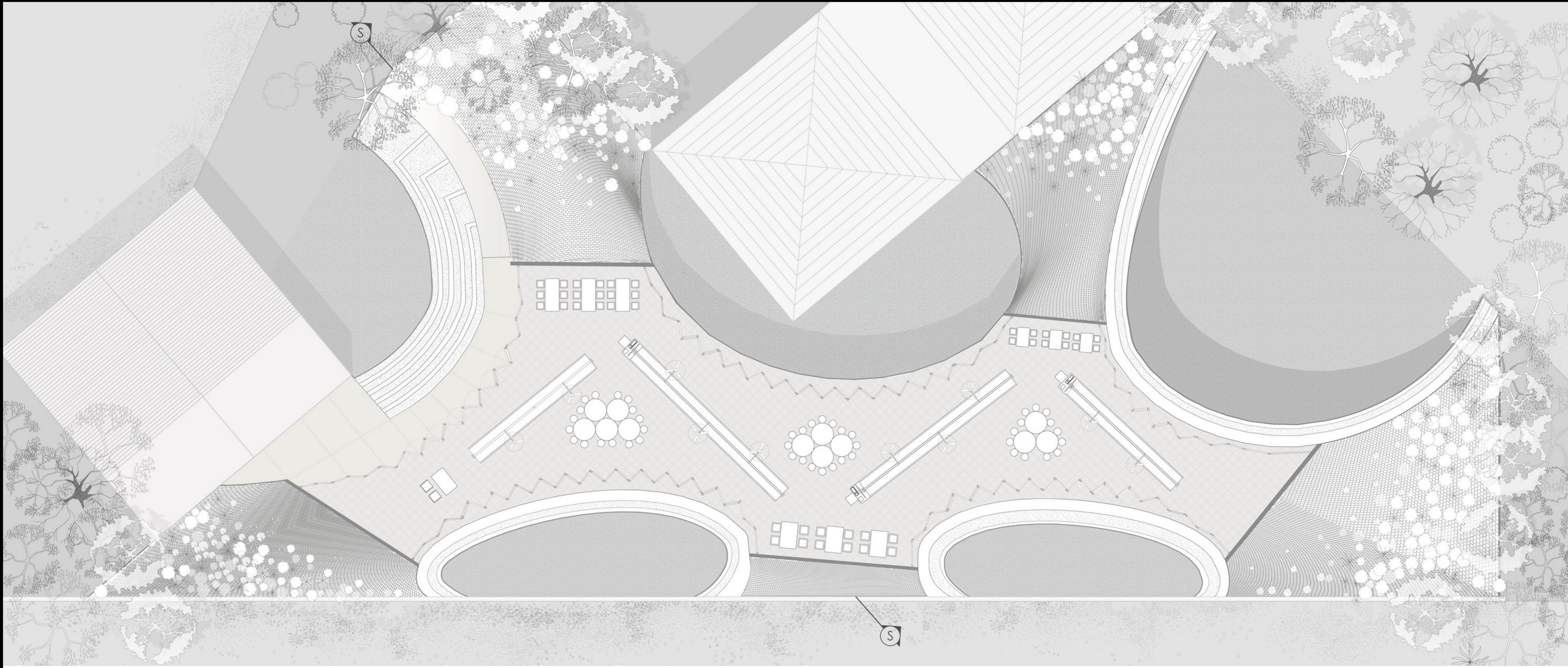
MAYA SOMAIYA LIBRARY - SHARDA SCHOOL

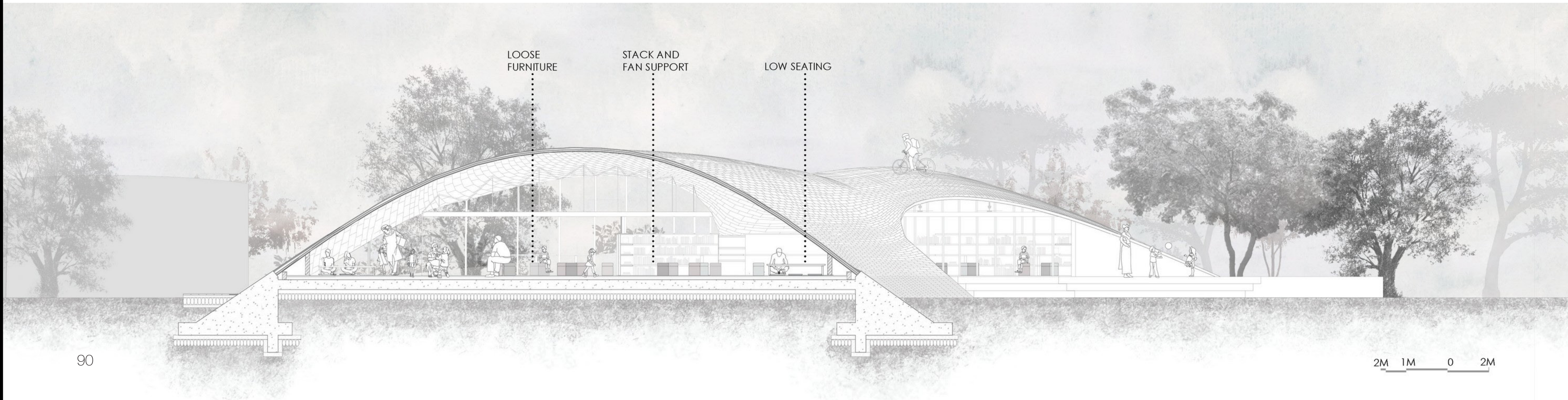
Architect: **Sameep Padora & Associates**

Location: Kopargaon, Maharashtra, India

Year: 2018

Located in a school's site in the rural area of Maharashtra, the project's form aimed to be an extension of the terrain, mimicking it. In that way, the form, through its expressiveness, serves as an attractor to the students as the roof is a sort of playground and, at the same time, the interior is a studying place. The materials used are ceramic tiles, built under the Catalan tile vault method, created in the 16th century and vastly used in the USA by Rafael Guastavino, in the 19th and 20th centuries (Ochsendorf, 2013). Another reference taken by the project was the work done by the Uruguayan architect Eladio Dieste. Dieste worked with ceramic bricks combined with reinforced concrete to achieve thin shell structures. The roof's design, working under pure compression, was reached by manipulating the software RhinoVaults, developed by Block Research Group, ETH Zürich. The project is a mixture of old techniques and cutting edge computational technology, inserted in a context in which low-tech building systems are the predominant reality.




LOOSE
FURNITURE
STACK AND
FAN SUPPORT
LOW SEATING
2M 1M 0 2M

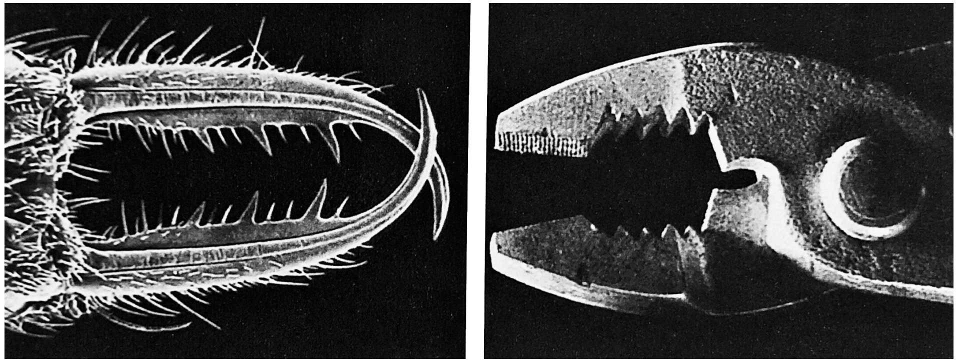
5. Biomimetics

"I am confident that humanity's survival depends on all of our willingness to comprehend feelingly the way nature works."

Buckminster Fuller

All Images and captions extracted from the book "Form Follows Nature". pages 139-144

1. Upper jaws of the ant lion and combination pliers.
2. Wood drills from the giant ichneumon warsp and drill rasps.
3. Bending vein on a tiger beetle wing and bending column on a torch.
4. Suckers of the great diving beetle and suction soap holder.
5. Laying drill and rasps drill.
6. Dog flea's hooked claw and special dowel for securing cables.
7. Zip system on dwarf back swimmer and technical zip.
8. Saber saw on saw flies and technical penknife saw.
9. Static inter-hooking on the back-swimmer's coupling system and tecnical Velcro.



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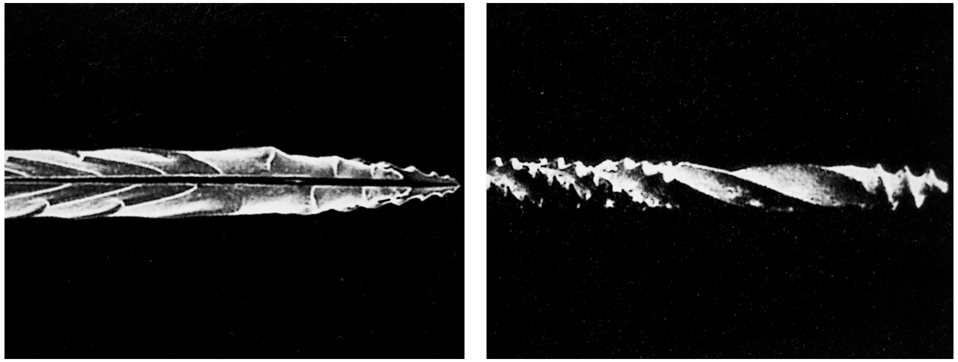

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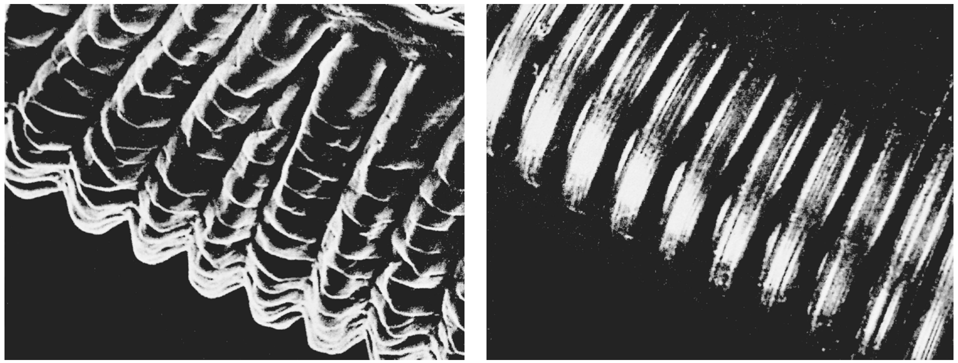

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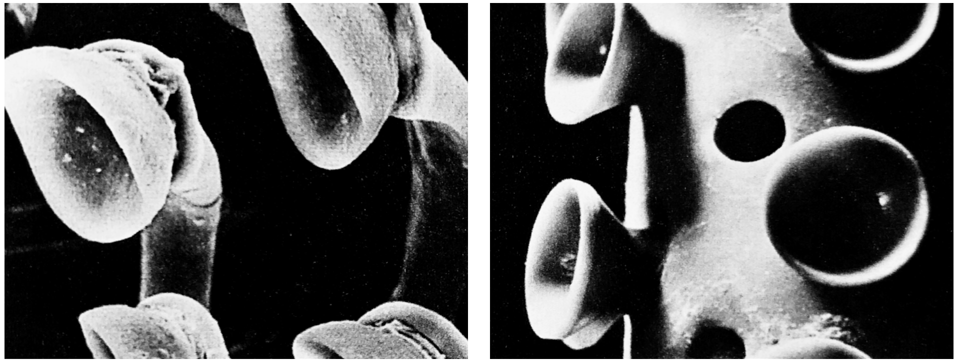
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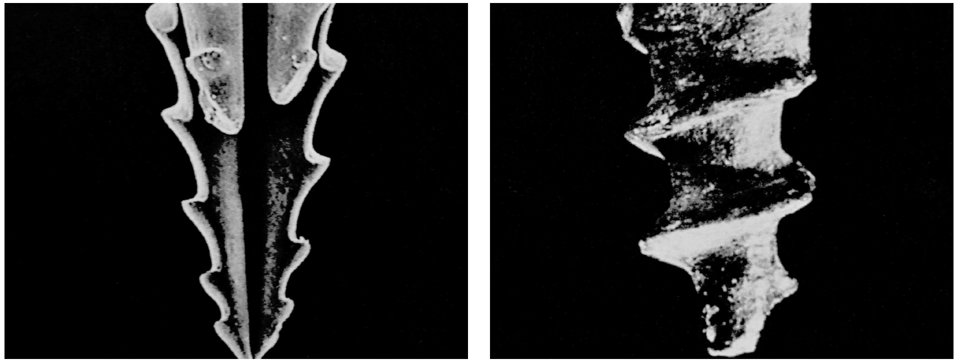
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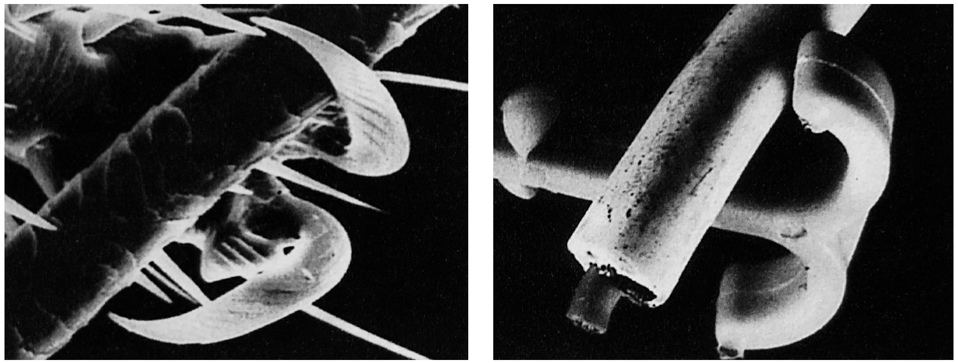
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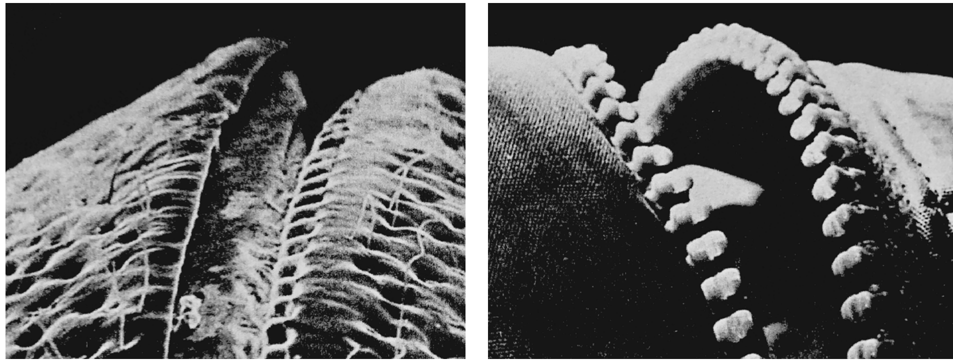
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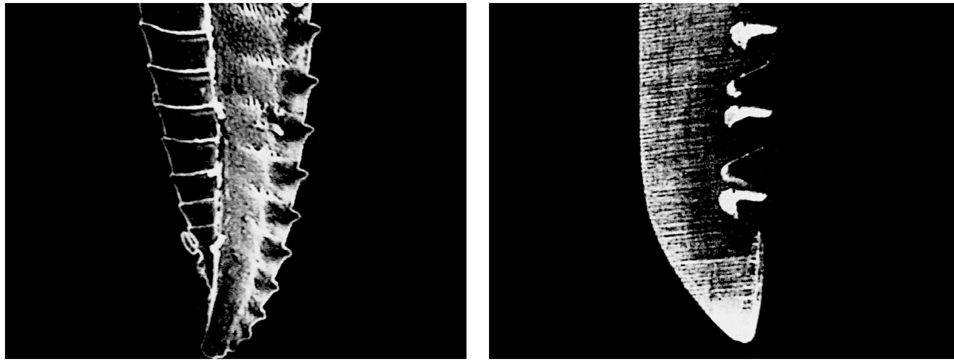
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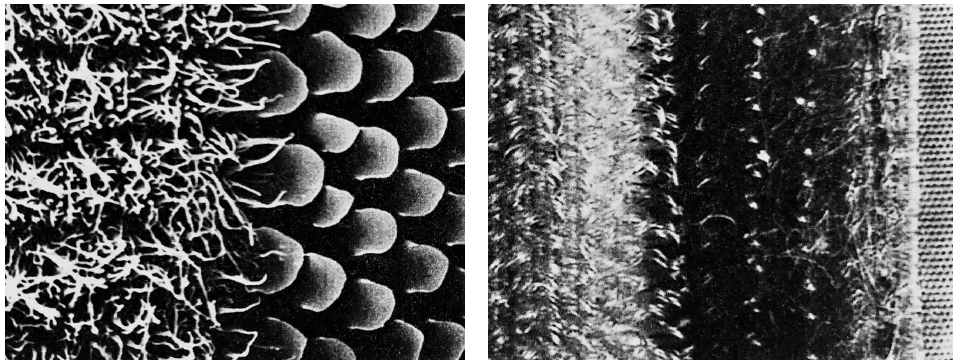
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> *"Biomimicry is an approach to innovation that seeks sustainable solutions to human challenges by emulating nature's time-tested patterns and strategies."*
>
> Biomimicry institute

The term 'biomimetics' was coined by the American polymath Otto Schmitt in 1957 (Bhushan, 2009), based on the combination of the words Biology - the prefix bio meaning life - and Mimesis - meaning imitation. Also, the term 'bionics' has the same meaning and consists of the juxtaposition of the words Biology and Technics (Speck & Speck, 2008).

Despite the fact that the term was coined only in 1957, the first publication relating biology and human-made structures date back to 1917 throught the work of D'Arcy W. Thompson. He extracted mathematical descriptions of forms by making a parallel between structural engineering and biological systems (Pacheco-Torgal, 2015).

The natural environment as we see today is a result of the evolutionary process of natural selection over millions of years. The boundaries imposed by Nature have driven all living systems to adapt towards what is currently observed as 'natural systems', solving the challenges that we still do not have using an optimal amount of material and energy. As a result, Nature is the final integration and optimization of natural processes (Pacheco-Torgal, 2015) and based on this principle biomimicry sets its ground.

Considering the interdisciplinarty of such approach, it is indispensable to achieve an active integration between professionals from different areas. The fields of expertise to be considered intrisically combined are, for example, biology, engineering, architecture, mathematics and physics, and they should be working in close coordination in other to apply the information produced cohesively (Speck & Speck, 2008).

Fluid and organic shapes found in Nature are based on a rigid and robust logic, as "form follows function" (Pacheco-Torgal, 2015). Sustainable solutions must come from the systematic observation of the problems that Nature has already solved. It is important to reinforce that biomimetics is not about a mere process of copying Nature, as the name suggests, but it is a search for the laws that guide Nature and how to apply them into the artificial world (Nachtigall, 2014).

> *"When an engineer wishes to copy Nature, he is bound to fail. Nature does not provide any blueprints for technology. However, it provides structures, procedures and evolutionary principles which man, when he gets it right, an inexhaustible reservoir of use to great advantage for technological advances."*
>
> Werner Nachtigall, 2014
>
> Nature - a Test Lab. Form Follows Nature

The process of form-finding, is based on the natural mechanical response of elements subjects to constraints imposed by the natural environment. The biomimetic abstraction process has combined different fields of expertise, allowing the permutation of knowledge among them. By understanding biology, the goal is to transfer, scale, and apply the abstracted principles into architecture. (Lienhard, Schleicher and Knippers, 2015)

Advancements in the application of knowledge abstracted from Nature into the human-made world were achieved due to new digital tools. Such technology is based on simulation and calculation of digital models as inputs, turning structural engineerinto an essential part of the design process. (Lienhard, Schleicher and Knippers, 2015)

In this process, as is based on the holistic approach of form, material and function working together, it is fundamental to consider the natural mechanical response of the used material (Pacheco-Torgal, 2015). The material is a constraint that guides the project from the beginning until the end of the design process, and each element of the structure should also be thought in such holistic manner (Oxman and Oxman, 2015).

Nature-inspired solutions can be seen in the building sector in diverse situations. From the development of innovative materials until the implementation of entire systems of responsive façades, biomimetics is playing a significant role in the development of architecture and civil engineering in the twenty-first century. The microscopic level of precision in which natural structures defines and distributes the material throughout its form throught self-organization corresponds optimally with function each part must perform. (Oxman, 2010)

Throughout human history, man uses Nature as a source of knowledge. The humankind has always used the forms of Nature as a base to produce our synthetic form. Although Nature has been a constant source of inspiration for humans, it was only in the XV century, with the experiments done by Leonardo da Vinci, that the natural environment passed from a source of inspiration by its form to a source of knowledge by the interpretation and application of its physical principles (Mazzoleni, 2013).

Model of the "endless House", Kiesler, 1959 - MoMA

Kiesler claimed the need for an architecture that linked close together man and nature. He considered the "primary house" to be the egg, being the light and architecture deeply correlated.

> *"The 'endless house' is not amorphous, not a free- for-all form. On the contrary, its construction has strict boundaries according to the scale of our living. Its shape and form are defined by inherent life forces, not by building code standards or the vagaries of décor fads... The endless house is not a machine for living. It is rather a living organism with a very sensitive nervous system..."*
>
> Frederick Kiesler,
> Notes on Architecture as Sculpture,
> 1966.

XIX and XX centuries:

Montreal Biosphere, Buckminster Fuller Source: Rodrigo Maia - archdaily.com

The years between da Vinci's biomimetic explorations until the 19th century, with the spread of engineering and other applied sciences, there are not much information about the application biomimetics. Last century, the futurist Buckminster Fuller (1895 - 1983), by observing and exploring Nature, made famous the term tensegrity, applying this mechanical principle into his designs (Mazzoleni, 2013). He observed such phenomena giving structural stability in almost all natural beings, from the study of the microbiological structures of the radiolaria until the mechanism of compression and tension of bones and muscles. He also points out in his book "Synergetics Explorations in the Geometry of Thinking" intuitive uses of this principle, such as wheels, structural joints and even in sports such as gymnastics. Based on tensegrity, Fuller has developed his world-wide know geodesic design.

In the last couple of centuries, many architects were worth mentioning regarding their biomimetic explorations. In the present work, the Frei Otto and Antoni Gaudi and Heinz Isler are briefly referenced as examples of pioneers in this kind of study. They have extensively applied principles learned by observing Nature, bringing together form, material and structure.

Although the 20th century and the modern movement had many examples of biomimetic explorations, an important architect was well known for going against the deliberate and careless use of it. Le Corbusier considered that Nature presented itself as chaos, and architecture had the role of bringing order to it, so we should look beyond what Nature presents us at first sight and go deeper into its guiding rules. (Feireiss, 2014)

> *"Nature presents itself to us as a chaos; the vault of the heavens, the shapes of lakes and seas, the outlines of hills. The actual scene which lies before our eyes, with its kaleidoscopic fragments and its vague distances, is a confusion. There is nothing there that resembles the objects with which we surround ourselves, and which we have created. Seen by us without reference to any other thing, the aspects of Nature seem purely accidental. But the spirit which animates Nature is a spirit of order; we come to know it. We differentiate between what we see and what we learn or know. Human toil is regulated by what we know. We therefore reject appearance and attach ourselves to the substance."*
>
> Le Corbusier
>
> City of Tomorrow, pp. 24-25.

"Form follows nature". This quote wrote by Louis Sullivan (1856–1924) is very pertinent under the present subject, biomimetics. Sullivan used biomimicry when relating ideas of organic growth and architecture, involving form, structure and function, interpreted as multilayered systems of growing complexity (Dollens, 2006). Frank Lloyd Wright, who worked with Sullivan in his early in his career and was greatly influenced by him. Wright was one of the first to use the term "organic architecture", referring to a broader view of architecture in an interdisciplinary reality, learning by Nature and its elements. (Finsterwalder, 2014).

Pneu Plaster Model - source: Frei Otto - Thinking by Modeling, 2017

BIOMIMETIC DESIGN IN THE DIGITAL AGE

Nature holds answers to several questions and has always been an inexhaustible source of knowledge to humanity. Now, having as main concern sustainable strategies, it is imperative to extract from nature its ability to optimize the use of materials and energy, translating it into the built environment. Due to technological advancements, it is now possible to explore natural systems more than ever before. (Pacheco-Torgal, 2015) (Lienhard, Schleicher and Knippers, 2015)

The explorations made possible with technological improvements bring new possibilities in decoding nature's patterns, understanding then and applying their underlying principles into new architectural solutions, which are deeply connected with material organization and natural systems (Weinstock, 2014). That means that such improvements reach biomimetics from extracting data from the environment, analyzing and materializing them in the real world (Dollens, 2006).

By interacting with nature and learning its hidden mechanisms, we came up with solutions from the material's granular scale until complex systems like responsive façades. Digital simulation and scripting play a central role in the development of such ingenious creations, making possible precise and mathematically calculated models of what before was only intuitive methods. The idea of an evolutionary system in order to build complexity has the essential concept of local differentiation of elements, arriving at highly adaptive mechanisms (Oxman & Oxman 2014).

Many are the biomimetic approaches that can be followed in order to solve a problem. One single solution that is optimized to answer multitasking problem does not exist, being necessary to analyze each circumstance to establish a procedure regarding also its implementation in the physical world. (La Magna, Gabler, Reichert, Schwinn, Waimer, Menges, Knippers, 2013)

The present work explores the digital morphogenesis of natural systems designed to perform structurally in an optimal way considering what Hooke's law states. In this context, the primary constraint is the mechanical performance of the material to be and gravity acting upon the system, in a material-oriented method. (Oxman & Oxman, 2014)

> *"Morphogenesis is the theoretical foundation and body of knowledge related to the evolution of structure of an organism in natural phenomena. The study of the structure of organisms in Biology and Geology, the field has a rich philosophical background. Morphogenic studies in design involve concepts and scientific research that have significant theoretical implications for form generation and design."*
>
> Rivka Oxman and Robert Oxman
> Theories of the Digital in Architecture
> 2014

Antoni Gaudi, Frei Otto and Heinz Isler, already mentioned in this work, exploit the same biomimetic procedure, but with analogous models instead of computational ones. Those models, although coming from the same principles, not as efficient as the computational ones. They are time demanding and are subject to limitations due to human errors.

In the project, the aim is to think of all elements as one complex system of integrated form, material and structure, responding together to the input constraints, generated by parametric tools. (Menges, 2015). The sequence of steps in the creation of a natural form is information, formation and materialization. Material properties provides the information to posterior formation and materialization, as a genotype (material information) that set the ground rules for a phenotype (architectural form) (Menges, 2017). Taking into considering the mechanical response of fragile materials such as ceramic bricks and concrete, structures responding optimally to compression are required.

Form-Active systems, as defined by Heino Engel, respond to the environmental parameters actively. Frei Otto also defined this natural process of adaptation of form accordingly with material characteristics as 'Selbstbildung', in English self-forming (Menges, 2015). This principle is explored in the following propose by vaulted shell structures working in compression and hanging sill ties working in tension.

> *"Living forms, like non-living forms, exists in a field of forces, and alterations in those forces will inevitably produce the response of evolutionary changes to forms."*
>
> Michael Weinstock
> Evolution and computation
> 2015

These kinds of structures present themselves in nature under different circumstances. Shells can be found as infinite versions of loadbearing systems, such as carapace for mollusks, as eggshells protecting unborn birds and skulls capsule structure acting as a protective case for the brain in the animal kingdom. In all cases, they perform the role of protection of soft and vulnerable tissues, bearing loads efficiently, with minimal use of material.

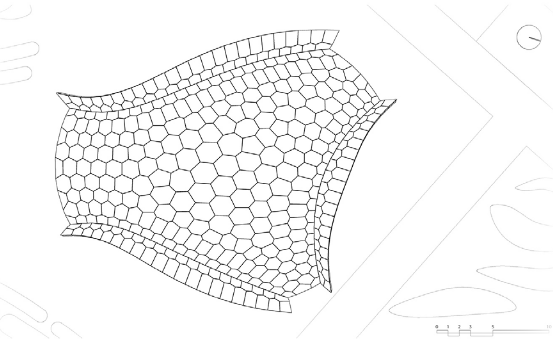
One big issue is the constructability of the non-planarity imposed by natural systems. Technological innovations have brought new possibilities of tools and materials to be explored to produce complex non-euclidian forms, largely supported by the emergence of Fablabs throughout the world. Such advancements impacted largely on costs, execution and precision in the building sector. The following chapter goes deeper into the issue of materialization and fabrication.

ICD/ITKE Research Pavillion 2015-16 - ICD + ITKE + University of Stuttgart

The pavilion consists of 151 elements robotically fabricated, and its morphogenesis is based on a biomimetic approach. A multidisciplinary team of architects, engineers, biologists and paleontologists, through computational abstraction of biological systems analyzed the building morphology of sand dollars, considering, holistically, material, form and robotic fabrication. This way, the outcome is a very light structure, weighting a total of 780 Kg, spanning 9.3 meters, over an area of 85m2.

(c) ICD/ITKE University of Stuttgart Source: https://icd.uni-stuttgart.de

BUGA WOOD PAVILION



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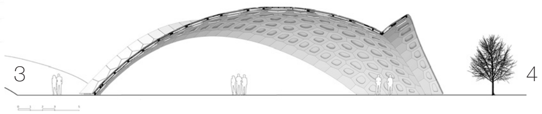

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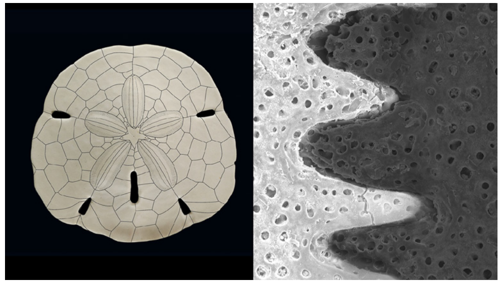

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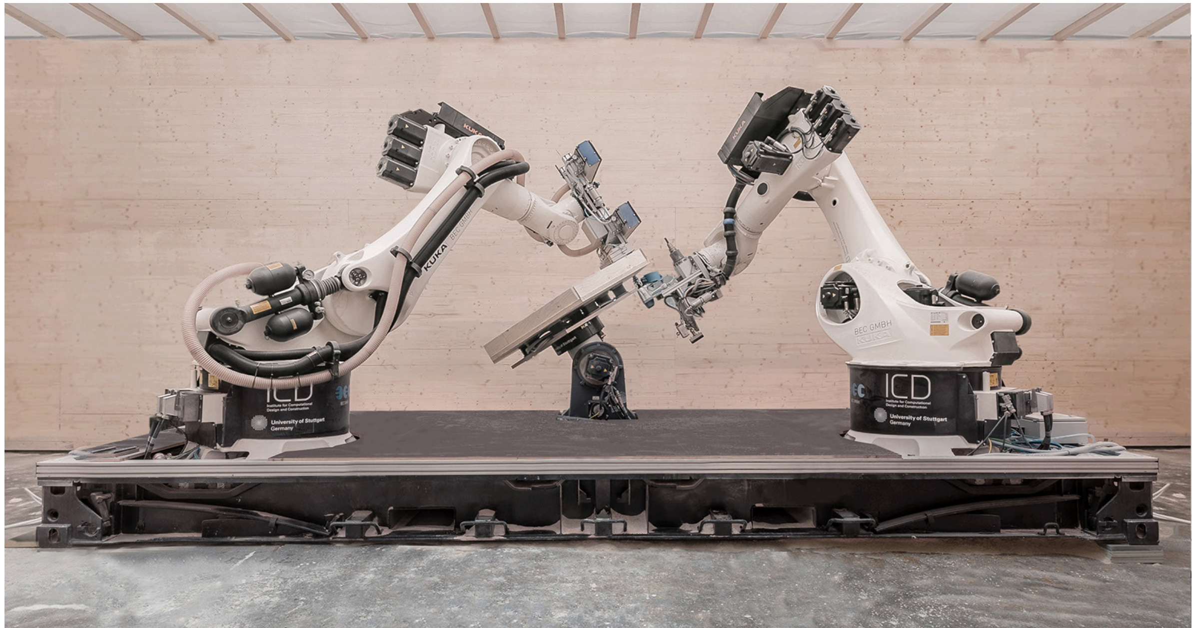
All images extracted from the website: https://icd.uni-stuttgart.de/

1. North View of BUGA Wood Pavilion , © ICD/ITKE University of Stuttgartt
2. Top View, © ICD/ITKE University of Stuttgart
3. Section, © ICD/ITKE University of Stuttgart
4. Sea Urchin © ICD/ITKE University of Stuttgart
5. Crane Lifting Building Group, © ICD/ITKE University of Stuttgart
6. 14-Axis Robotic Platform. © ICD/ITKE University of Stuttgart
7. Elements' Layering Strucure. © ICD/ITKE University of Stuttgart



6

Bundesgartenschau, Heillbronn, 2019
Year: 2019

PROJECT PARTNERS

ICD– Institute for Computational Design, University of Stuttgart
Prof. Achim Menges, Martin Alvarez, Monika Göbel, Abel Groenewolt, Oliver David Krieg, Ondrej Kyjanek, Hans Jakob Wagner

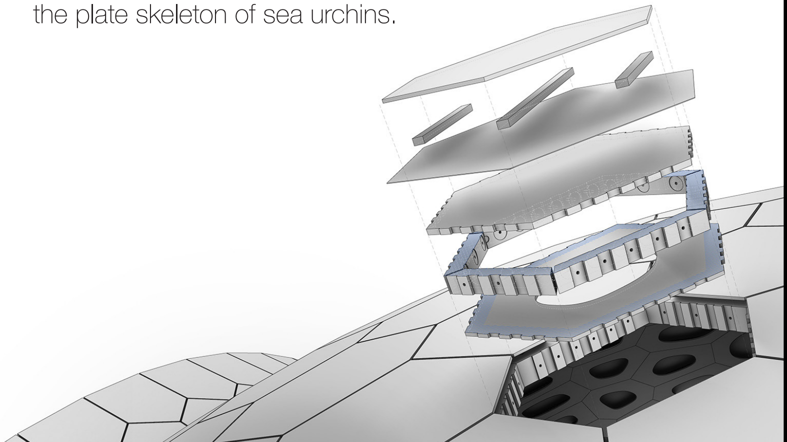
ITKE – Institute of Building Structures and Structural Design, University of Stuttgart
Prof. Jan Knippers, Lotte Aldinger, Simon Bechert, Daniel Sonntag

Müllerblaustein Bauwerke GmbH, Blaustein
Reinhold Müller, Daniel Müller, Bernd Schmid

BEC GmbH
Matthias Buck, Zied Bhiri

Bundesgartenschau Heilbronn 2019
Hanspeter Faas, Oliver Toellner

Spanning over 30 meters and weighing only 38kg/m^2, the pavilion is a benchmark for an expressive and efficient piece of architecture. It counts with 376 plate segments and 17 000 different finger joints based on the connecting structure of the sea urchins' plates (fig. 4), designed by an interdisciplinary team. The full-constructed system behaves as a form-active structure, and not only the joints were based on a biomimetic approach, but the whole form/structure takes advantage of morphological principles from the plate skeleton of sea urchins.



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BUGA FIBRE PAVILION

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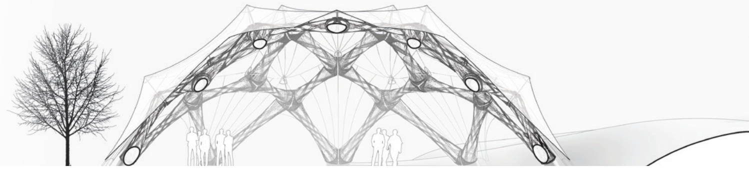

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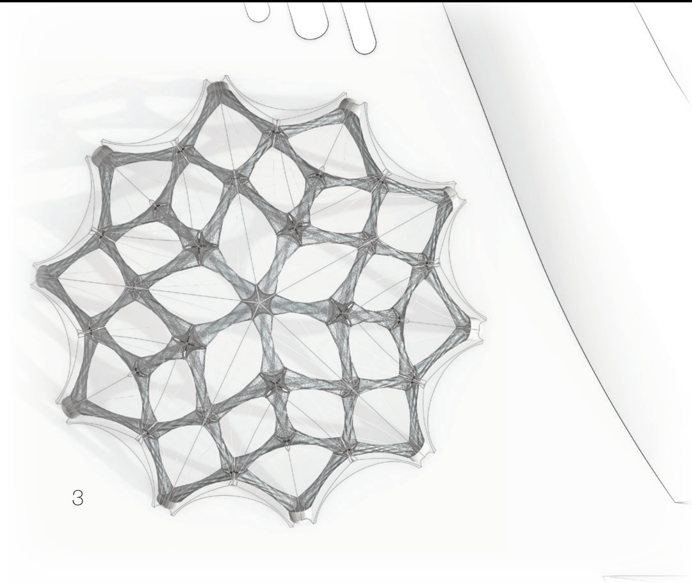


3

Bundesgartenschau, Heillbronn, 2019
Year: 2019
PROJECT PARTNERS

ICD – Institute for Computational Design, University of Stuttgart

Prof. Achim Menges, Serban Bodea, Niccolo Dambrosio, Monika Göbel, Christoph Zechmeister

ITKE – Institute of Building Structures and Structural Design, University of Stuttgart

Prof. Jan Knippers, Valentin Koslowski Marta Gil Pérez, Bas Rongen

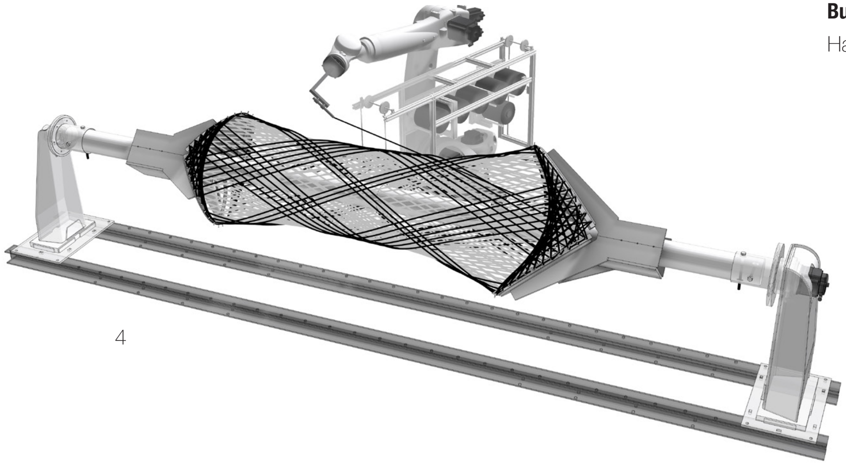
FibR GmbH, Stuttgart

Moritz Dörstelmann, Ondrej Kyjanek, Philipp Essers, Philipp Gülke

Bundesgartenschau Heilbronn 2019 GmbH

Hanspeter Faas, Oliver Toellner

Covering a floor area of about 400 m2 and spanning over 23m, the BUGA Fibre Pavilion counts with more than 150.000m of spatially arranged glass and carbon fibres. These fibres, as in nature, are responsible for the load-bearing structure alone. This piece of architecture is the result of many years of research in the biomimetic field at the Institute for Computational Design and Construction (ICD) and the Institute for Building Structures and Structural Design (ITKE) at the University of Stuttgart. In the project, to optimize the use of material, the fibres are placed by additive manufacturing between two rotating winding scaffolds by a robot. Each element is locally calibrated to receive the fibres optimally and, as the structural elements are assembled by winding, there is no mould needed, turing out to be a strong point regarding sustainability. .



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All images extracted from the website: https://icd.uni-stuttgart.de/

1. View across the Landscape, © ICD/ITKE University of Stuttgart
2. Section, © ICD/ITKE University of Stuttgart
3. Top View, © ICD/ITKE University of Stuttgart
4. Protoyping Setup, ICD CCLab 3, © ICD/ITKE University of Stuttgart
5. Crane Lifting Last Building Group, © ICD/ITKE University of Stuttgart

6. DIGITAL FABRICATION

> *"Design must be logically deconstructed, in order to be encoded, and in the encoded procedure should also lay the underlying principles for its posterior fabrication."*
>
> Mark Burry - Dimensions - 2015

Digital fabrication is any type of manufacturing aided by computers. There are three different basic categories: Additive technologies, Subtractive Technologies and Hybrid Technologies. Although those are cutting edge technology, their essence is anything beyond an analogous process of traditional methods that are already performed by human abilities. The advantages of such methods are their accuracy and ability to perform a large number of steps meticulously, turning out to be, most of the time, faster, safer and cheaper. (Leach, 2017; Carpo, 2017)

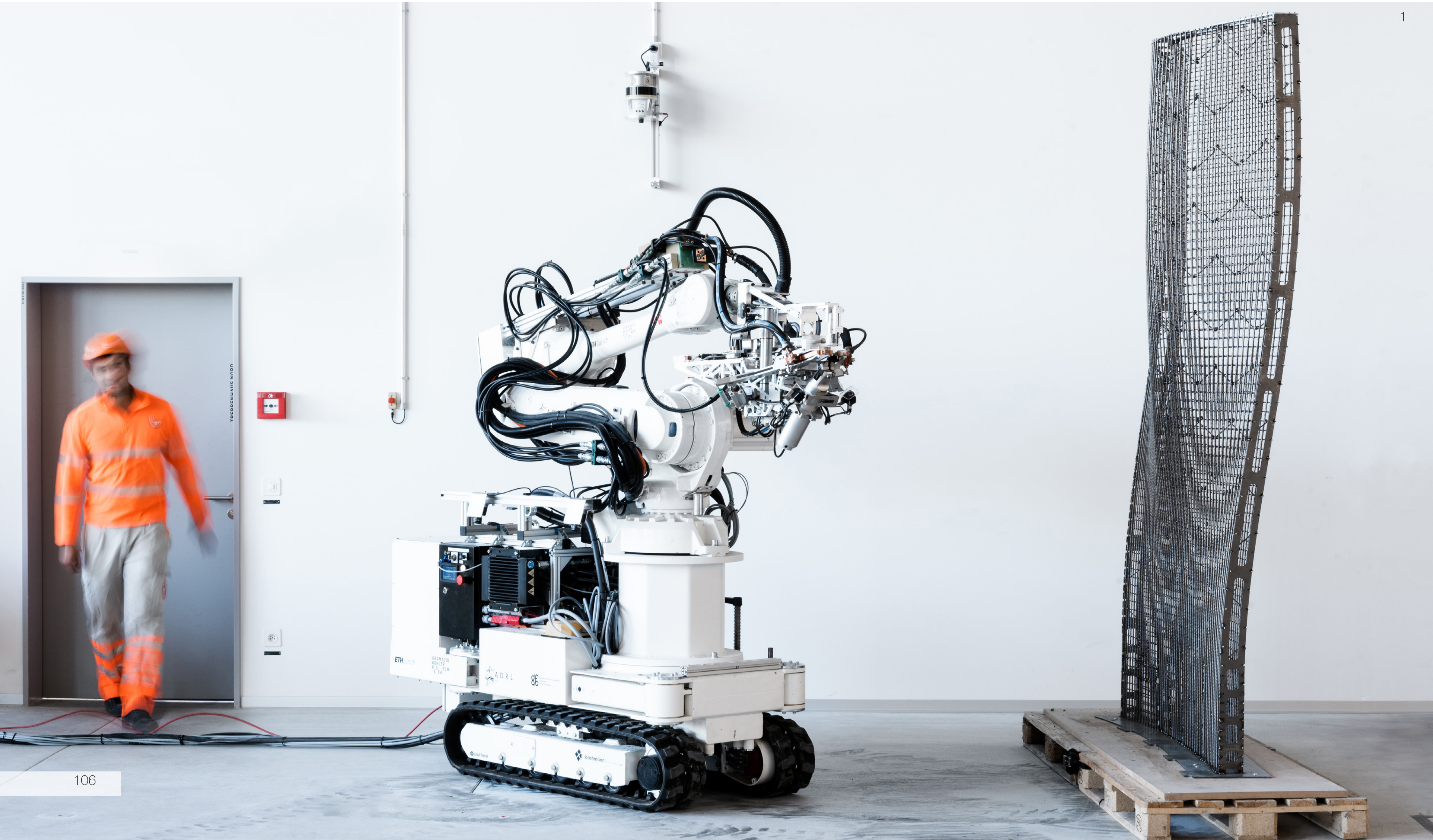
Rapid prototyping is now an integral part of the design process in which the generation, materialization and fabrication is a combined operation. To achieve such integration is demanded from the architect a more significant domain over material's technology. (Oxman, 2014). Nowadays many materials can be used in such processes, like polymers, metals, salt, sand, soft materials and even organic tissue (Leach, 2018)

> *"The development of digital design and fabrication technologies is enabling an expanding interrelationship between technology and design. Material-based design is defined as a computational informing process that enhances the integration between structure, material, and form within the logic of fabrication technologies."*
>
> Rivka Oxman, 2015

1. Robotic Winding Unit, © ICD/ITKE University of Stuttgart https://icd.uni-stuttgart.de
2. Flight Assembled Architecture (c) François Lauginie http://gramaziokohler.arch.ethz.ch

PROTOTYPING

1. Mesh Mould (c) Gramazio Kohler Research, ETH Zurich https://afab.space/
2. Basento bridge 1:10 Scaled prototype, 1970 - Sergio Musmeci https://medium.com/designscience



1

" Prototyping is the revelatory process through which the designer gains insight into how well their experiment is proceeding. Failure offers important information."

Mark Burry & Jane Burry

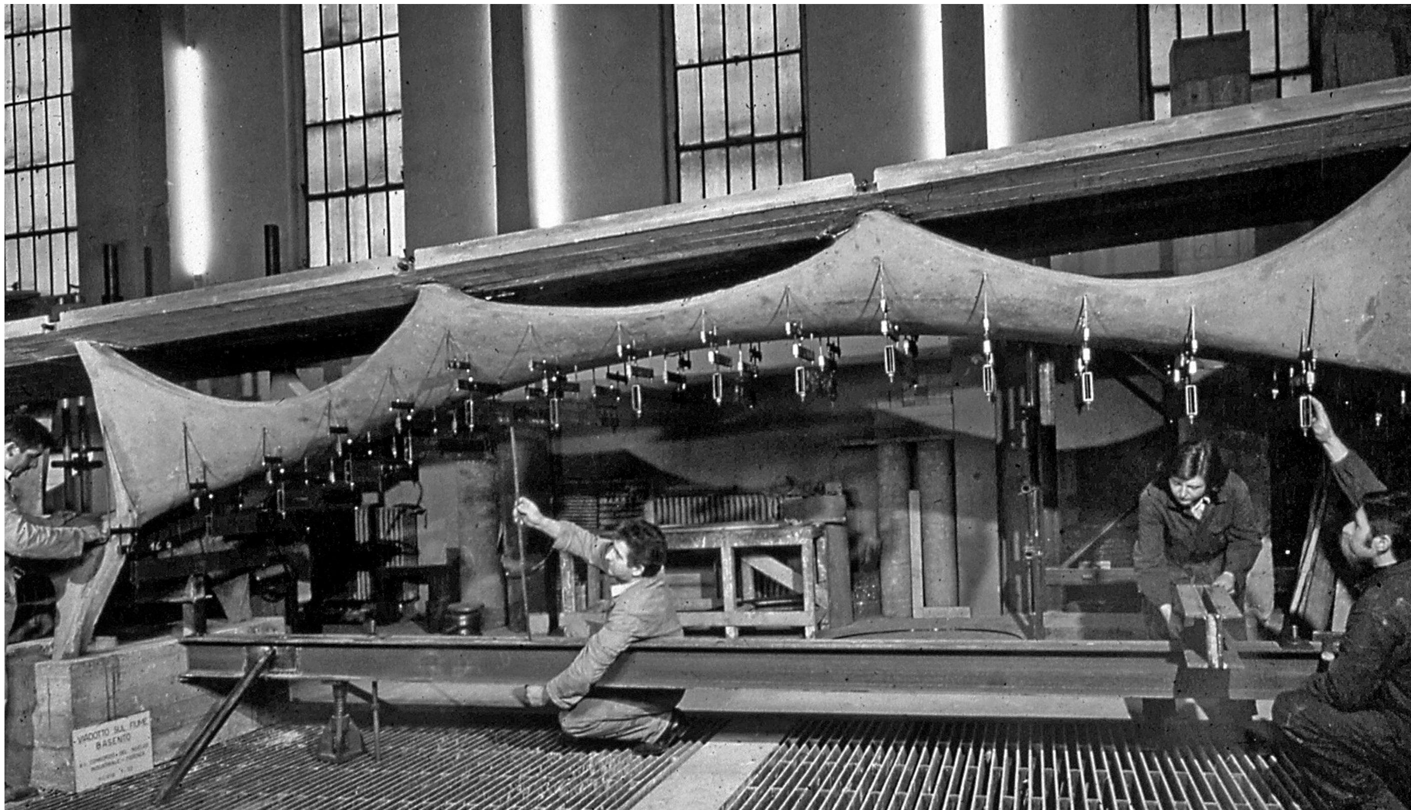
It is known that digital models accept unproven inputs, and their behavior in the physical world often diverges from the ideal. Prove concepts in a design process is needed in order to discard and accept options. By prototyping, the designer is able to test the viability of parts of the design, being an important tool for decision-making. It is also a fundamental tool for getting new insights and solutions, answering questions regarding the materialization of an initial plan. The following paragraphs are based on the book "Prototyping for Architects" written by Mark and Jane Burry.

"A Prototype is both a question and answer".

Bob Sheil
Prototyping for Architects
Foreword

In the book it is established the differences between Prototypes, Models and Mock-ups, by their definition found on the Oxford English Dictionary. Prototypes are "the first and primary of anything; the original (thing or person) of which another is a copy, imitation, representation, or derivative, or to which it conforms or is required to conform; a pattern, model, standard, exemplar, archetype". The Model is "a representation in three dimensions of some projected or existing structure, or of some material object artificial or natural, showing the proportions and arrangement of its components parts". The Mock-up is "An experimental model (often full-sized) of a projected air-craft, ship, apparatus, etc., used especially for study, testing, practicing or display". The Mock-up can also vary into high-fidelity and low-fidelity, being primordial for spotting possible weak points in the design. (Burry, 2016)

Prototyping suffered a dramatic shift due to the development of digital tools for fabrication. Both subtractive and additive technologies has brought together designers and engineers and has enhanced their participation in the crafting of prototype models, in all scales and for different goals.



Techniques

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1. Photo of the robotic wood trimming process with a blade saw.© ICD/ITKE University of Stuttgart
2. Photo of the robotic styrofoam trimming process with a foam milling tool. © ICD/ITKE University of Stuttgart
3. Types of CNC milling machines - 2D, 2.5D and 3D. Drawing based on image from Arturo Tedeschi's Book "Algorithms-Aided Design" page 315.
4. Diagram of the OMAG Blade5 NC900 5-axis CNC machine with all axes. Source: Calvo Barentin, Cristian & Rippmann, Matthias & Mele, Tom & Block, Philippe. (2016). Computer-controlled fabrication of a freeform stone vault.

Subtractive Technologies

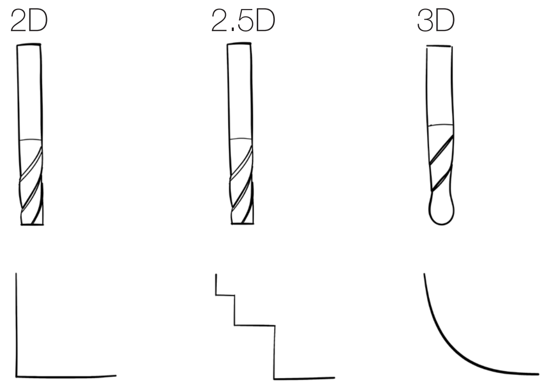
Spread in the late 1990s along with personal computers, CNC machines operate with instructions fed by computational software, in order to accomplish tasks. As a result of this new technology, the gap between virtual design and fabrication, created by digital design tools in the same decade, started to shrink. The term "Rapid Prototyping" arose, and this meant the possibility of the designer to take control of the process in an affordable and fast way.

The CNC devices consist of a cutting blade moving in one, two or three dimensions, being the fourth dimension the displacement of the blade over a period of time. This cutting system functions by extracting material from an initial block, working by carving material, according to a stepper motor making precise fractions of revolution. A computer defines the number of steps, position of the blade and most importantly, its speed (Burry & Burry, 2016). The carving apparatus can be a milling cutter, a lathe, a laser or waterjet cutter. (Tedeschi, 2016) Today, with the constant improvement in technology, these machines operate with a feedback system, which informs and adjusts the procedure according to unforeseen issues. (Burry & Burry, 2016)

The most common CNC milling machines are the 2D, 2.5D and 3D machines. The difference between the 2D and 2.5 milling machine is that the first operates bi-dimensionally only and the second operates three-dimensionally, but not simultaneously, working in bi-dimensional steps (Tedeschi, 2016). Sometimes the design demands slanted cuts in the material, and for that, the cutting machine needs more than degrees of freedom to operate. (Burry & Burry, 2016). The 3D machines operate in all three dimensions at the same time. The milling machines operating in 5 axis uses digital geometries to set tooling paths with low restrictions.

However, this technology can also be implemented to work as an additive technology. By replacing the carving tool by depositors, the machine works by extruding material with high precision in layers.

Other digital fabrication tools using subtractive technology are the Hot-wire foam cutter and the robotic arms. The first consists of cutting polymers foams materials with a heated wire, being able to cut from simple bi-dimensional paths until complex non-planar surfaces. (Tedeschi, 2016)



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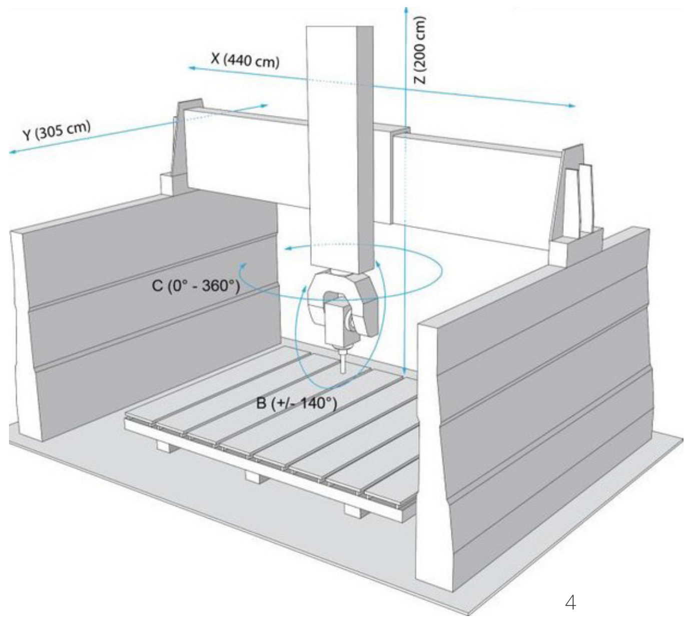

4

Additive Technologies

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1. Construcution ‘rock print pavilion’ image © gramazio kohler research, ETH zürich https://www.designboom.com/
2. 3D sand-printed formwork - The Smart Slab © Tom Mundy | ETH Zurich
3. Futurecraft 4D by Adidas. Photo by: Adidas / YouTube

Commonly known as 3D printing or 'rapid prototyping', additive manufacturing is consists of the deposition of a predetermined material into layers, based on information extracted from a digital model. In this process, it is firstly needed to create a buildable model with a pre-established thickness, and then this model is translated into a code so the machine can read and print it. This technology was created in the early 1980s and was used mainly by the aeronautical and automotive industries. Only in the late 1990s, it started to get accessible and affordable for architects, being used principally for scaled models (Burry & Burry, 2016).

There are many types of 3d printing: Stereolithography (SLA), Selective Laser Sintering (SLS), Fused Deposition Modelling (FDM), Digital Light Processing (DLA), Selective Laser Melting (SLM), Electron Beam Melting (EBM), Laminated Object Manufacturing (LOM), Blinder Jetting (BJ) and Material Jetting (MJ) (Leach, 2017). Among these, three common types of 3d printing methods are described by Arthuro Tedeschi in his book AAD - Algorithms-Aided Design.

The first one is the Stereolithography (SLA), developed in 1983 by Chuck Hull, which through steps informed by computer models, uses laser lights to cure liquid resin into solid in different layers, resulting in high definition objects. After all layers are deposed and cured, it is applied a liquid solvent on the whole model and cure it into a UV oven and take off the supports used in the building procedure.

The second one is the Selective Laser Sintering (SLS), developed in 1986 by Carl Deckard. It starts with the deposition of layers of dusty material over a platform and the use of a roller to spread it evenly. Between each layer, a laser is used to fuse the material into the bidimensional sections of the object with a thickness determined by the dust deposition.

The third and most popular method of 3d printing is the Fuse Deposition Modeling (FDM). This method also operates in layers, by depositing melted filaments of material over a platform, and as the SLA method, it is also needed the use of supports during the printing process. Usually, the material used is plastic filaments of type ABS and PLA.

Another type of 3d printing to be presented as an example in this present work is the 3d sand-printers. Those work like the SLS printers, but with two differences. The first is that the materials used are usually sand-like materials as silica sand, ceramics, or metal particles. The second difference is the fact that there is no use of heating lasers in order to fuse the material and bind it together. Instead, to bind the particles together, it is used a binding polymer, through the technology of binder jetting. In this process it is possible to use local and cheap material, in a process of upcycling, arriving at a sustainable outcome (Rael and Fratello, 2018). Later, as an example, it will be presented the 3d sand-printed slabs, made by Block Research Group, EHT Zürich.

In the 3D printing process, the size of the manufactured object limits possible outcomes. This happens because the volume rises in a cubic ratio in comparison with other dimensions, resulting in higher use of material and critical structural performance. (Leach, 2017)

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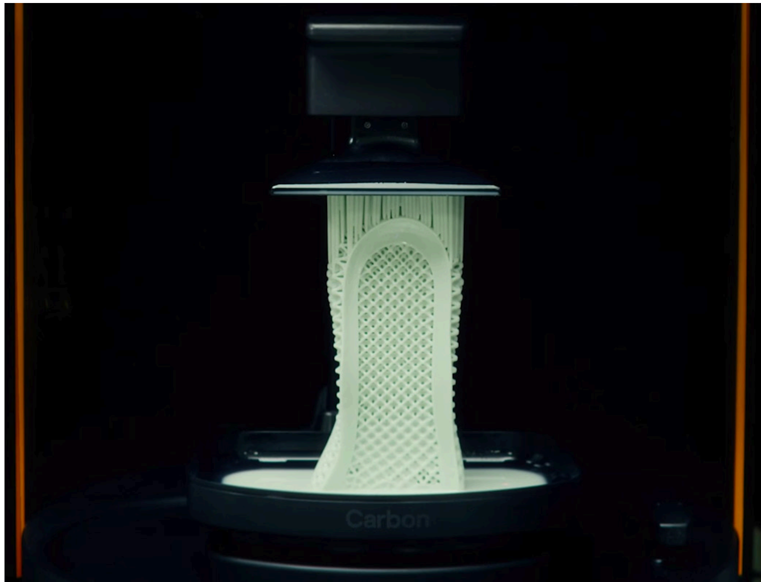
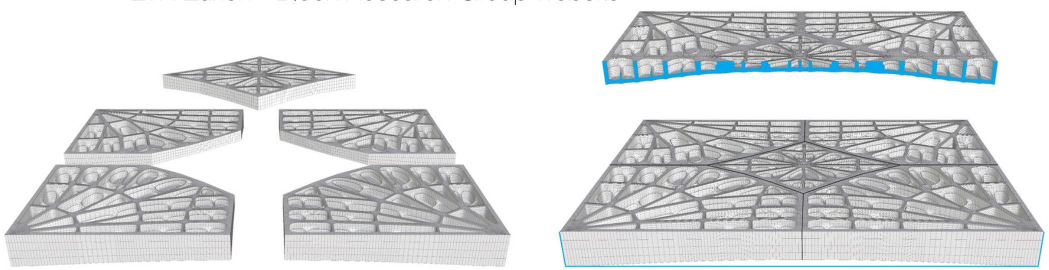


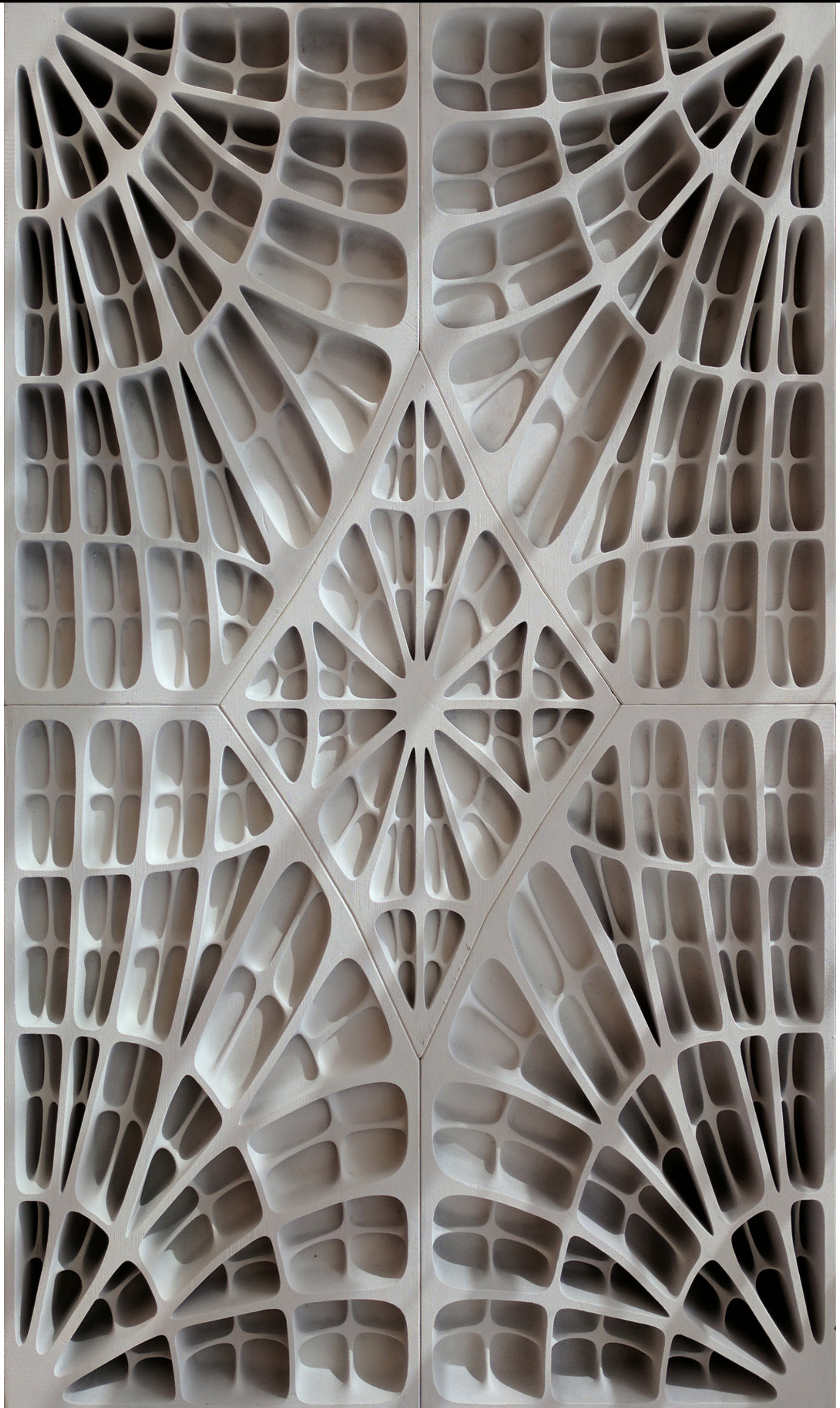
Example - Additive Manufacturing

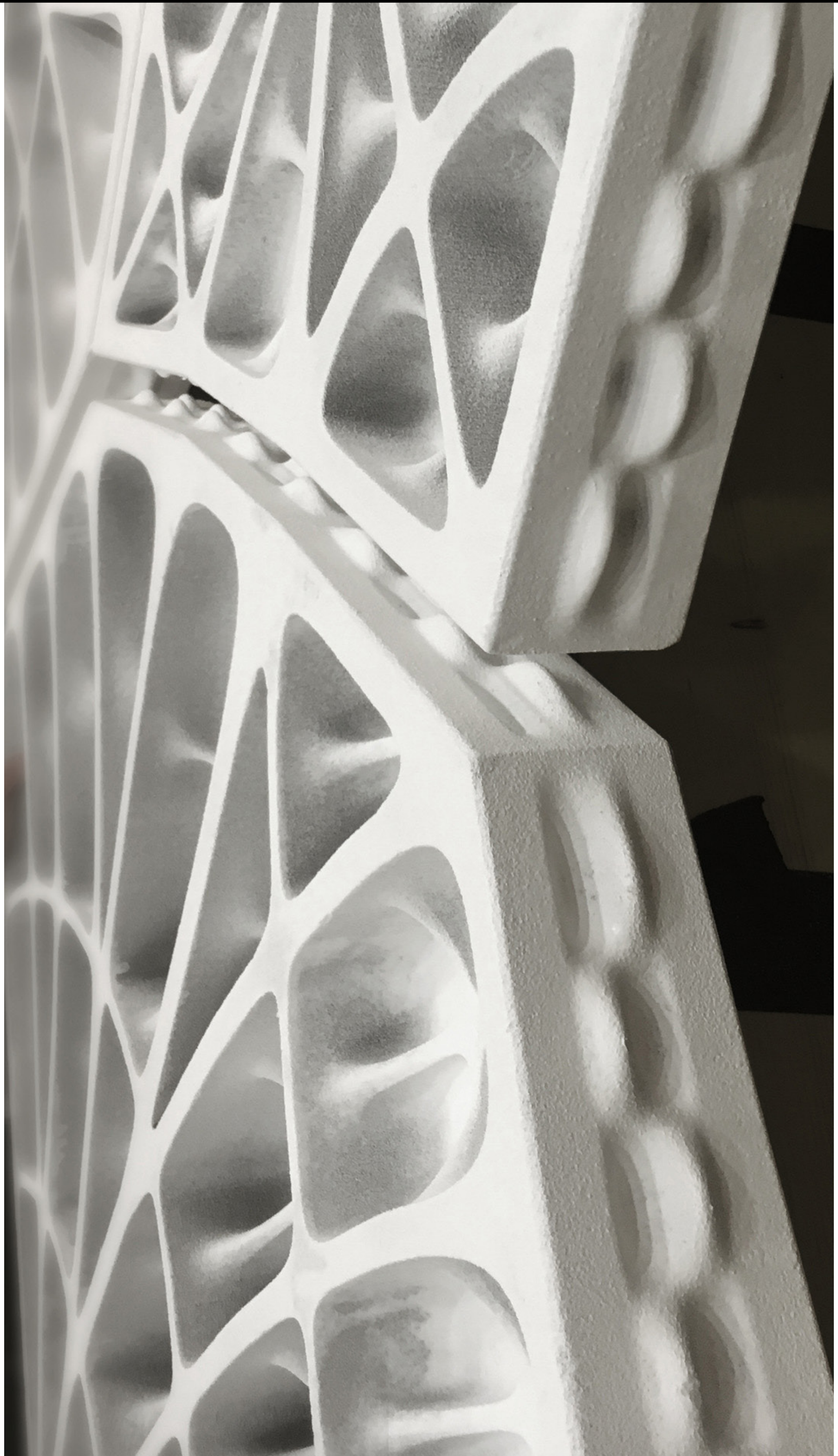
3d Sand-Printed Slab

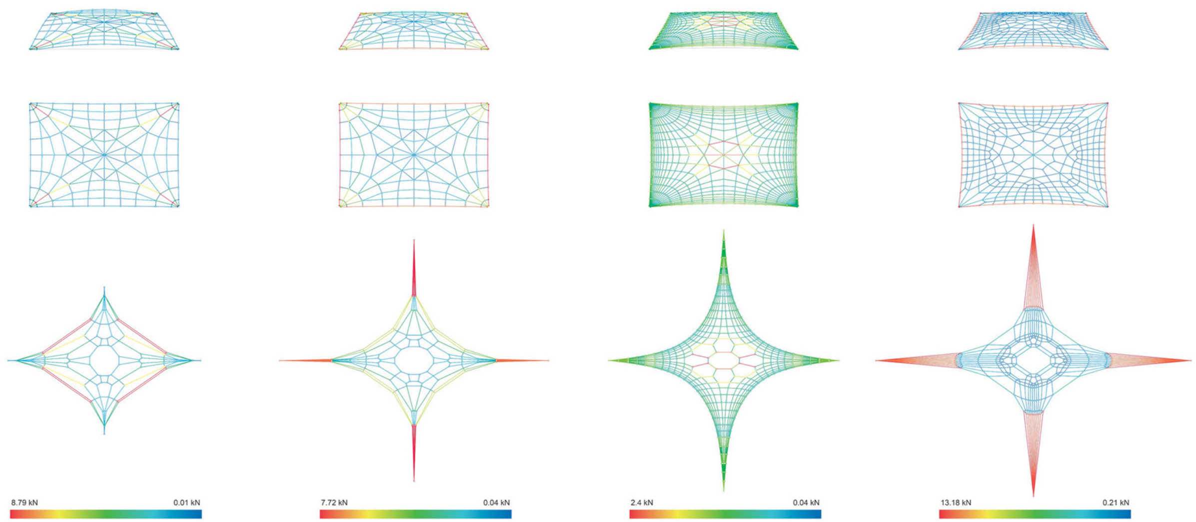
Created by ETH Zürich - Block Research Group, this slab system uses as form-finding process the Thrust Network Analysis, through the interface of RhinoVAULT. It is a two centimetres thick shell, built with 3d sand-printer, taking advantage of a Form-Active system. In this system, the horizontal plate is hold vaulted ribs. The ribs works in compression, redirecting the loads to the foundations. This kind of compression-only structure saves up to 70% of material when compared with regular slabs presenting flexural stresses. Beyond the save in sand material, the fact that there is no use of concrete nor moulds shifts this slabs to a high environmental performance. There is another huge advantage regarding the reduction of the overall weight of the structure, leading to lighter foundations. All the following images were extracted from ETH Zürich - Block Research Group website.

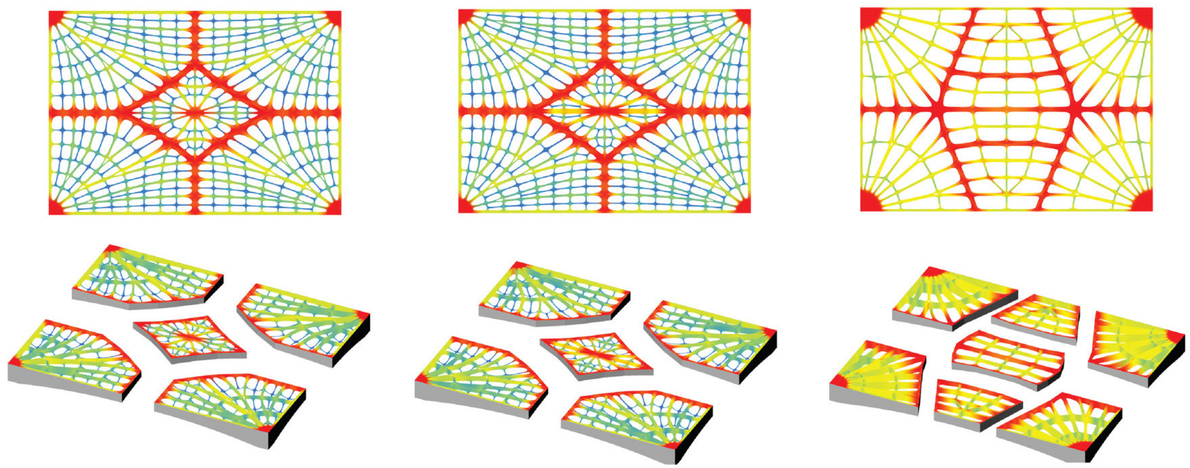


(a) (b)









1. All the images were extracted from the work of Block Research Group - http://block.arch.ethz.ch/brg/
2. Pieces separetly fabricated (a) and section (b)
3. 3d printed slab
4. 3d printed slab - connections
5. Form and Force Diagrams from different proposals - RhinoVAULT
6. Simulation of mechanical solicitations from different proposals

Robotic Assemblage

Robots have been used for manufacturing since the last century, but now it has vastly shifted its use towards revealing new creative opportunities. The word 'robot' comes from the Czech word 'robota', meaning 'forced labor'. Traditionally they have been used to perform repetitive tasks with that demanded high precision, being intensively used by the Japanese car industry in the 1970s (Linder et. al., 2019). Now we face a new reality, the use of robots to perform highly customized material manipulation, in order to achieve the differentiation of elements necessary in complex architectural forms. (Burry & Burry, 2016)

The use of robotic arms in the architectural field spread due to their sinking costs. The lower costs are consequences of technological advances and also a result of the economic crises that started in 2008. The crises affected the automobile industry deeply, leading them to sell their equipment cheaply to start-ups engaged in implementing digital technology to mass customization. Start-ups played a significant role in filling the gap between conception and fabrication, also serving as a bridge between the University and Industry. (Feringa, 2014)

The implementation of robots in architecture is changing the relationship between the virtual and the real world. It is narrowing the gap between design and fabrication, giving designers more autonomy to create, and, at the same time, inserts them in fields of fabrication and materialization. The creative process is not unidirectional, and the constant communication of design and fabrication achieved by using robots as an interface between information and realization brings the whole process to a loop.

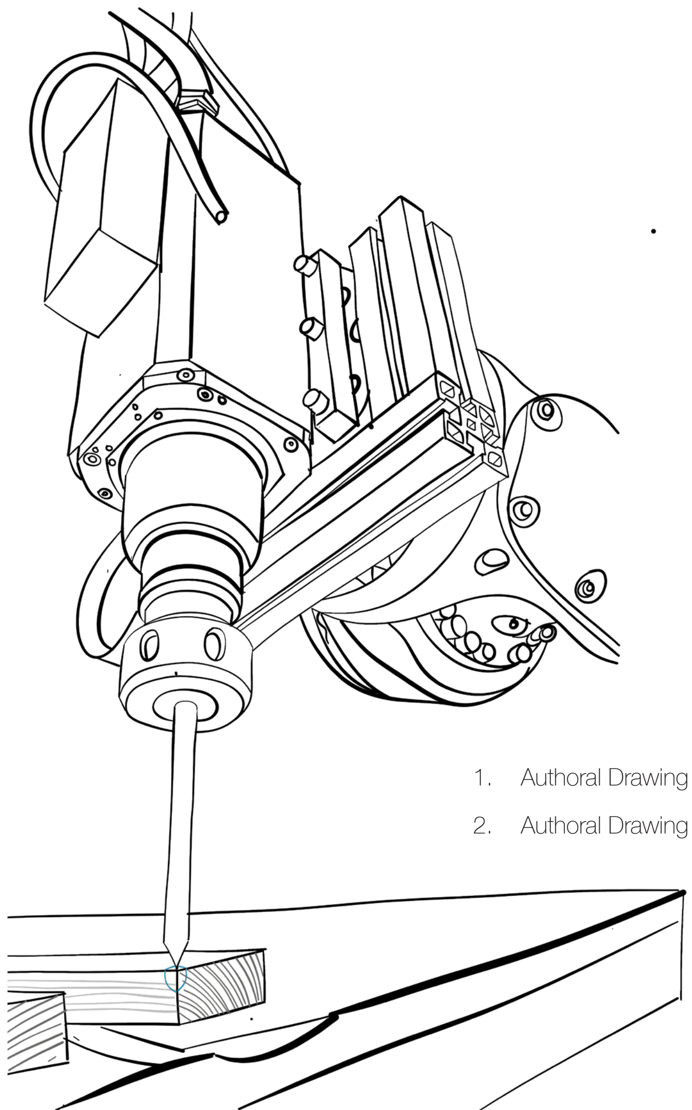
Robotic fabrication is an interaction of both hardware and software. The software translates geometric information, like coordinates, curvature and vector, into robotic movement paths. The hardware is the tools that are attached to the robotic arm, enabling the manipulation of different materials through precise techniques in small and large scales.

As Robotic arms can be equipped with almost any tool, it is either an additive and subtractive method, also performing other kinds of manipulations as folding, knitting, forming, bending, folding, stacking, weaving, welding and stitching, with real-time feedback informing the design process (Leach, 2017; Burry & Burry, 2016). The feedback system is of extreme importance in order to recalibrate the whole assemblage according to discrepancies that exist between the virtual design and the material properties in the real world (Willmann, Gramazio & Kohler, 2017) Such vast application narrows the gap between conception and fabrication, having as primary constraint a material-driven design. As robots are digitally programmed to perform physical tasks, the interface makes the virtuality to influence the reality directly. (Gramazio & Kohler, 2014)

Although robotics brought the possibility to fabricate even entire structures through 3d printing or welding, the dominant reality now in architecture is not yet a digitally integrated and whole mass-customized process. Constructing architecture is still based on the assemblage of standard parts together with customized components, having as an outcome a low production in volume (Bechthold). That said, the interaction between people and machines is unavoidable and required.

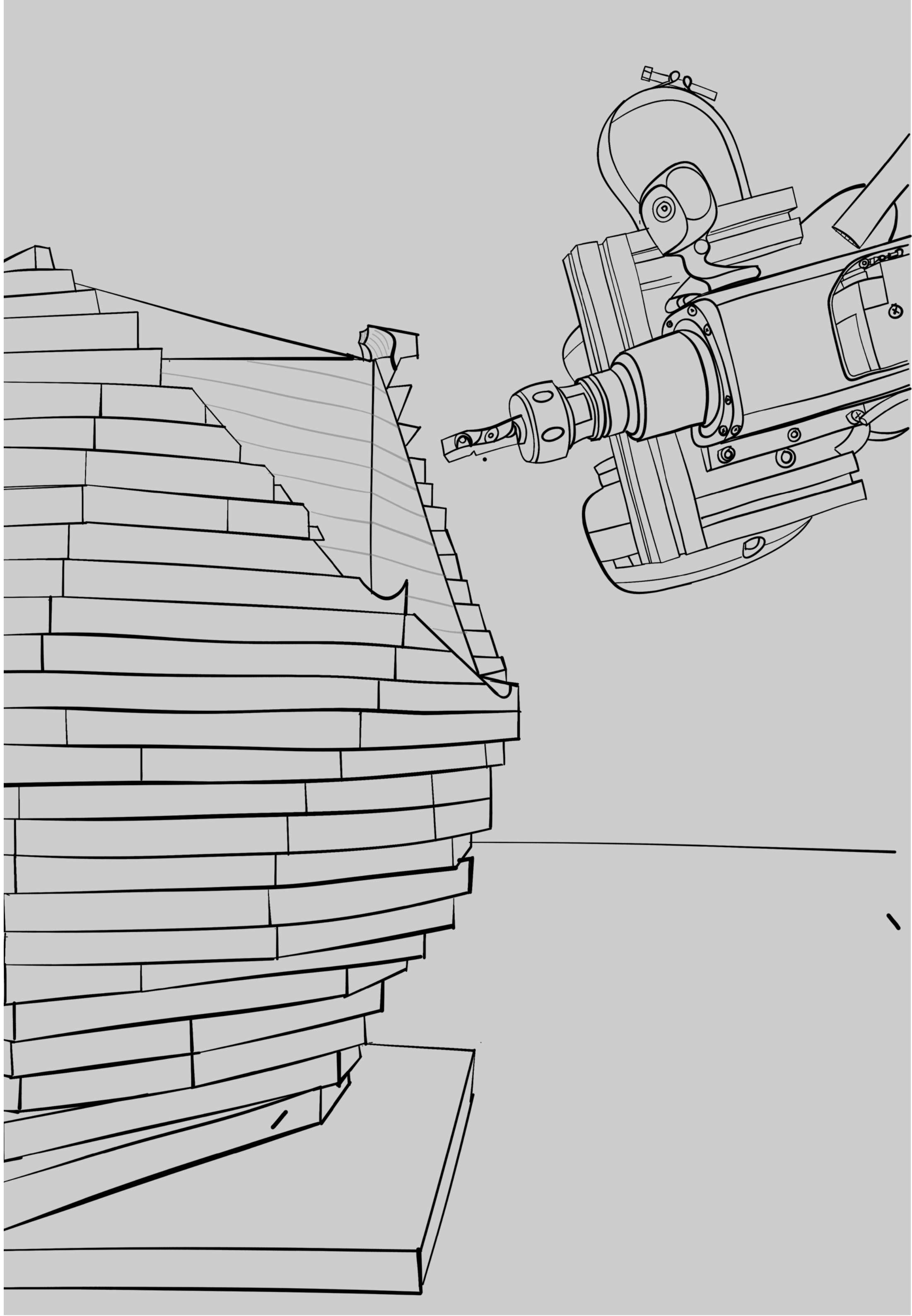
In this context, instead of an in situ fabrication is predominant the pre-fabrication of the different parts. The need for high-precision in manufacturing modular elements combined with the fact that robotic arms are still pretty vulnerable to the outdoor environment demands the assemblage of such components in indoor and protected places.

The introduction of robotics shifted the role of the architect from being only responsible for representing the project through drawings and models, to being actively present throughout the conception, materialization and fabrication process of the design. Coupled with this broader role, also came the need for a broader interdisciplinary knowledge.



1. Authoral Drawing from a Kuka Robot during calibration
2. Authoral Drawing from Kuka Robot doing a milling operation

1.



2.

Example - Robotic assemblage

additive manufacturing

MX3D Metal-printing

Based on robotic additive technology, this system used industrial robotic arms combined with a welding tool, guided by computational instructions. It prints, without the need for supports, spatial structural frames, both small and large scale complex elements, using steel, stainless steel, aluminium, bronze and copper. For different types of forms, the software must recalibrate for different settings, like pulsing, pauses, size of layers and tool orientation.

Standard Robot +

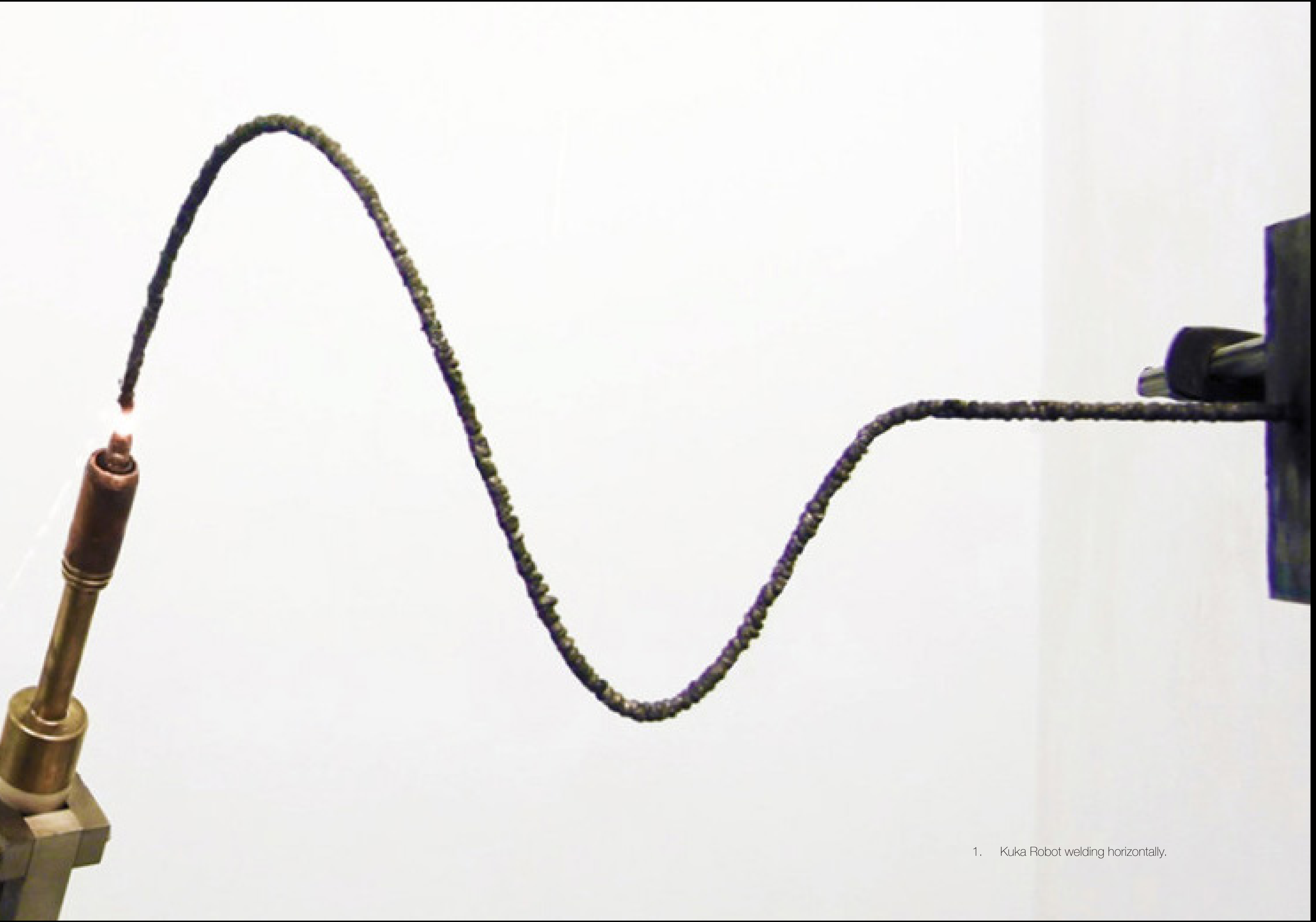
Standard Welding Machine +

MX3D's proprietary software

Speed: 1-3 KG per hour per nozzle

Size: virtually unlimited

Materials: most weldable metal alloys like stainless steel, steel, aluminium, bronze, inconel and other high strength steels



1. Kuka Robot welding horizontally.

Smarter Bridge

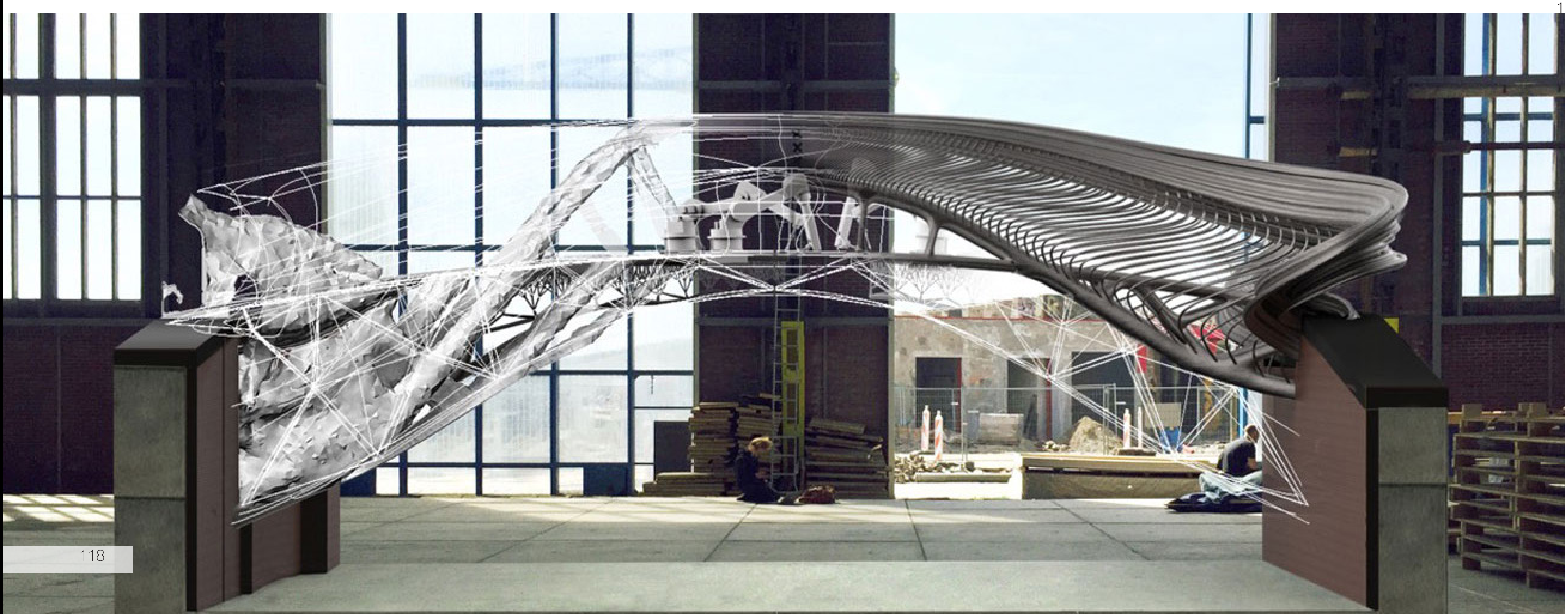
The partners joining the MX3D project include: Autodesk, The Alan Turing Institute and the Amsterdam Institute for Advanced Metropolitan Solutions (AMS).

First announced in 2015 and completed in 2019, this project is based on the 3d metal-printing technology. The bridge consists of a twelve-meter long structure, made of stainless steel, placed in the city of Amsterdam. In the first stages of the design project, it was thought to be fabricated in situ, but due to safety reasons, this idea was abandoned. The bridge is equipped with real-time sensors, collecting data from its mechanical behavior, along with local environmental factors. This data is connected to the bridge so it can process information such as the number of crossing people and their pace, so later it could be used to generate further structures in an optimized way.

All the images are extracted from MX3D's website: https://mx3d.com/projects/bridge-2-2/

1. First Project -Robotically self-assembled idea
2. Finalized bridge
3. 3D Robotic welding process

1



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Material-based design - Informed Tectonics

As the digital design and fabrication start from the holistic approach of conception, materialization and fabrication, it is essential to explain the concept of tectonics and digital tectonics briefly. Informed Tectonics is about the computational exploration of material and fabrication process in the design process. This architectural generation approach bases itself on a performative thinking, leading to a performance-oriented output, structurally optimized.

> *"Tectonics pertains to the generics of a theory of structuring. Architectonics pertains to the generic conditions of the tectonic contents of architecture. Tectonics in architecture is therefore the culturally defined symbolic relationship between material structure and architectural form"*
>
> Rivka Oxman & Robert Oxman, 2014

Considering tectonics as being the process in which architectural form is driven by conditions imposed by material, Rivka and Robert Oxman affirm that the digital phenomena is at the same time responsible, as well as an outcome, of this approximation between architecture and material behavior, and simultaneously growing apart of merely formal expression. The study of material behavior and posterior material manufacturing techniques are fundamental to a bottom-up approach in architecture. (Yuan, 2017)

Tectonics is connected with material, and material improvement depends on technological innovations. We now live in an environment in which information management is responsible for technological improvements, consequently, information management is the base of digital tectonics architectural form. As material tectonics is the manipulation of numerical and geometrical relationships between elements, it is not merely representational, but generative. The information contained within the material that is the performative considerations drives the architectural form (Belogolovsky, 2019).

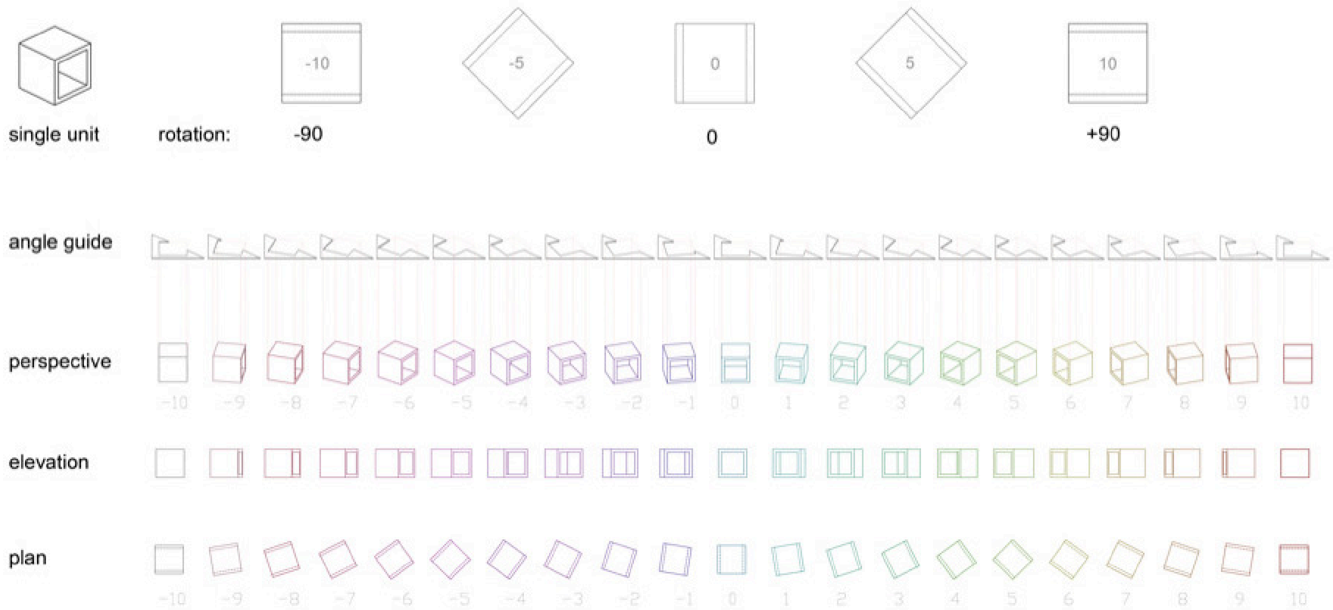
Related to technology, material Tectonics has a historical evolution over different periods in architecture (R. Oxman, 2010). It has away relied not only on material innovations, but also immaterial aspects such as cultural and social. As in vernacular architecture, we face a deep connection between material, form and fabrication, we search now, in informed tectonics, such coherence in the design process from conception until fabrication, with the fabrication process implicit in the generation of the architectural form.

We face now a reality of mass-customization. Digital tools enabled the creation of complex forms through the manipulation of B-Splines (Bénzier splines) and NURBS (Non-uniform Rotational B-Spline Surfaces). By manipulating algorithms and parameters, we can spread and collect a massive amount of differentiated information throughout the model, which would be impracticable accomplishing manually. The challenge now lays in the fabrication and assemblage of such complex customized elements. (Scheuer, 2014)

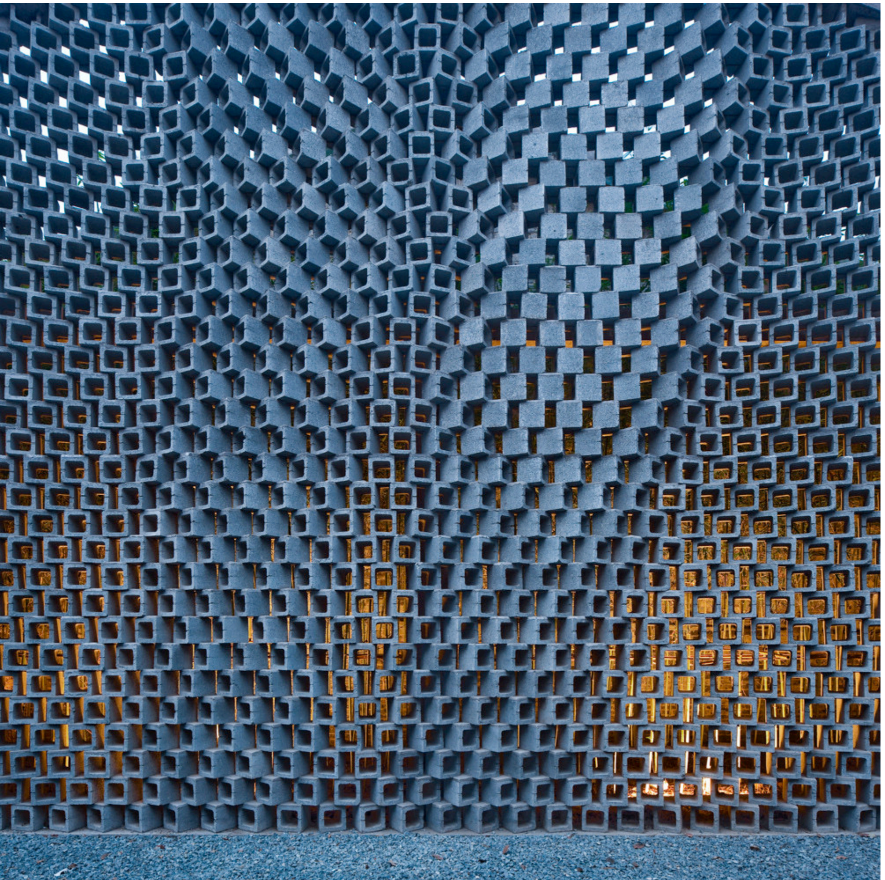
All the following images are of the project called "Silk Wall" and were extracted from the book: "Collaborative Laboratory - works of Archi-Union and Fab-Union".

1. Assemblage method and guides angles
2. Silk wall view
3. From concept to assemblage
4. Construction method
5. Cement blocks

Silk Wall . Archi-Union



1



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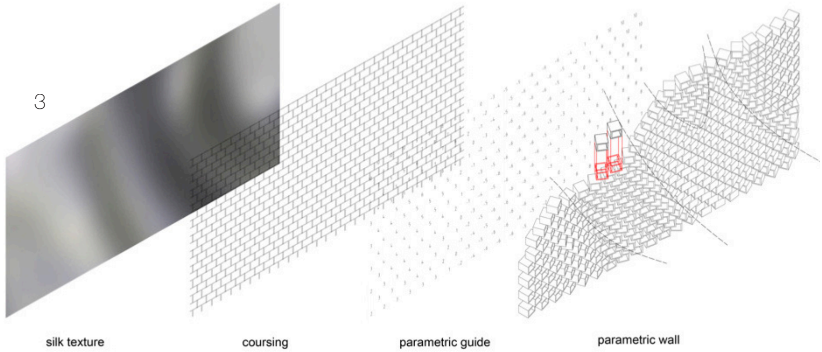


4

5

Regionalism

Within the topic of tectonic, in which regards materialization and fabrication processes, it is worth mentioning their adaptability to regional peculiarities. An essential figure in this approach is the architect Philip Yuan, founder of Arch-Union Architects and Fab-Union Technology. Based in Shanghai, he explores the intersection between digital tools and vernacular architecture.

Yuan says that if Parametricism should not base the design process only by new digital techniques. He aims to enrich architecture by taking regional characteristics as a starting point to the design process. He does so by combining digital fabrication, local materials and local craftsmanship, paying close attention to embodied features of traditional materials. Beyond the mere use of digital tools for conception and fabrication, there is a search for social engagement. The result is an architecture that simultaneously preserves the regional heritage and has a robust expressional value by the manipulation of complex geometry. (Belogolovsky, 2019)

"The material-based performative tectonics will be an effective tool in the vernacular architectural design to explore an integration of the complex form, structure, as well as the fabrication technique, and make the future towards a brand new regional tectonic culture."

Philip Yuan, 2019

PART TWO

THE PROJECT

7. Goals

Low physical density of the city due to planning regulations is a massive obstacle to students in the city, leading to a high price of living and poor transportation infrastructure. Combined with the fact that students usually have no income, the result is a significant housing problem. The idea is to create a student housing in an integrated approach, propitiating the interaction among the residents, and reinforce the intrinsic characteristic of community in the University.

The project's goal is to introduce a performance-oriented architecture, achieved by the exploration of digital parametric tools that elevates the exploration of new forms beyond the mere formal conception and brings it to a reasonable use of materials, seeking beauty in a structurally elegant form and providing a great architectural experience with a optimal use of materials.

It is an utopic exploration of digital design tools and advanced fabrication techniques. The city of Brasilia was not chosen merely for personal reasons, but mainly for being a place that carries utopia in its history. Built from scratch from the '50s, the city built up from an idea that was firstly taken as architectural reverie. Another intersection point between the project and the city is the relation that the technological exploration has to do with the modern movemen. As at the time reinforced concrete was the latest technology, the city is marked by testing the limits of this material, either by straight line elegance or by free form plasticity.

Seeking to re-establish the limits within which technology can reach, it also reconsiders new ways of living for the 21st century. In order to take all the variables to the project level, it is necessary to take a holistic look, valuing not only technological explorations, but also sustainability parameters beyond construction, which include social aspects.

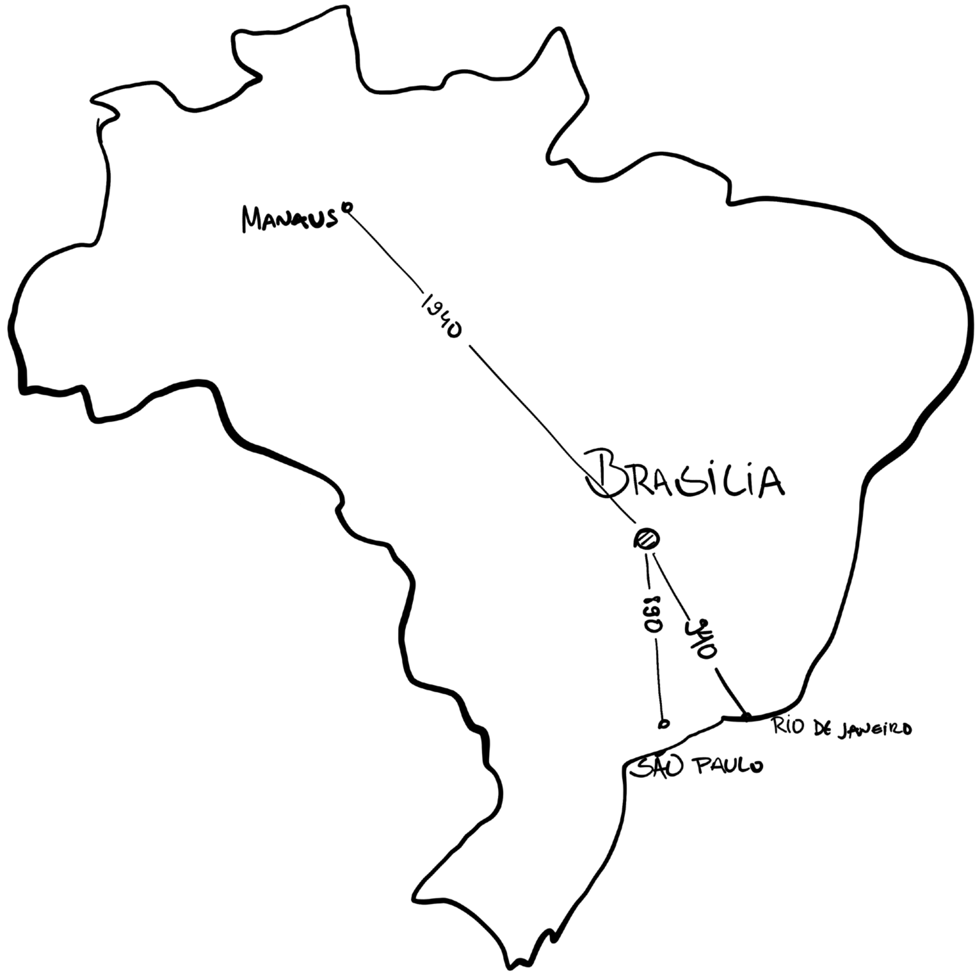
The idea of assigning such an unusual project idea to a student residence is due to the flexible character that young people usually have, adapting more easily to the changes imposed on them. Sharing is a strong strategy to solve the great problems of this century. Spatial sharing provides interpersonal relationships, emphasizing the idea of belonging to the group. Unfortunately, in Brazil, there is still no established culture of cohabitation, and the most effective way to implement this reality is by the youngest.

Besides the social issues that imply this way of living, there are also issues related to sustainability. By restricting the personal space to the minimum, without depriving the student of the right to privacy, collective spaces are better enjoyed. Prioritizing the use of collective rather than individual equipment has great impacts considering aspects such as energy costs, value of equipment/products and cost of land.

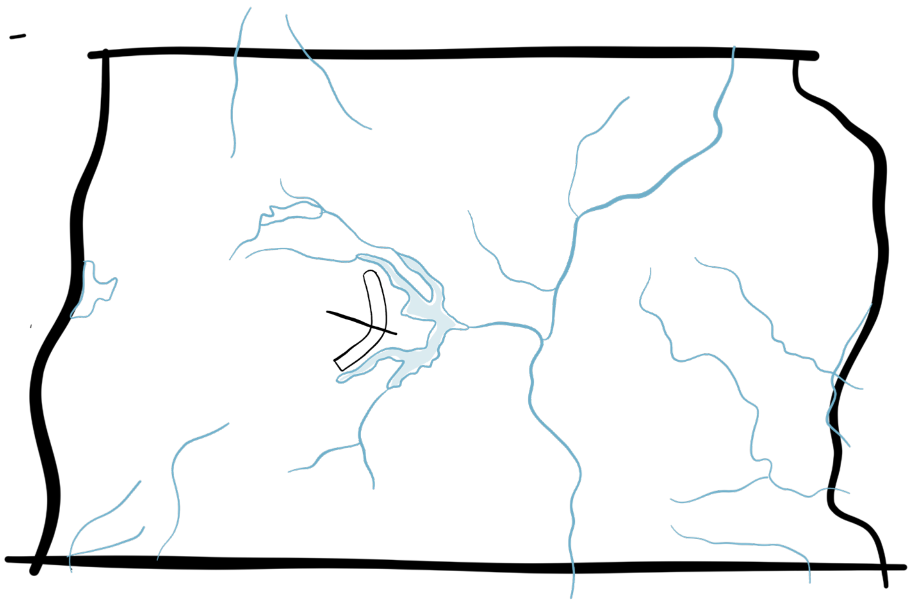
The execution relies on the concept of Mass Customization, that is deeply connectect to fabrication and design cutting edge technologies. As today we live in the informational era, we are impoving our communication with machines through coding and that is what enables the materialization of mass customized systems.

8. Context

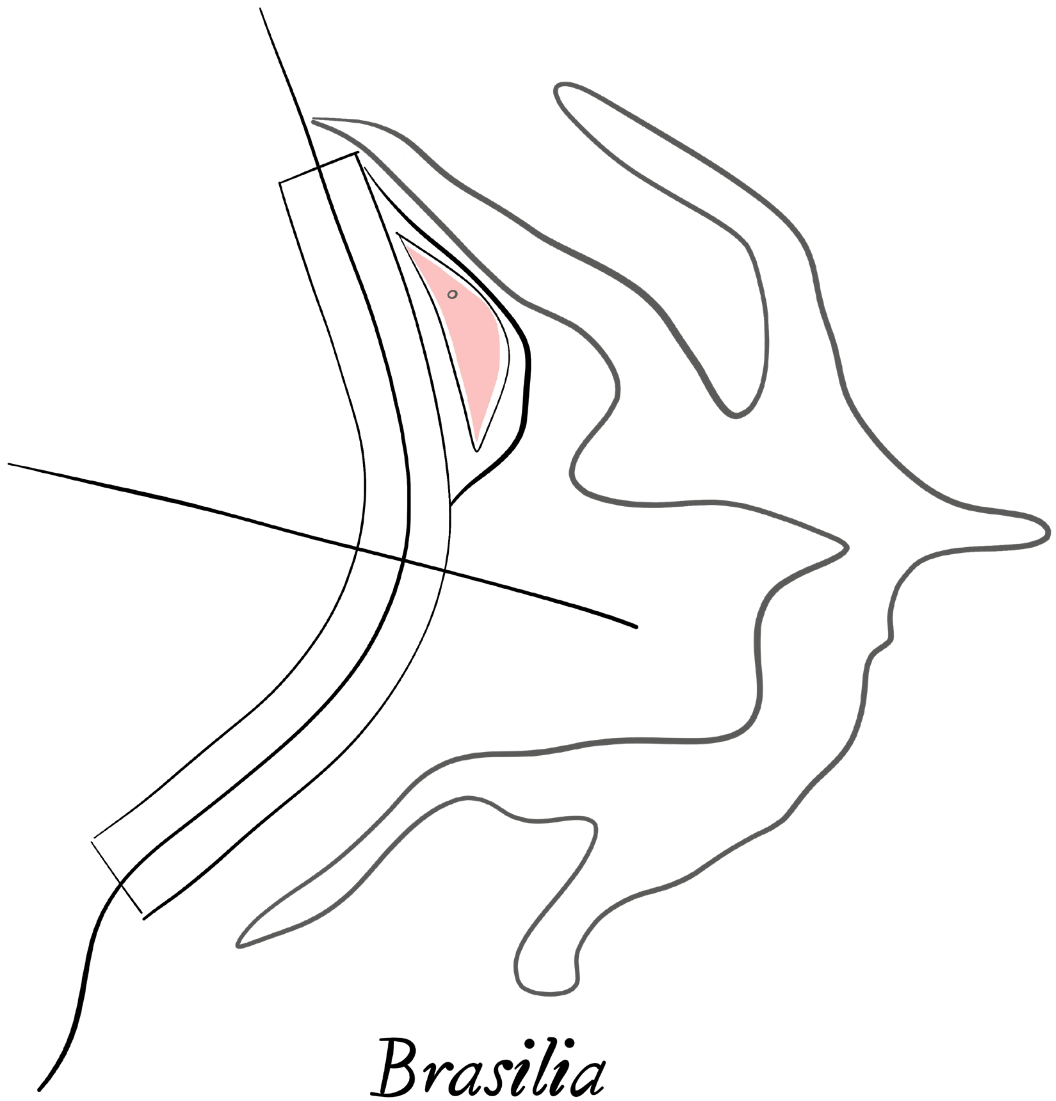
Region		Central-West	
Founded		April 21, 1960	
Area	Federal District	5,802 km^2	
	Plano Piloto	472 km^2	
Elevation		1,171 m	
Population	Federal District	3,039,444	523,86/km^2
	Plano Piloto	220,393	466,93/km^2
GDP		\$65.338 bi	
	Per capita	\$21,779 bi	
HDI		0,839	
Time Zone		UTC -3:00	
Climate		High-altitude tropical	
Average temp.	Summer	17°C to 29°C	
	Winter	12°C to 26°C	



Brazil



Federal District



Brasilia

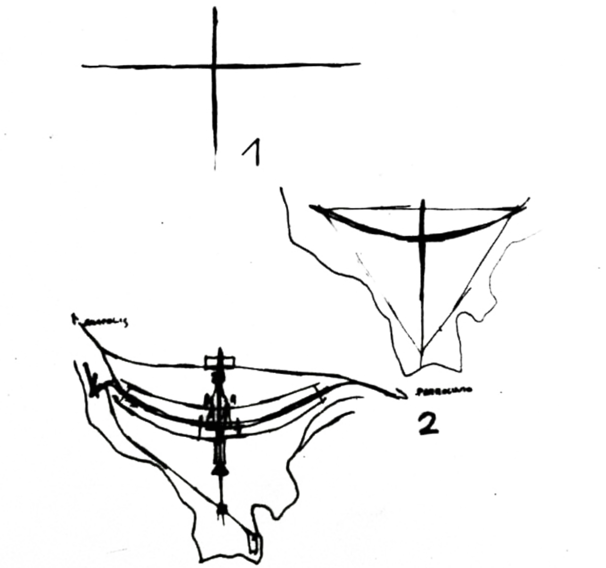
Brasilia

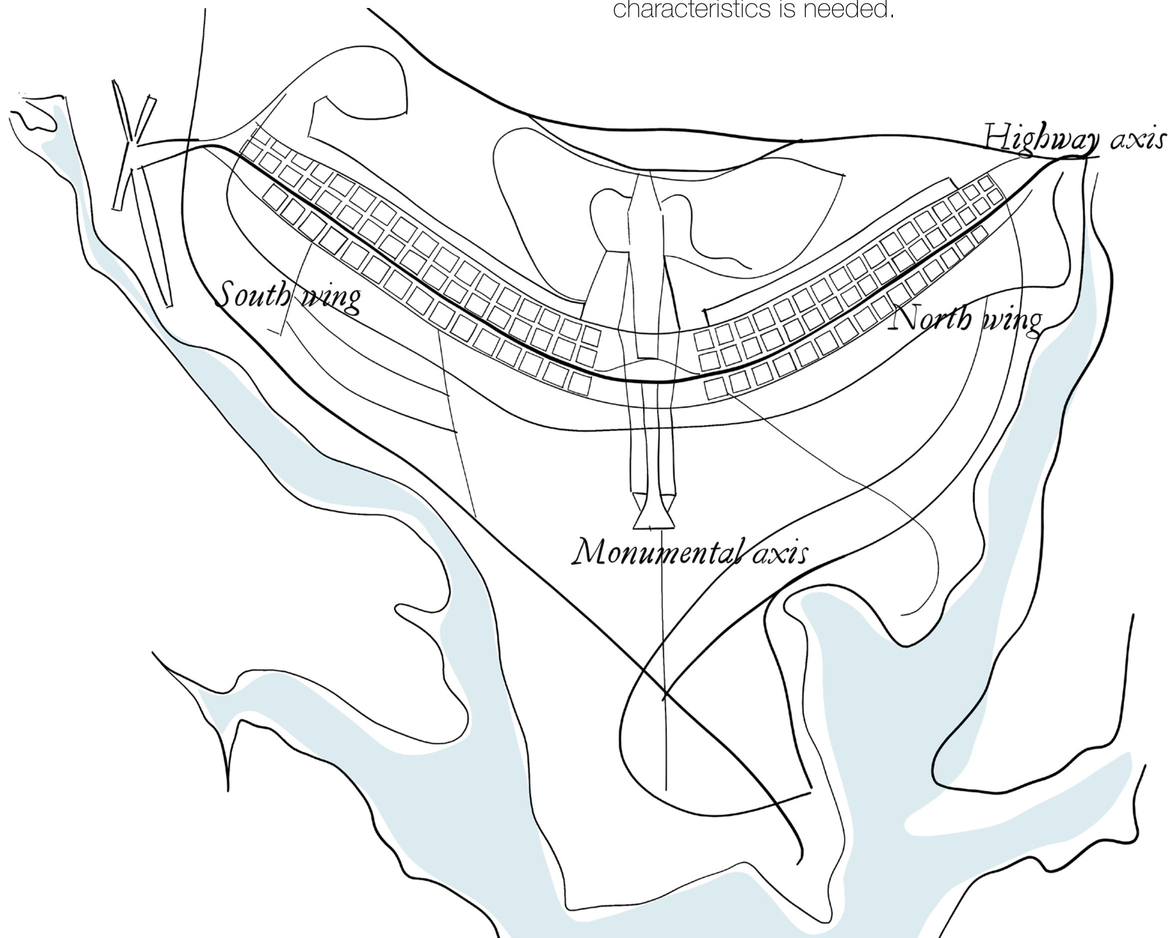
The project takes place in Brazil's capital city, Brasilia. The city is known among architects and urban planners by its unique history, being planned and built from scratch in the '50s by Lucio Costa, basing its principles in what would be expected for a modernist city by the time (de Carvalho, 1991). For this reason, a brief explanation about it is needed to make feasible such an innovative project. The idea is to introduce an architecture that shows a strong visual impact due to its shape, without disturbing the plastic integrity of the urban and architectonical set of the city-park.

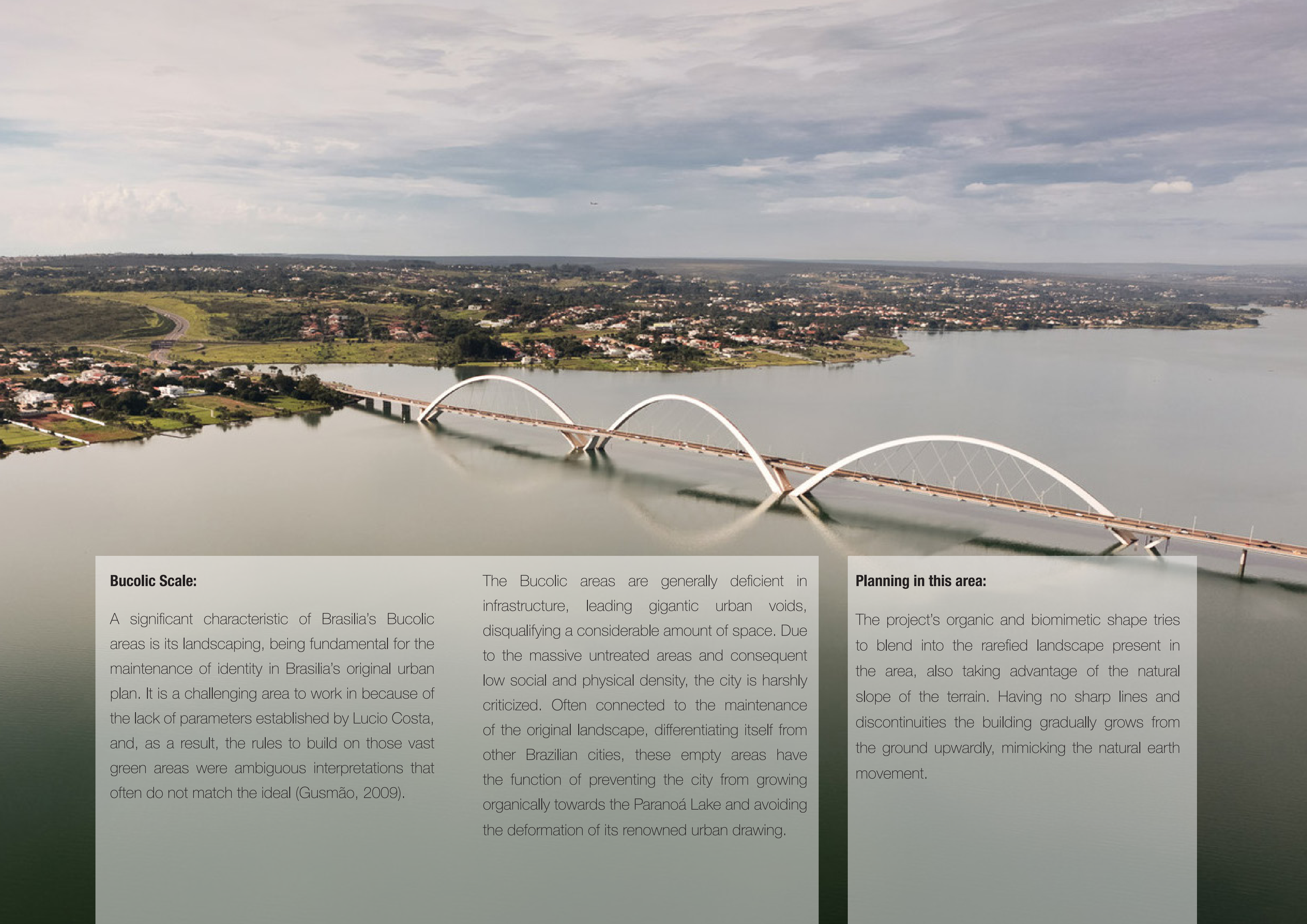
It is known that Brasilia was built according to the CIAM's (congrès internationaux d'architecture moderne) most important manifesto, the Athens Charter and it is still the closest model that corresponds to its principles (Holston, 1989). This manifesto sets the base for a modern ideal city, and, following its ideas, the city should be planned considering four different functions: housing, work, recreation and traffic. The traffic is what connects the other three functions, and, in the city of Brasilia, it plays a significant role, reflecting the amusement that the car caused upon a whole generation.

The city came from a simple cross, that now is known as highway axis and monumental axis. Following the highway axis, the Residential Scale shows itself in the form of the multi familiar superblocks. Besides the residential scale, the city presents other tree scales: Monumental, Gregarious and Bucolic Scales.

The area where the project takes place is the University of Brasilia. As it is situated inside an area of Bucolic Scale, a short contextualization of its characteristics is needed.







Bucolic Scale:

A significant characteristic of Brasilia's Bucolic areas is its landscaping, being fundamental for the maintenance of identity in Brasilia's original urban plan. It is a challenging area to work in because of the lack of parameters established by Lucio Costa, and, as a result, the rules to build on those vast green areas were ambiguous interpretations that often do not match the ideal (Gusmão, 2009).

The Bucolic areas are generally deficient in infrastructure, leading gigantic urban voids, disqualifying a considerable amount of space. Due to the massive untreated areas and consequent low social and physical density, the city is harshly criticized. Often connected to the maintenance of the original landscape, differentiating itself from other Brazilian cities, these empty areas have the function of preventing the city from growing organically towards the Paranoá Lake and avoiding the deformation of its renowned urban drawing.

Planning in this area:

The project's organic and biomimetic shape tries to blend into the rarefied landscape present in the area, also taking advantage of the natural slope of the terrain. Having no sharp lines and discontinuities the building gradually grows from the ground upwardly, mimicking the natural earth movement.

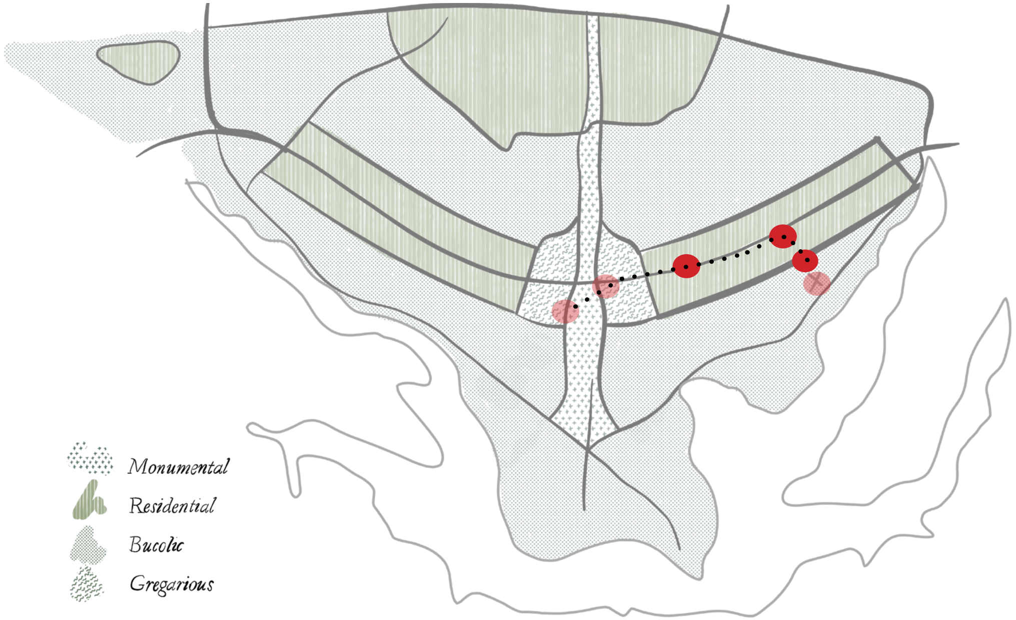
Monumental Scale

Fotos: Joana França

Gregarious Scale

Residential Scale

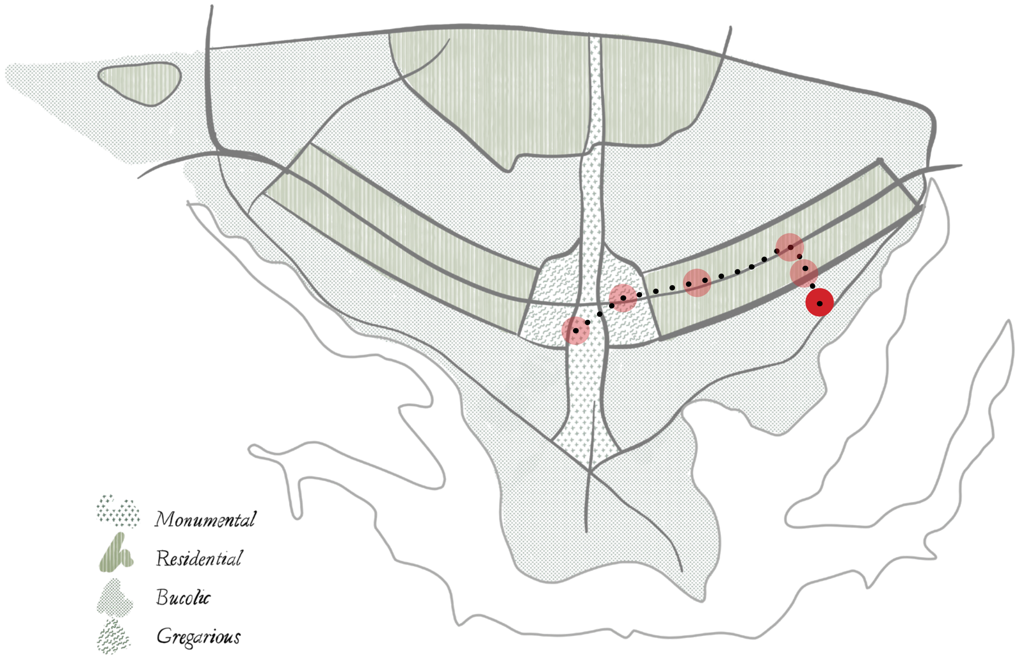
Fotos: Joana França



Fotos: Joana França

Fotos: Joana França

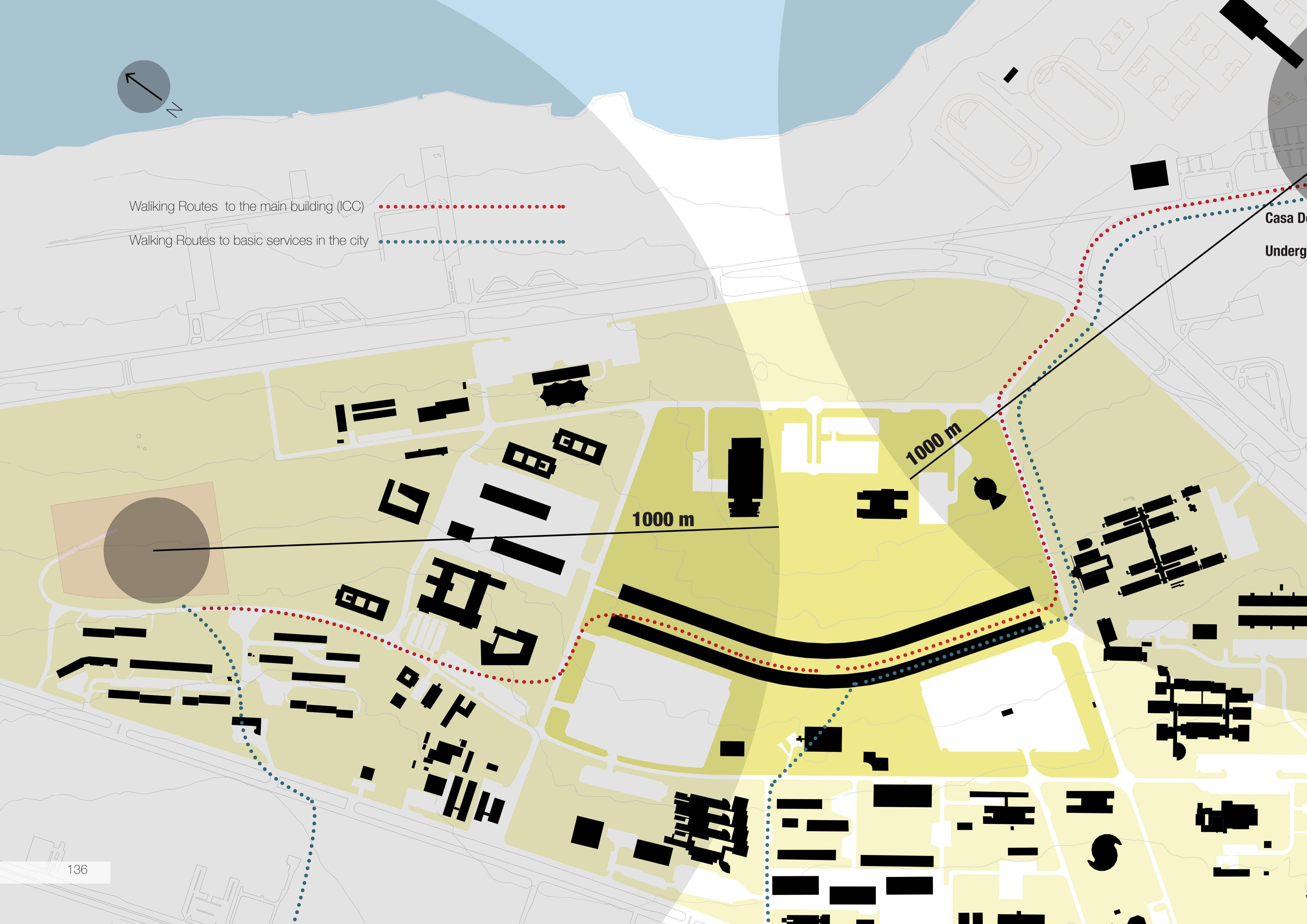
UNB - Campus Darcy Ribeiro



Founded in December of 1961, the University's first Campus, Darcy Ribeiro, is located between the North Wing and the Paranoá Lake. Planned by Lucio Costa, it follows the modernist precepts, inserted inside the city's Bucolic Scale and slightly segregated from the rest of the city (Baratta, 2007).

The site designated to the Campus is an area of 3.95 km2 and it hosts six different kinds of uses: residential, academical, administrative, commercial-services, leisure and mixed uses. Lucio Costa's project spatial distribution is characterized by vast parcels of terrains delimitated by traffic roads. Buildings that hold interest to the city, such as the University Rectory, the Library and the University Museum, are located in the central area of the Campus. Also located in this nuclear area is the iconic "Instituto Central de Ciencias - ICC" (Central Institute of Sciences). The ICC is a 720 meters long building, designed by Oscar Niemeyer, which hosts several different institutes such as Mathematics, Physics, Chemistry, Architecture, Design, among others.

Fotos: Joana França


N
Waliking Routes to the main building (ICC)
Walking Routes to basic services in the city
Casa Do
Underg
1000 m
1000 m

Residential use inside the Campus

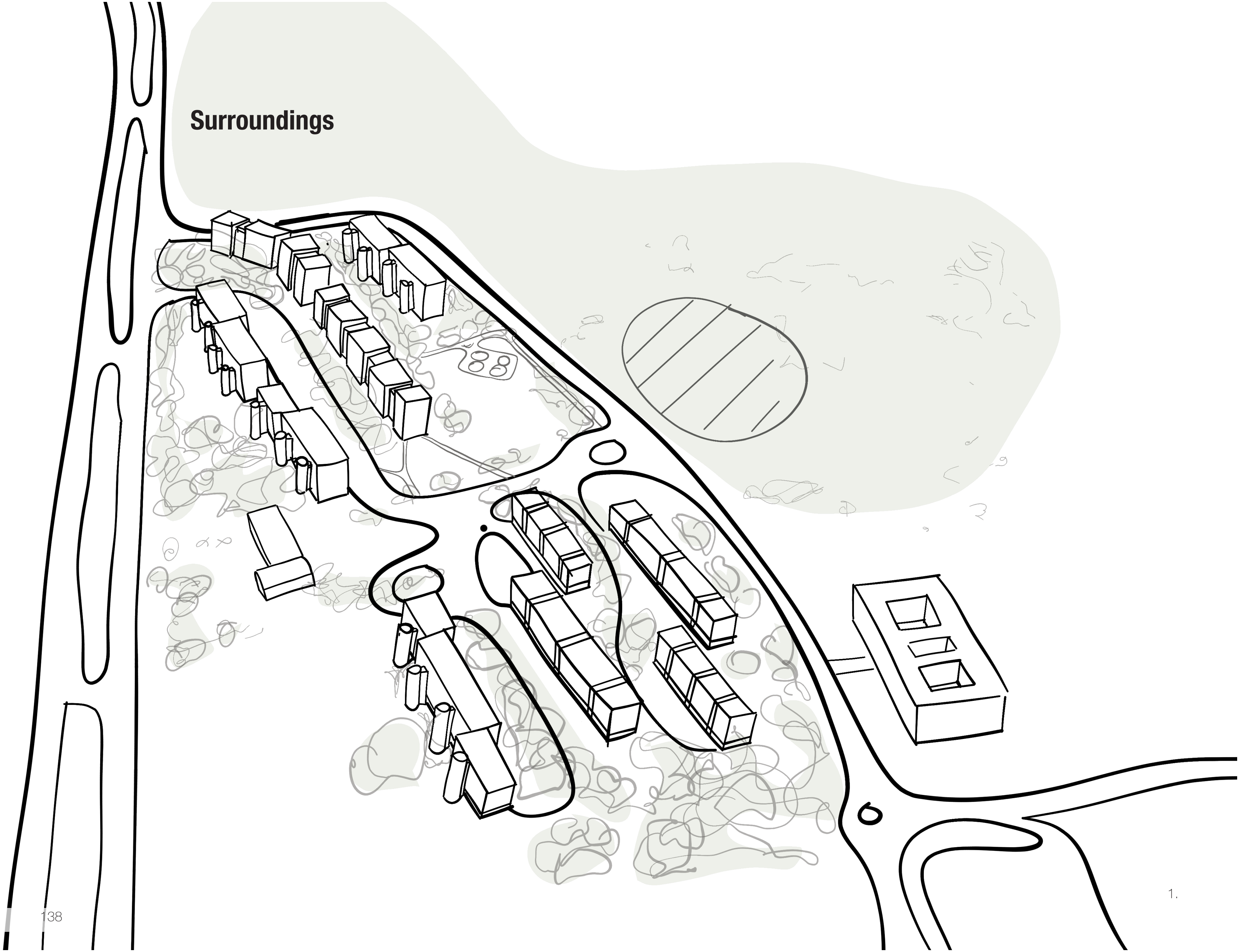
In the northern portion of the University's site is located the residential area, known as Colina. Built in 1963, this area consists of a group of eleven residential buildings attending the academic community, mainly Professors and international students. The residential blocks are known for their brutalist aspect and their pioneering use of prefabricated elements.

Another set of residential buildings, Casa do Estudante Universitario - CEU, attends undergraduate students. They are located slightly distant from the campus' core, next to the University's Olympic Center, in a walking distance of two kilometers away from the ICC. The set of two residential blocks were built in 1973 and counted with 90 apartments, housing 360 students.

Housing demand

The University of Brasilia offers housing assistance of R$ 530,00 (current value of approximately US$141,00) for students under social-economical vulnerability. Encompassing this modality, the University assists 1888 students, but this value does not match the real living cost present inside Plano Piloto, one of the most expansive square meters to live in the whole country [1].

1. Information extracted from "Anuário Estatístico da UnB - 2018"


Surroundings
1.

The University's Campus is historically known as being the place where new architectural explorations took place. Considering the consistent constraints presented by a Modernist Unesco's heritage city as Brasilia and its austere architecture of the city's "superblocks", the Univeristy is the best place to introduce new building technologies.

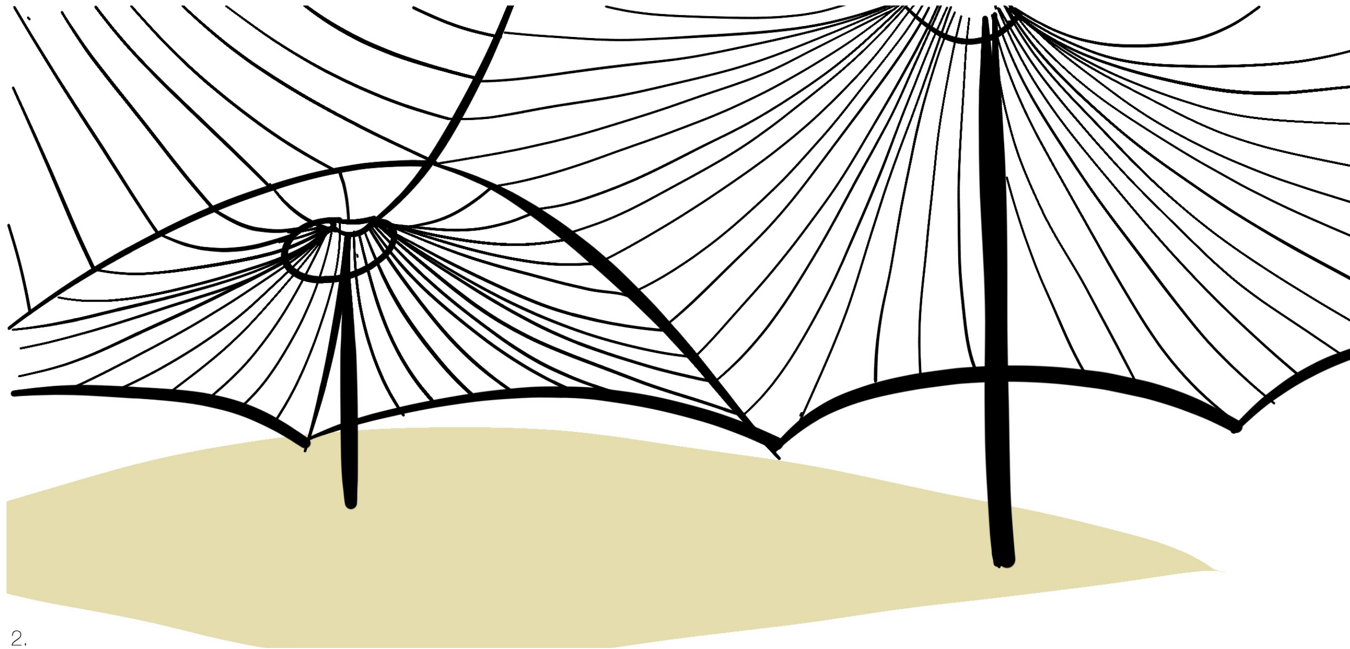
João Figueiras Lima, also known as Lelé, was a key figure regarding the exploration of building techniques in the city of Brasilia and the main University campus from the 1960s to 2000s. He was well known for his creativity regarding the logistics and rationalization in the construction site (Vilela Junior, 2011), besides his innovative exploration of structural possibilities.

In the Colina area, he was in charge to create a block of building to host housing for the academic professors called "Apartamento para Professores", 1962. The building was one of the first to use large prefabricated elements in the country and represented a new era for the construction sector in Brazil (Vilela Junior, 2011).

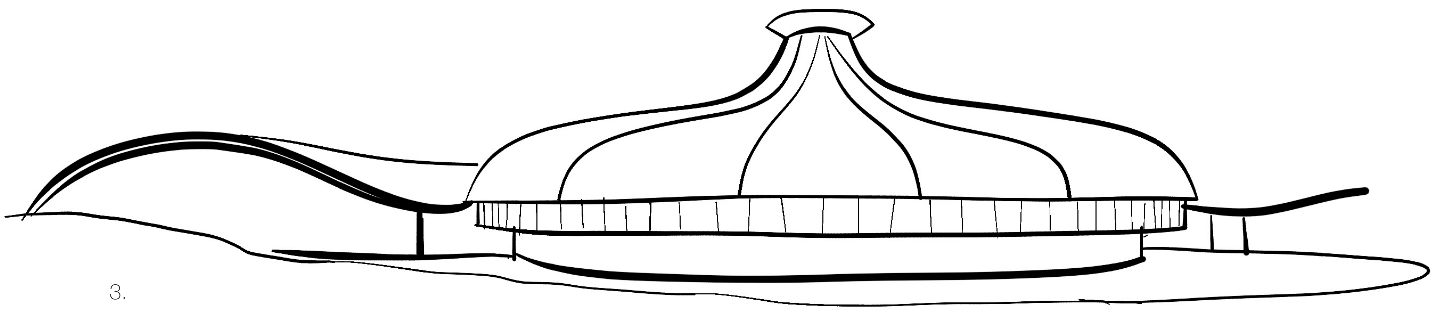
Besides the first prefabricated buildings, the Campus also shows examples of experiments with metallic structures and explorations of free form architecture.

Lelé breaks the linearity present in the architecture of Brasilia and introduces an architecture structurally smart and yet full of expression.

1.Authoral Drawing - Colina aereal view
2.Authoral Drawing - UnB's Center Convention
3.Authoral Drawing - UnB's "Beijodromo" building. Architect: Lelé



2.



3.

THE SITE

Relationship to the City: The scale issue

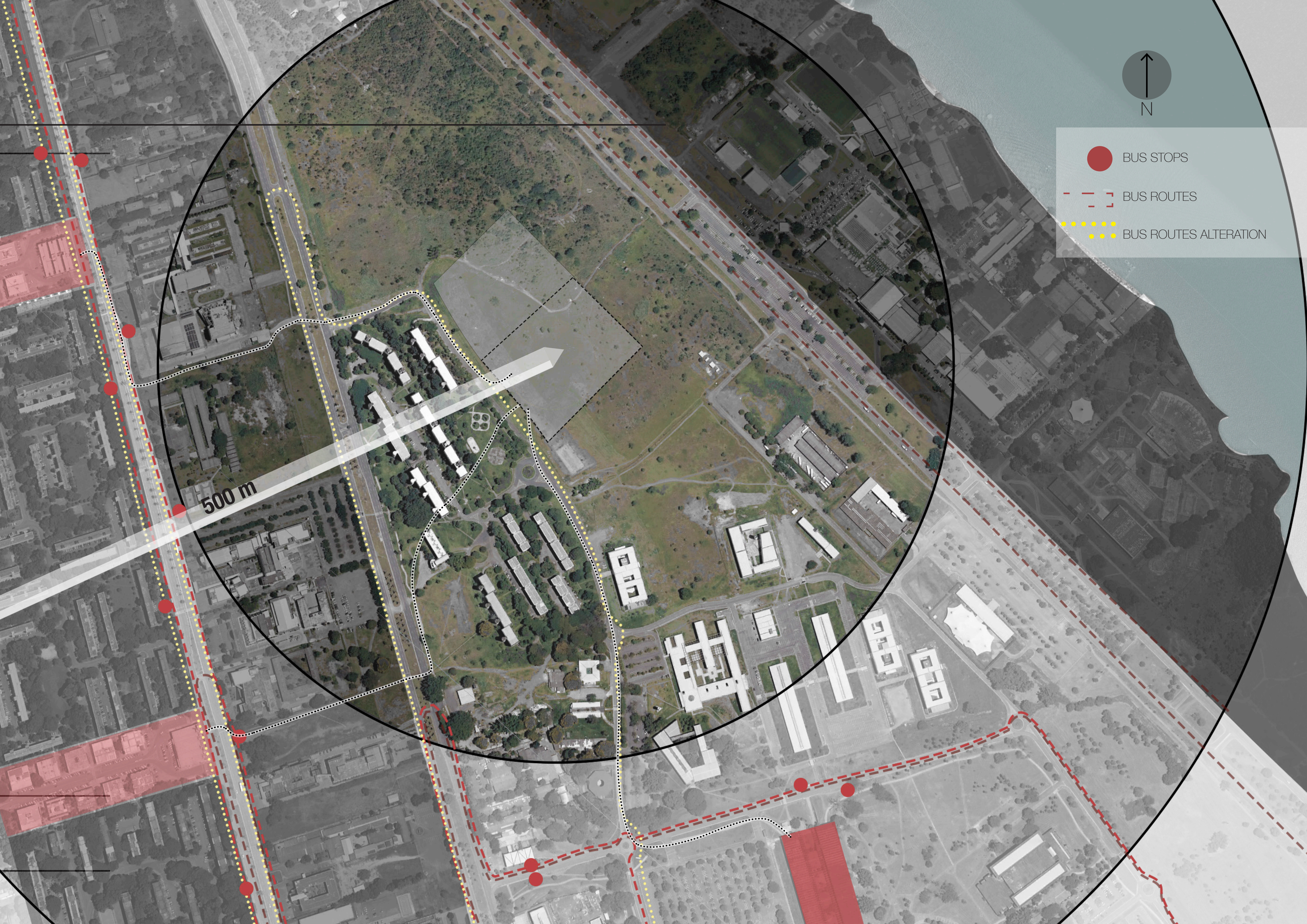
The following maps expose the relationship between the site and the city, highlighting how it articulates with the **public transportation** system and the **basic services**. The area presents itself as poorly connected to the city. That is a result of a **lack of sustainable urban density**, not limited only to this specific area, but a general problem derived from the original concept of the “modernist city”.

There are **no bus stops within a radio of 500 meters**, and the main university building is reachable by a 1000 meters walk. The closest commercial services, such as supermarkets, drugstores and restaurants, are about also about 1000 meters away.

It is essential, when analyzing those distances, to considerate the **scale in which the city is planned and its density of about 400 people per square kilometer.** To better picture these numbers, the populational density of the former Brazilian capital, Rio de Janeiro, is about 5300 inhabitants per square kilometer and Sao Paulo, almost 7400 inhabitants per square kilometer. Regarding this problem, there is not much that can be done due to the efforts in maintaining the modernist urban fabric and, consequently, the title of “Unesco’s Heritage”.

Although the area has many problems, it is still a strategic site for the Project. Since it is a zone originally destinated for residential use and urban equipment to support it, there are already eleven blocks of apartments established with over 320 apartment units hosting about 1130 inhabitants.

The idea of the Project is to create an unobvious structure that could also host academic and social activities beyond the residential use, attracting the whole community, raising the social and the physical densities of the area. As a result, it would enable commercial services to grow sustainably in the area, supplying the basic needs of the local population.


N
BUS STOPS
BUS ROUTES
BUS ROUTES ALTERATION
500 m

Legal Aspects

Occupation

The site to be used was firstly intended as a park, serving as a sort of buffer zone between the residential area and the academic enviroment. Latter, the idea was desconsidered due to the lack of a feasable density in the area and there are already plans to destinate it as an area of expansion.The project proposes to split the terrain into two, using only the southern portion of it.

In order to set reasonable and coherent building parameters, it was taken as references the parameters of the already established residential buildings "Colina", located in the same campus' area as the proposed project.

Building Coverage Ratio (BCR):

Up to 40%

Maximum height quote:

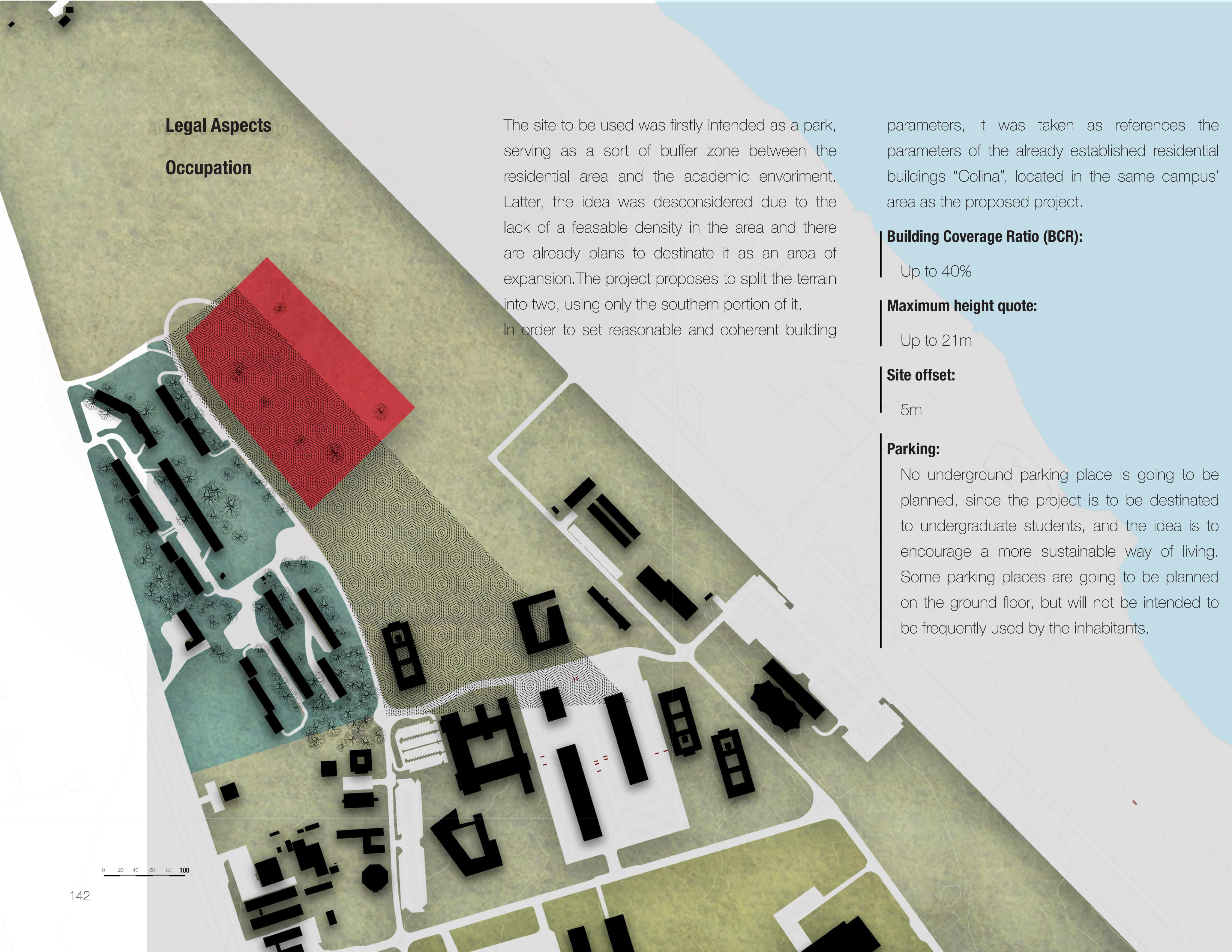
Up to 21m

Site offset:

5m

Parking:

No underground parking place is going to be planned, since the project is to be destinated to undergraduate students, and the idea is to encourage a more sustainable way of living. Some parking places are going to be planned on the ground floor, but will not be intended to be frequently used by the inhabitants.




Area's intervention plan
PROPOSED BY THE UNIVERSITY
N
Site
Open green area
Colina
Main Square
Area planned as a leisure park in the 70's
0 20 40 60 80 100

Legal Aspects . Occupation

The Area to be worked is marked as a Protected Territory 5 and should respect the following parameters:

Art. 45. The guidelines for safeguarding TP5 values are:

I. Maintenance of the function exercised by this territory, which establishes a morphological transition through less dense occupation towards the shore of Lake Paranoá;

II. Vegetation protection and intensification of the free areas that are part of the bucolic scale, which perform the function of contour and green framing, surrounding the limits of Asa Sul and Asa Norte;

III. Protection of the characteristics of rarefied occupation and the horizontality of the buildings;

IV. Implementation of the Bird Park and consolidation of the Asa Sul Multiple Use Park;

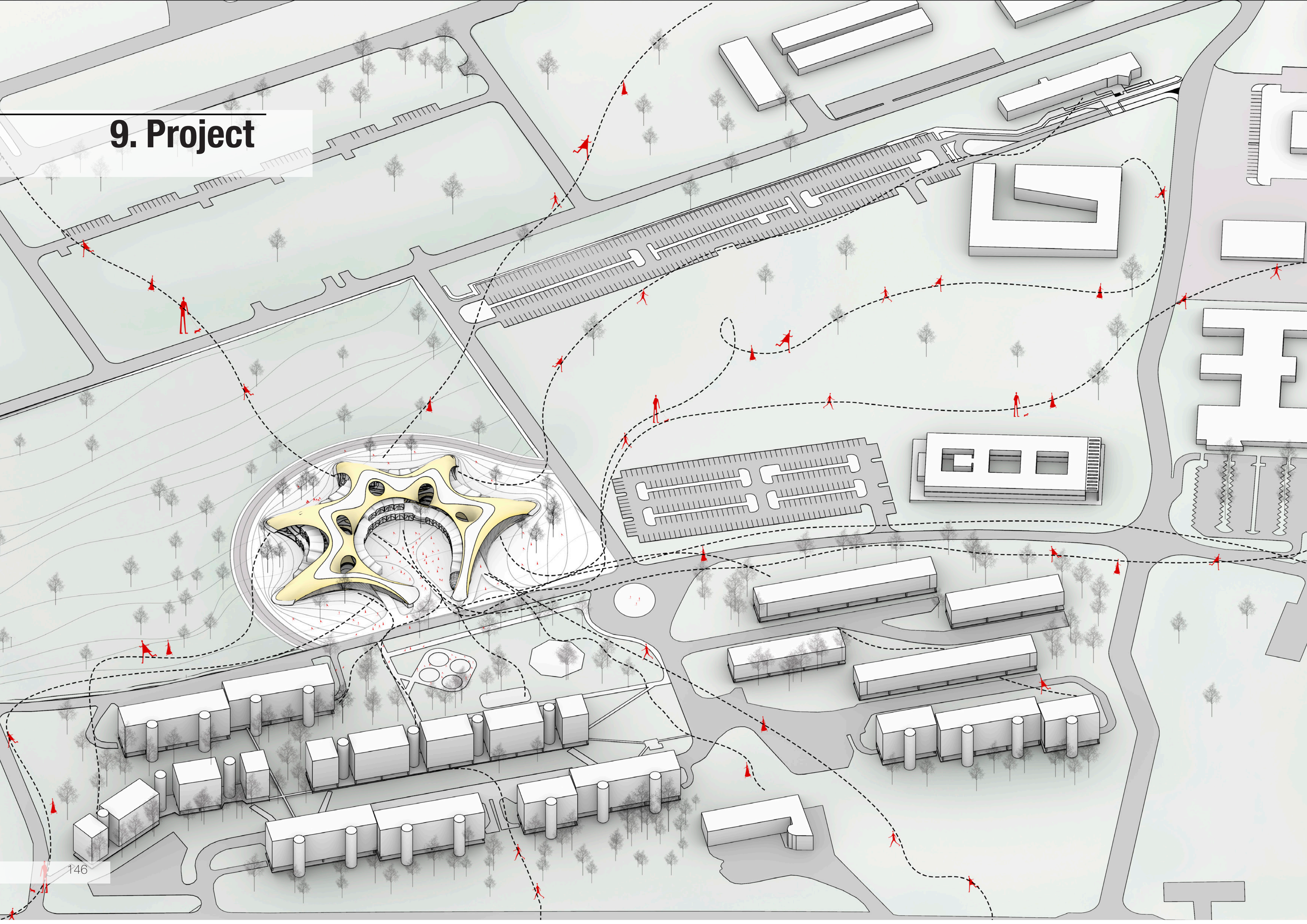
V. Maintenance of low land occupation and revision of the parceling model of the South Embassy Sector and the North Embassy Sector;

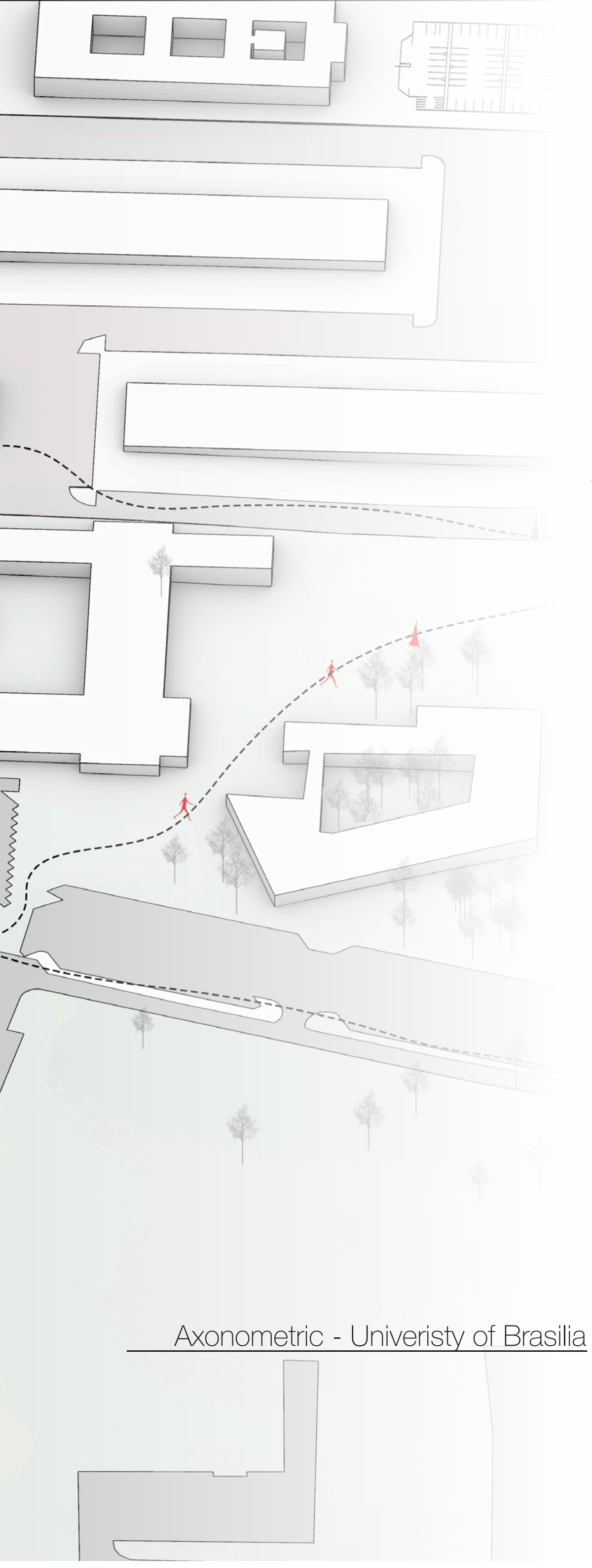
VI. Creation of a system of integrated linear parks, ensuring the maintenance of free green spaces in the South Embassy Sector, with intensification of vegetation and landscape treatment;

VII. Preservation of public free areas, intense afforestation and high soil permeability.

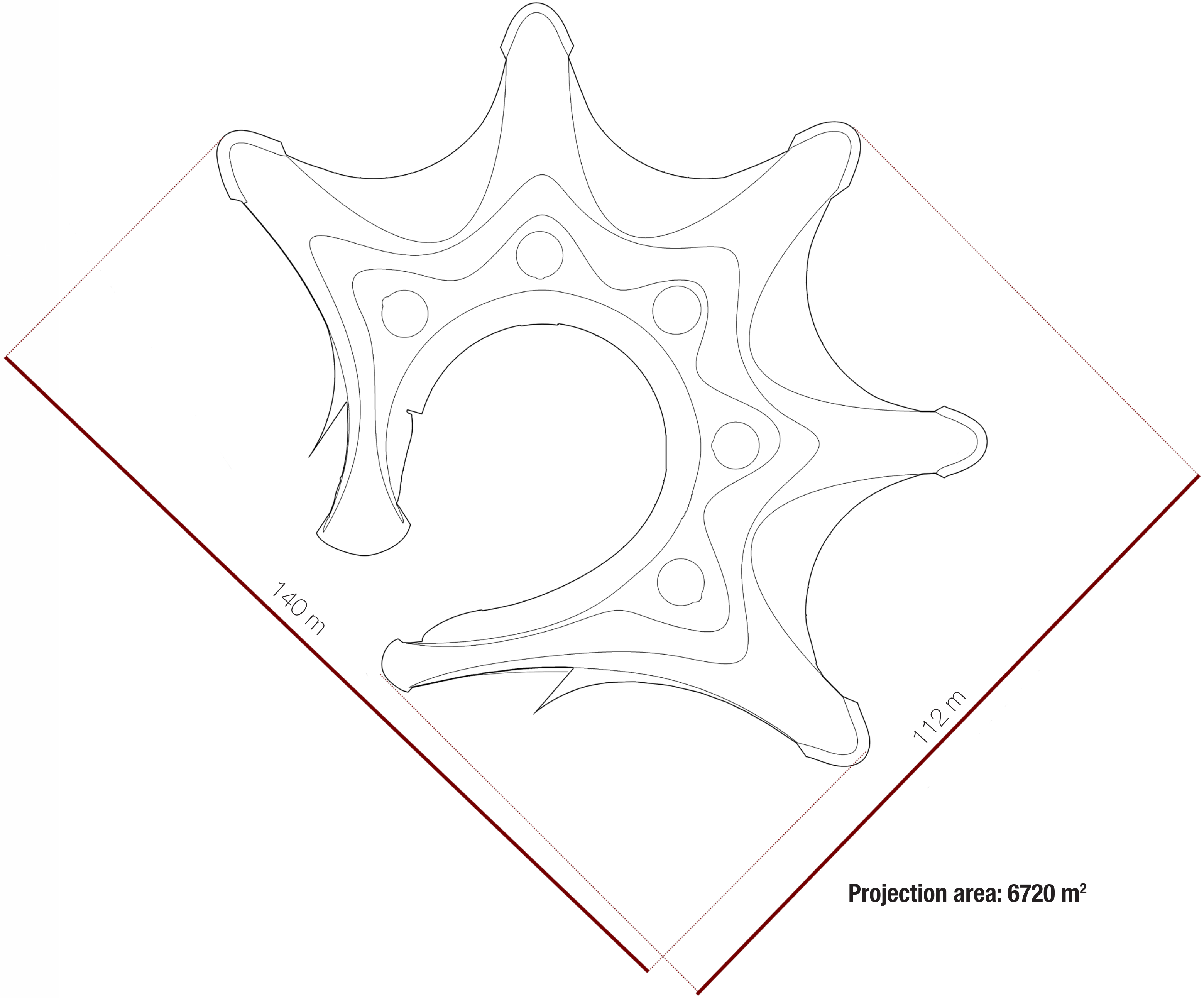
Plano de Preservação do Conjunto Urbanístico de Brasília
PPCUB
PROPOSTA DE MINUTA PLC PPCUB (2017)

9. Project





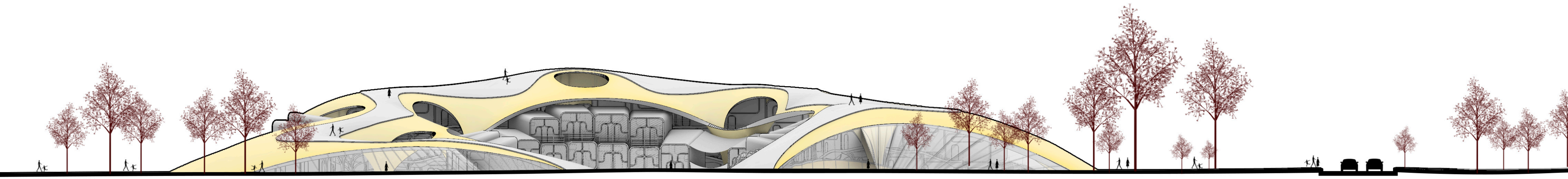
Axonometric - Univeristy of Brasilia

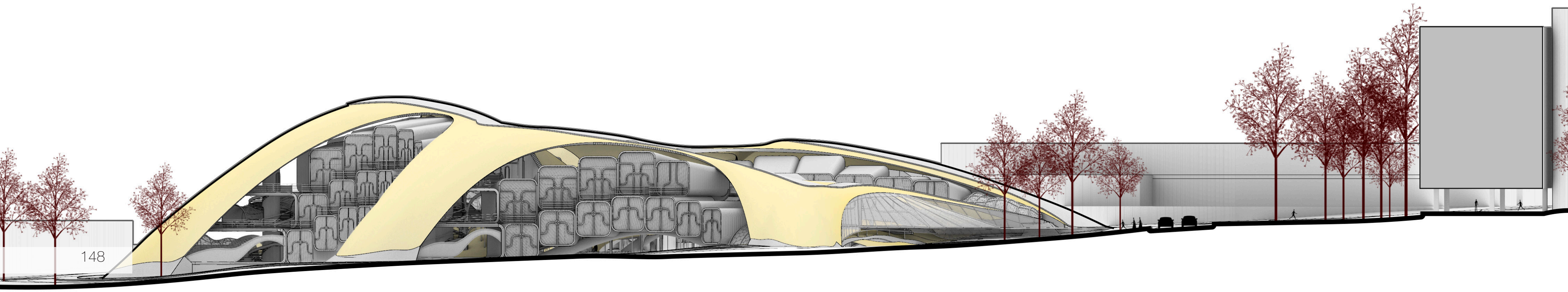


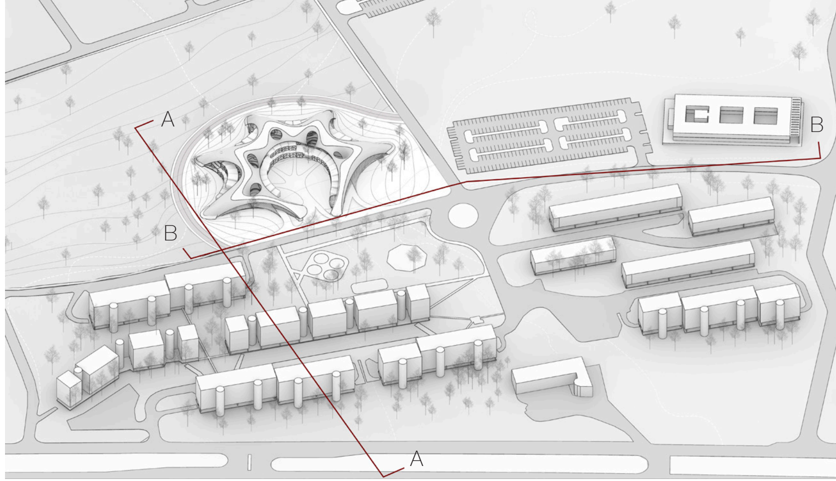
Sections

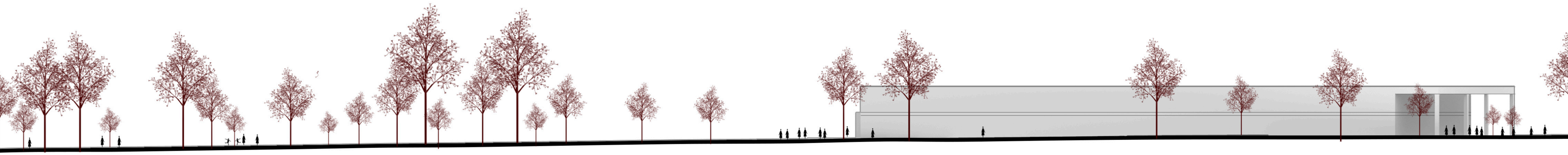
Urban scale

Legislation for the area of Colina establishes a maximum building height quote of 21m.
The building's gradual slope imposes less obstacles to the west predominant breeze

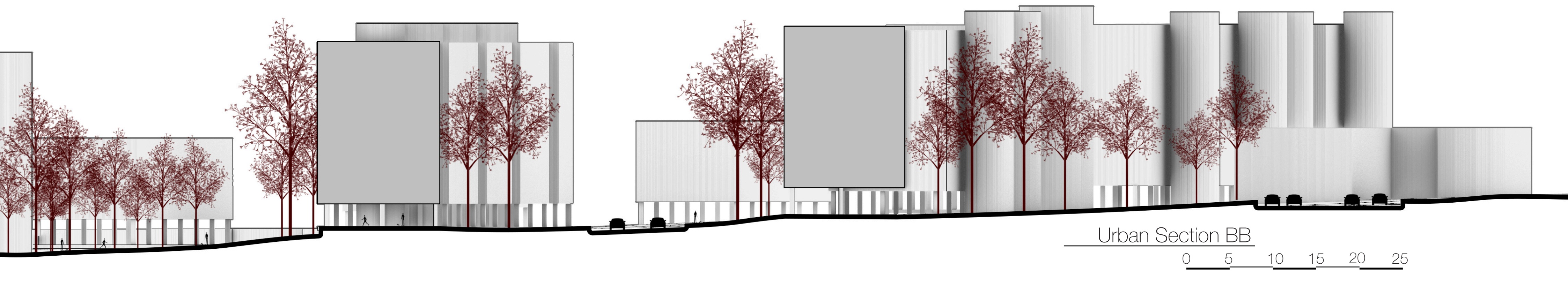




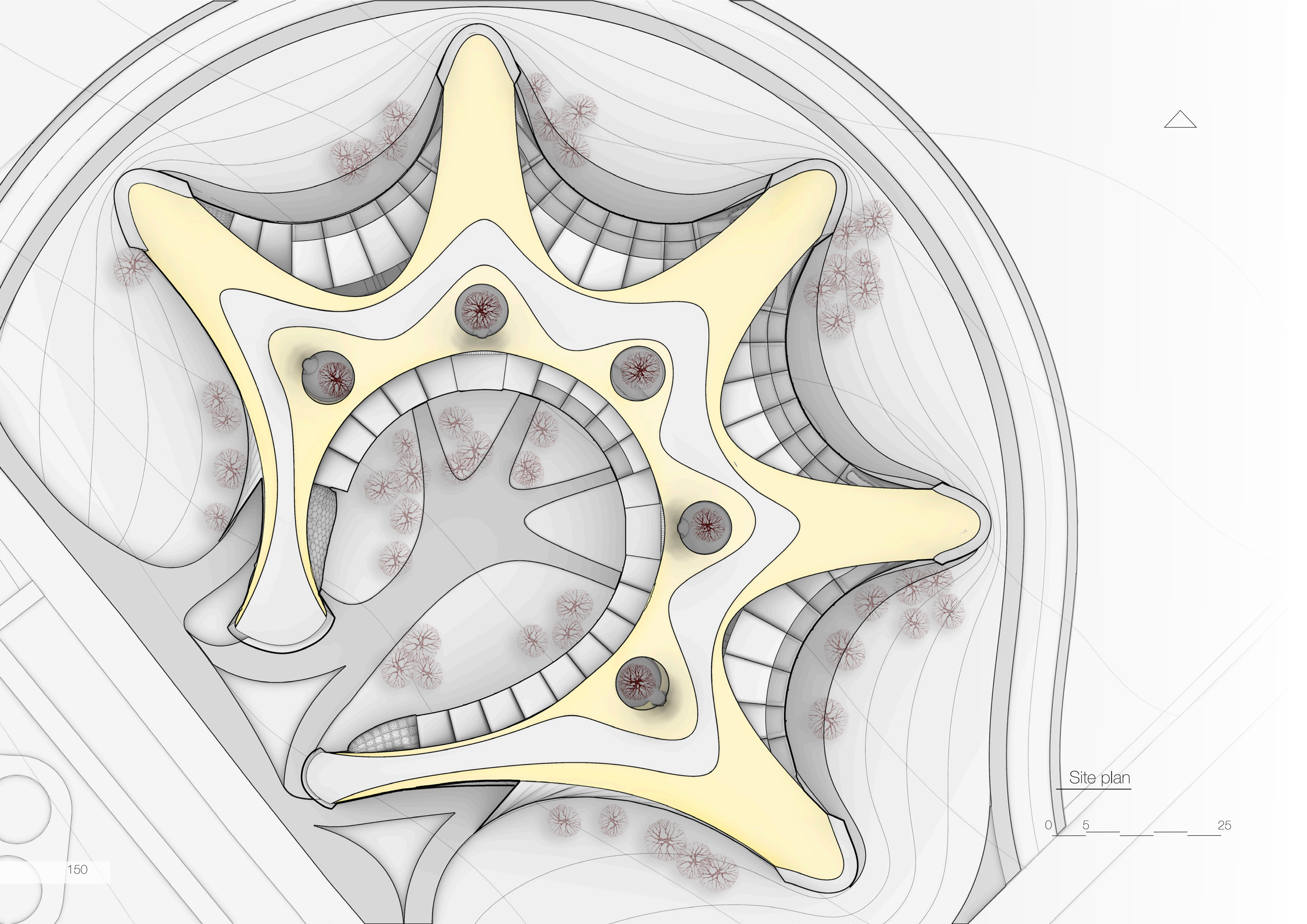


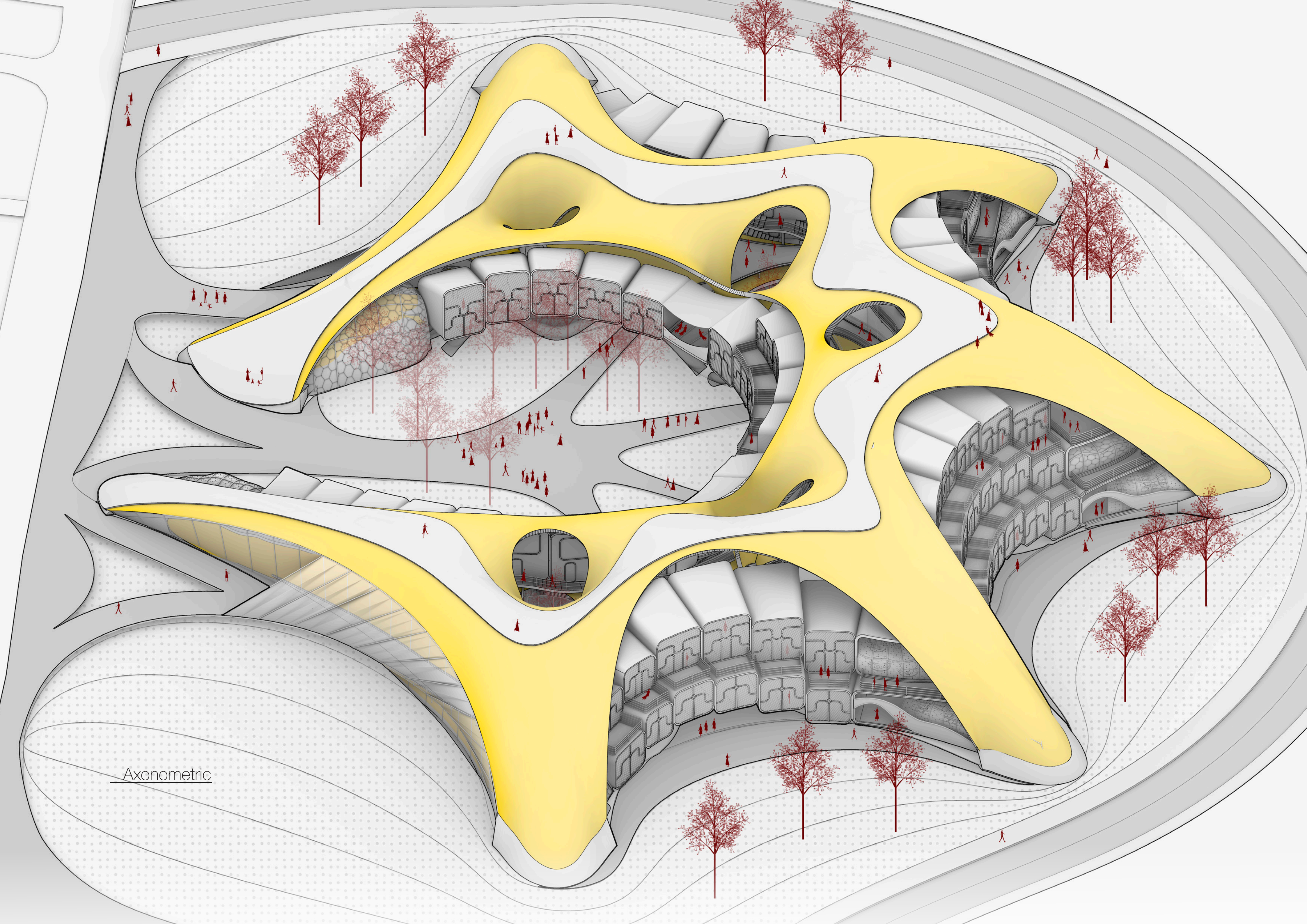


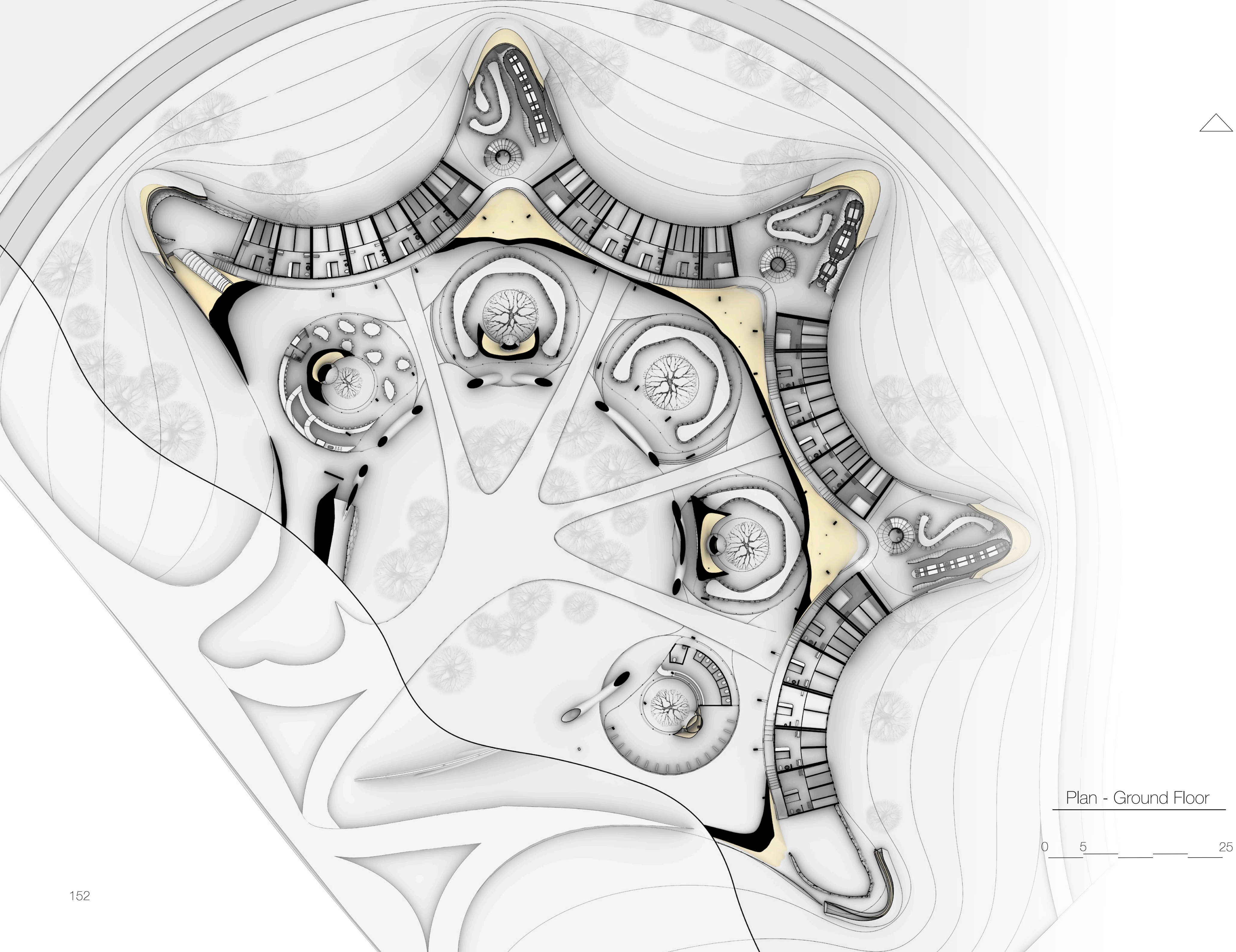
Urban Section AA



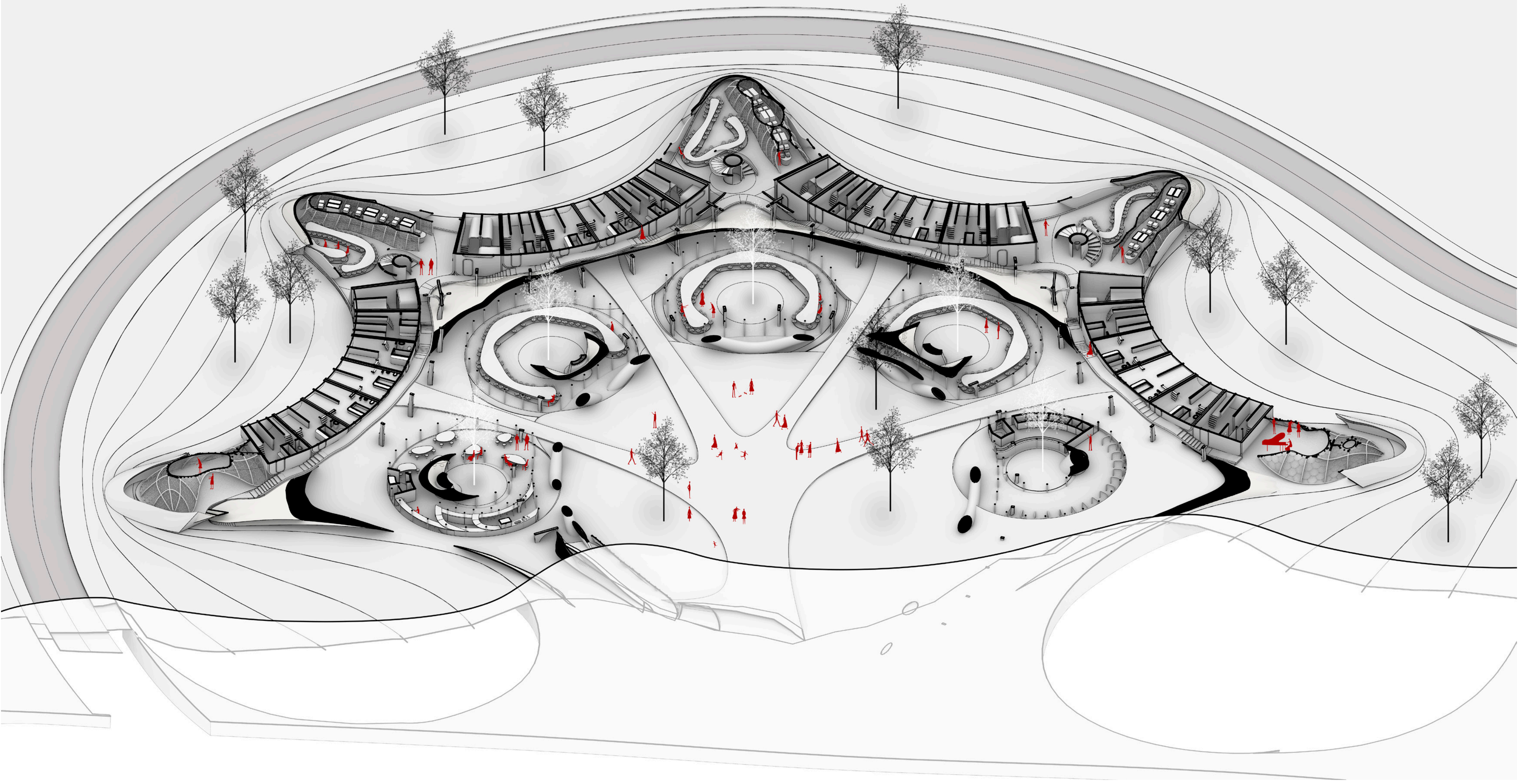
Urban Section BB


Site plan
0
5
25

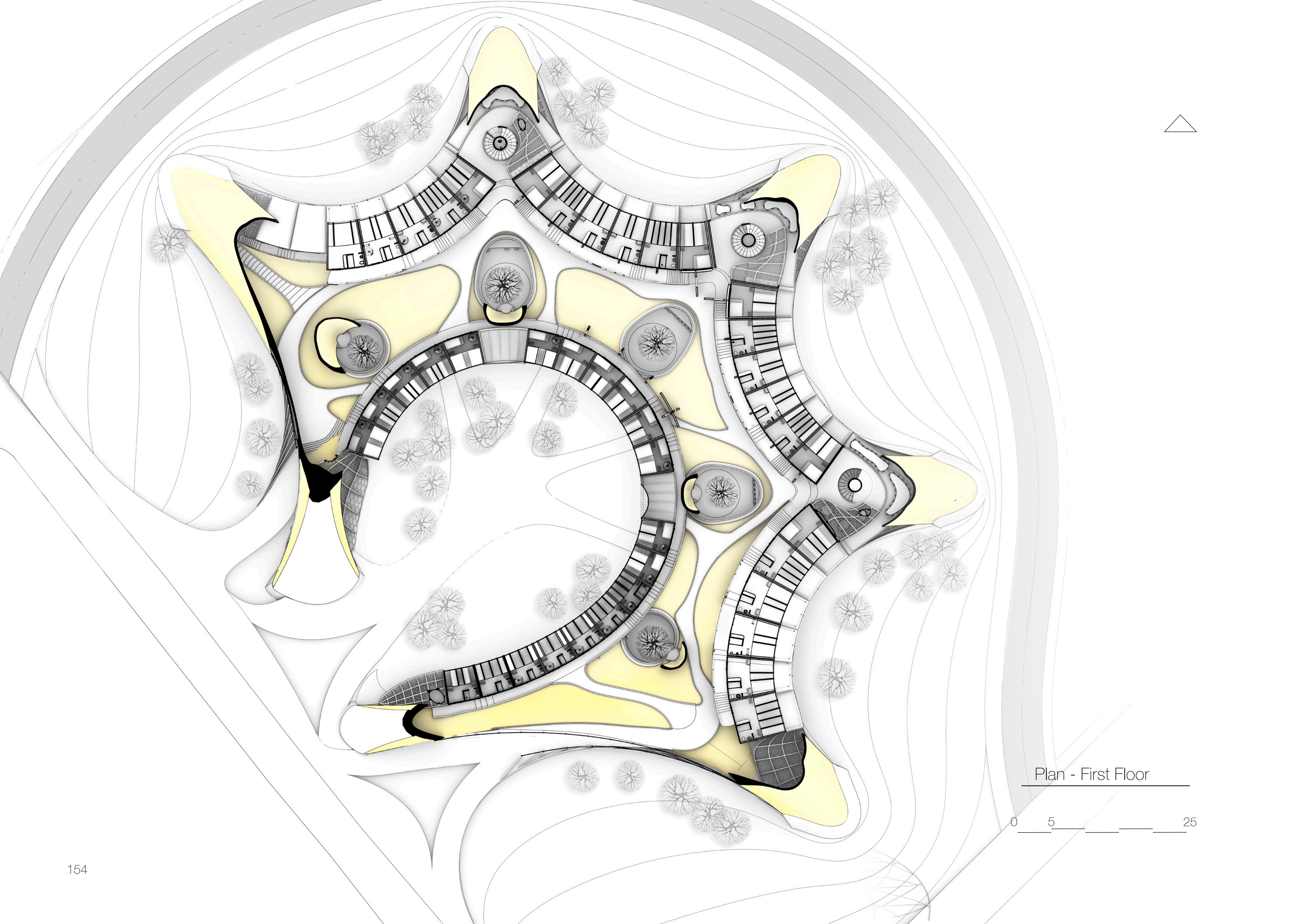

Axonometric

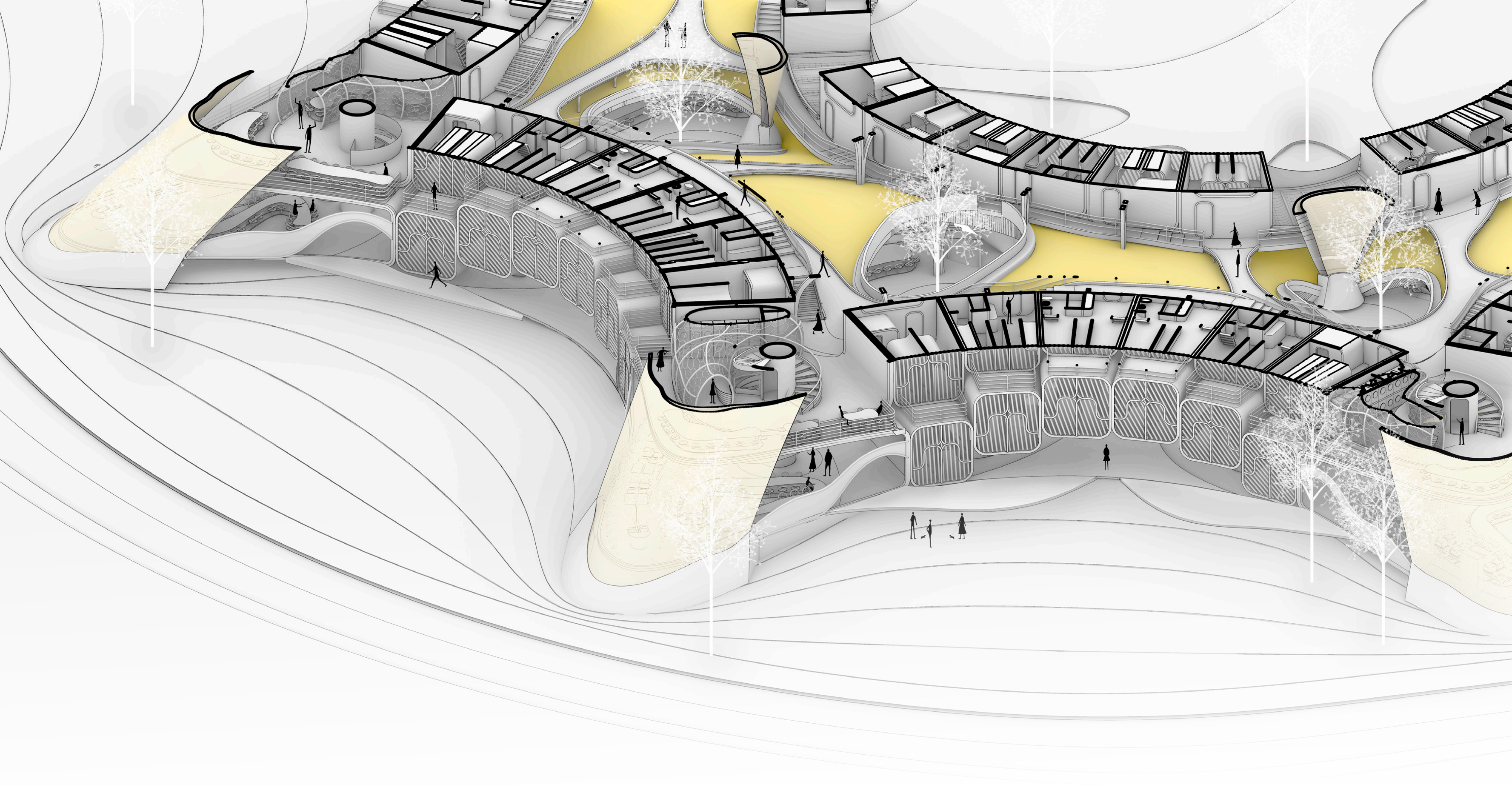


Plan - Ground Floor

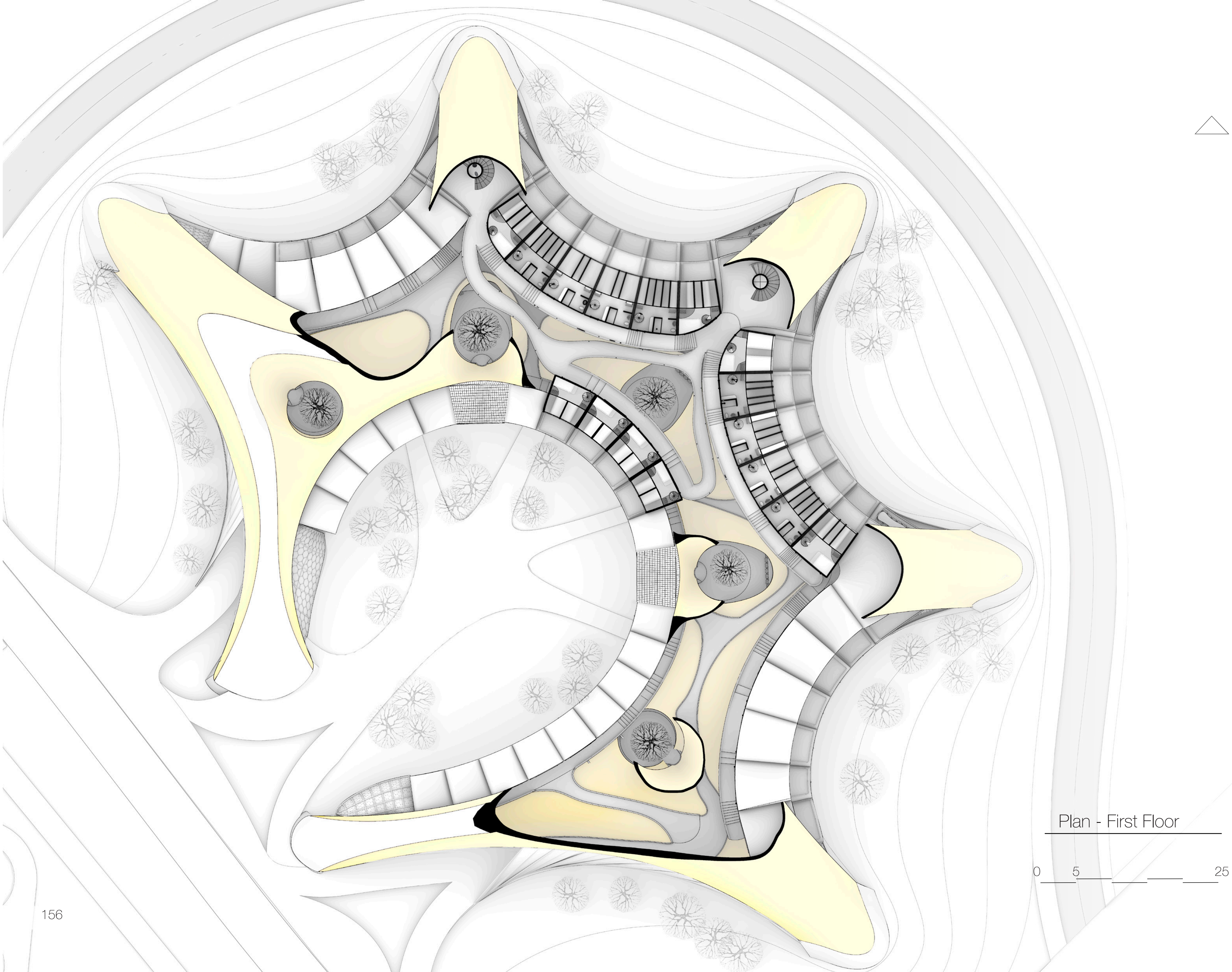


Axonometric - Ground Floor


Plan - First Floor
0 5 25

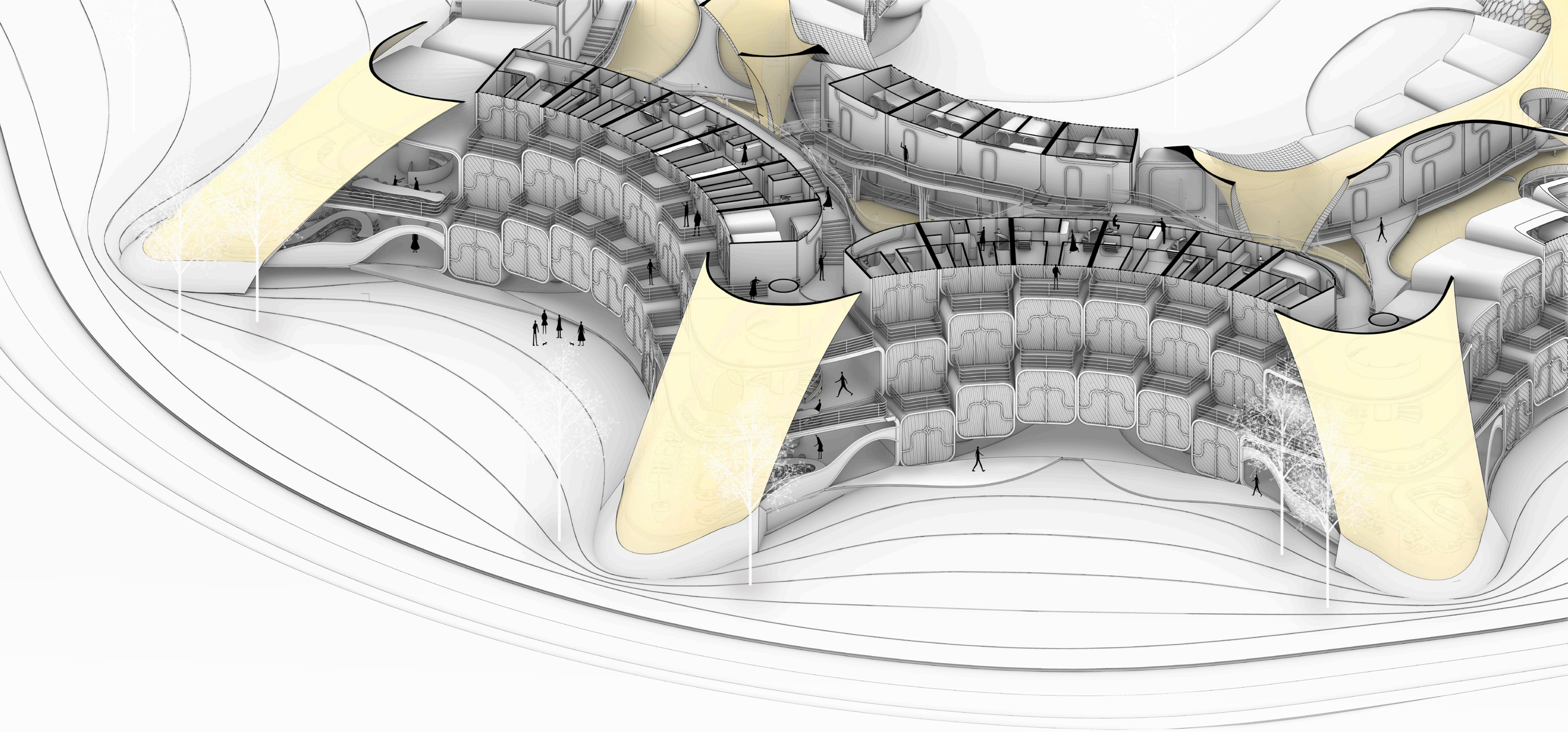


Axonometric - First Floor

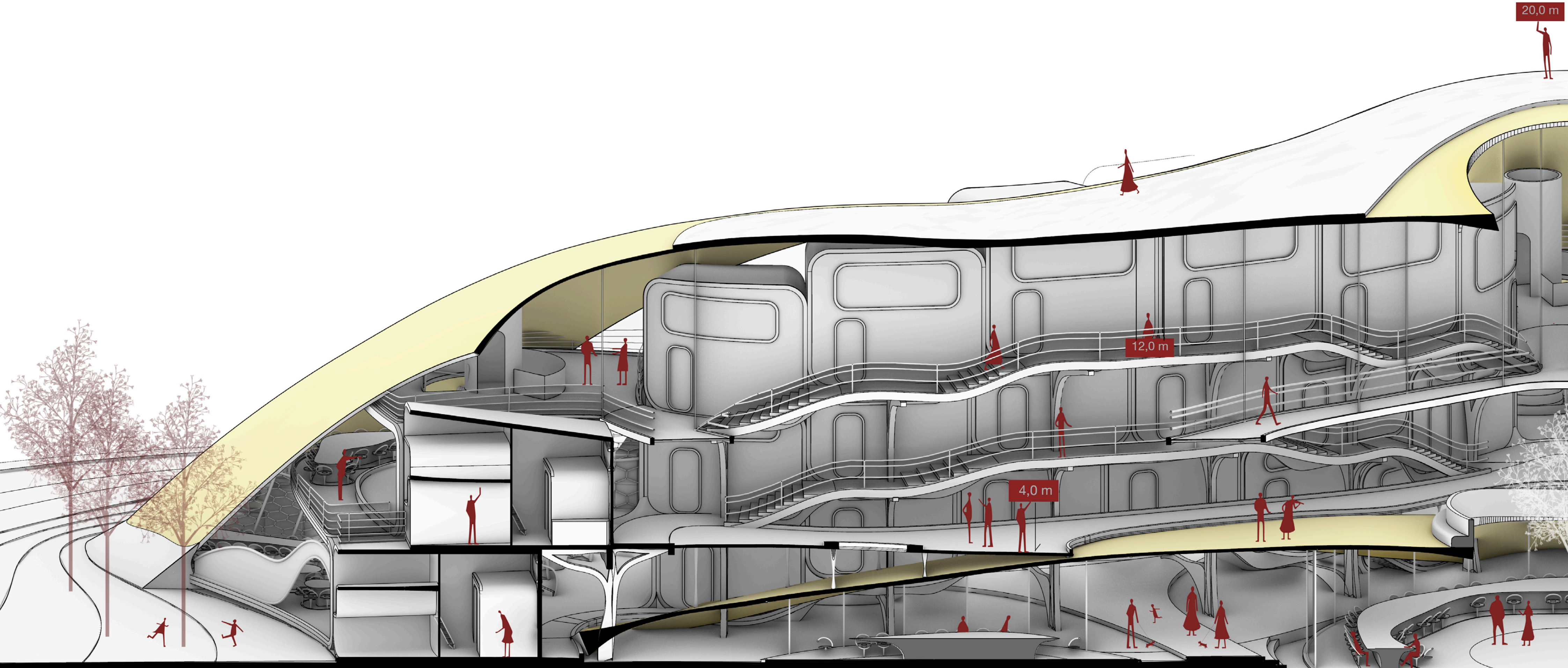


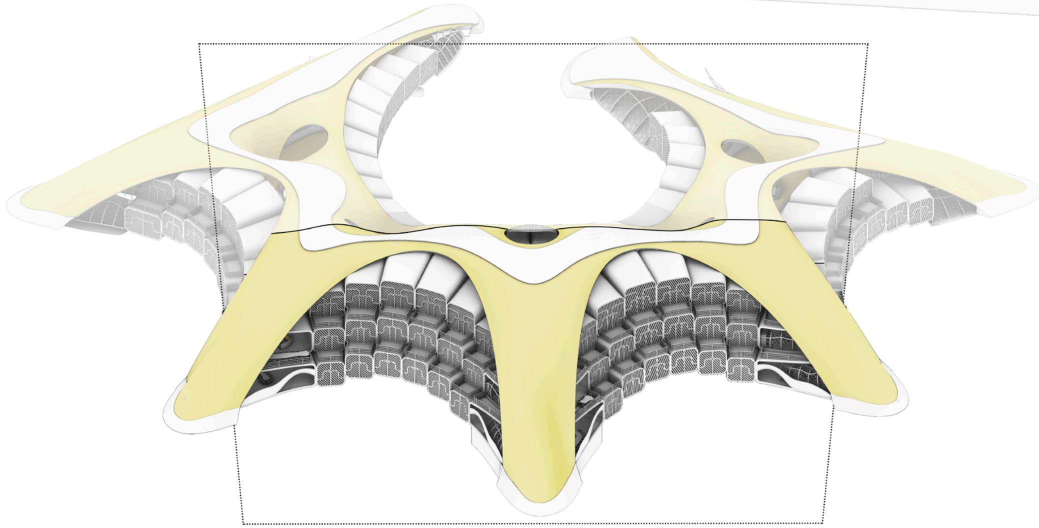
Plan - First Floor

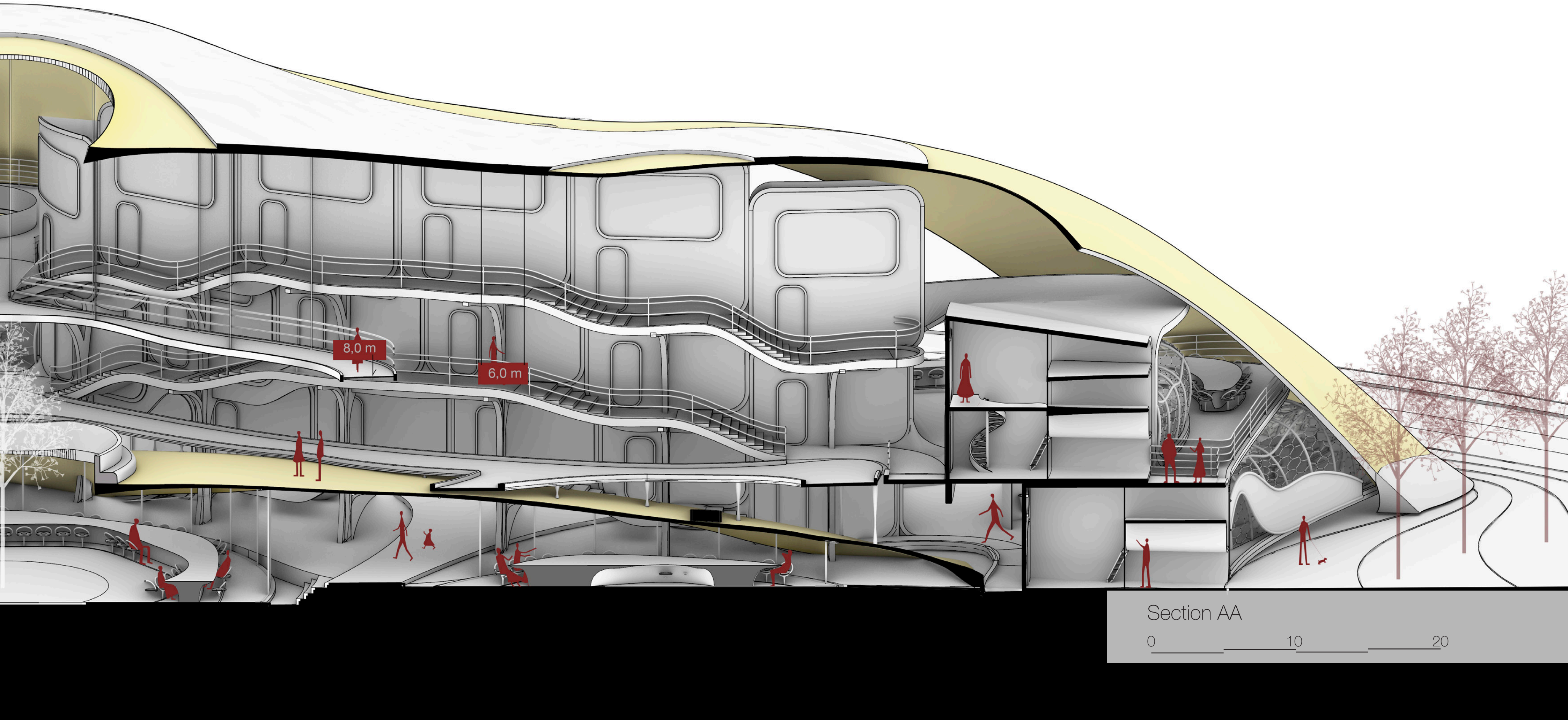
0 5 25



Axonometric - Second Floor

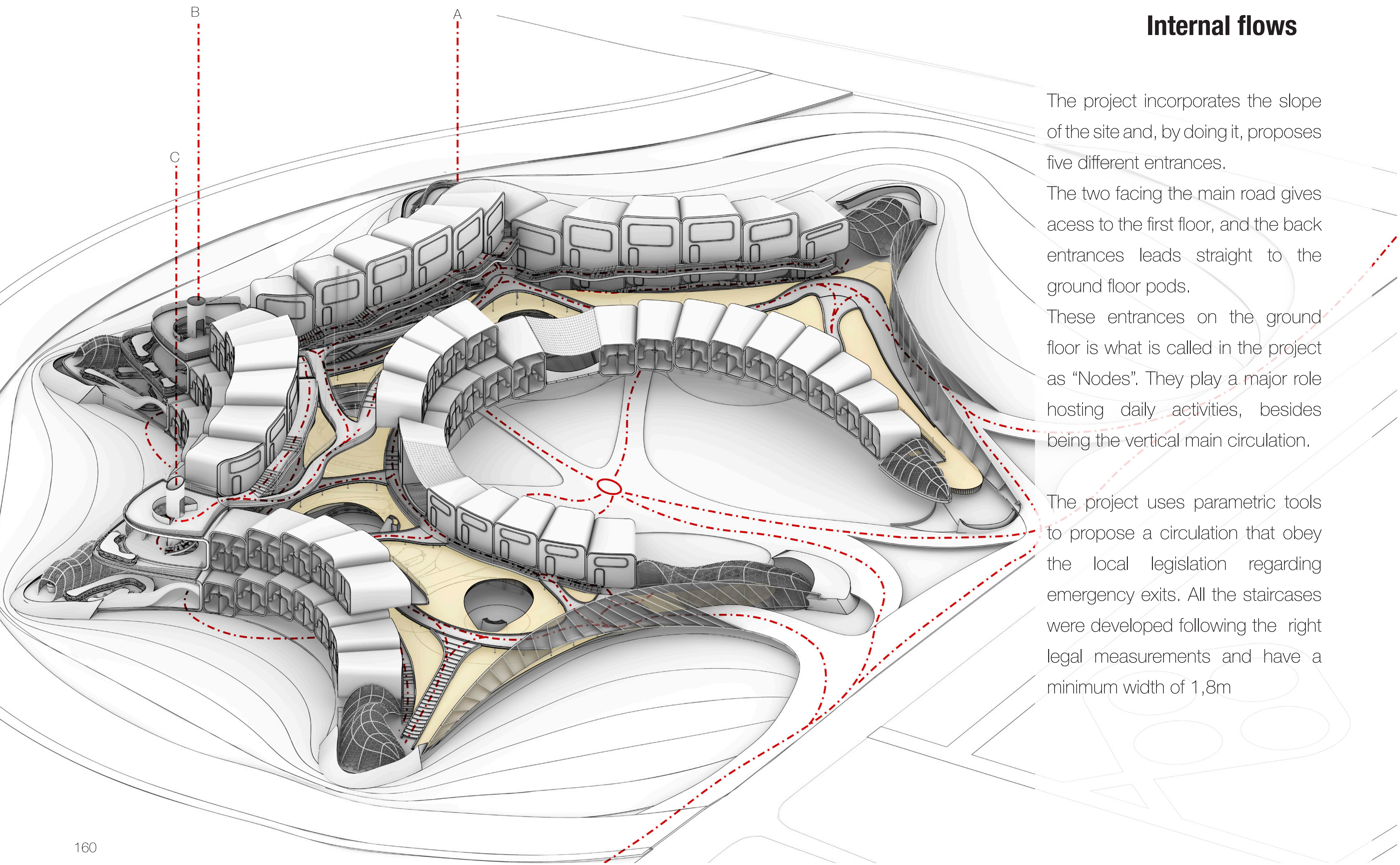

20,0 m
12,0 m
4,0 m





Section AA

0 10 20



Internal flows

The project incorporates the slope of the site and, by doing it, proposes five different entrances.
The two facing the main road gives acess to the first floor, and the back entrances leads straight to the ground floor pods.
These entrances on the ground floor is what is called in the project as “Nodes”. They play a major role hosting daily activities, besides being the vertical main circulation.

The project uses parametric tools to propose a circulation that obey the local legislation regarding emergency exits. All the staircases were developed following the right legal measurements and have a minimum width of 1,8m

Legal Aspects . Emergency Exits

The Normative taken as reference regarding the emergency exits was NBR 9077 - Buildings - Emergency exits - Procedure.

According to this Document, the project fits into the following categories

Classification of buildings according to their occupation:

A-3 . Collective housing (social groups equivalent to the family)

Classification of buildings in terms of height:

Heights counted from the entrance sill to the floor of the last floor, not considered edible in the attic for use in engine rooms and open terraces (H).

M . Medium height buildings - 6,00m<H≤12,00m

Classification of buildings according to their dimensions in plan:

As for the total area St (sum of the areas of all floors in the building)

W Very large buildings - St> 5000 m2

Type of emergency stairs:

According to the NBR 9077 - Buildings - Emergency exits - Procedure, the type of emergency stair needed is the **common stair**.

Maximum distances to be covered to a safe and open place

65 m between exits.

Calculating the widths of accesses, stairs and doors

The width of the exits must be sized according to the number of people that must pass through them, observing the following criteria:

a) the accesses are sized according to the number of people that serve the population;

b) the stairs, ramps and discharges are sized according to the pavement of greater population, which determines the minimum widths for the corresponding lanes to the other pavements, considering the direction of exit.

The Total Population
380 people.

The population served by each acess
30 people.

The pavement greater population
60 people, the number to ne expected to use each emergency staircase in case of emergency.

The Capacity of a passage unit was calculated, where the width is the division between the population number and the Capacity.

N=P/C

Capacity of a passage unit: Minimum width for the passage of a row of people, set at 0,55 m.

Note: Capacity of a passage unit is the number of people passing through this unit in 1 min.

Access: C.U. = 60

Population = 60

N= 60/60 = 1m

As the result is inferior than the minimum of **1,1m,** the minimum should be adopted.

Ramps and Stairs: C.U.= 45

Population= 60

N= 60/45 = 1,3m

Doors: C.U. = 100

Population = 90

N= 90/100 = 0,9m

In the project, the emergency doors adopeted were the 1,50m width.

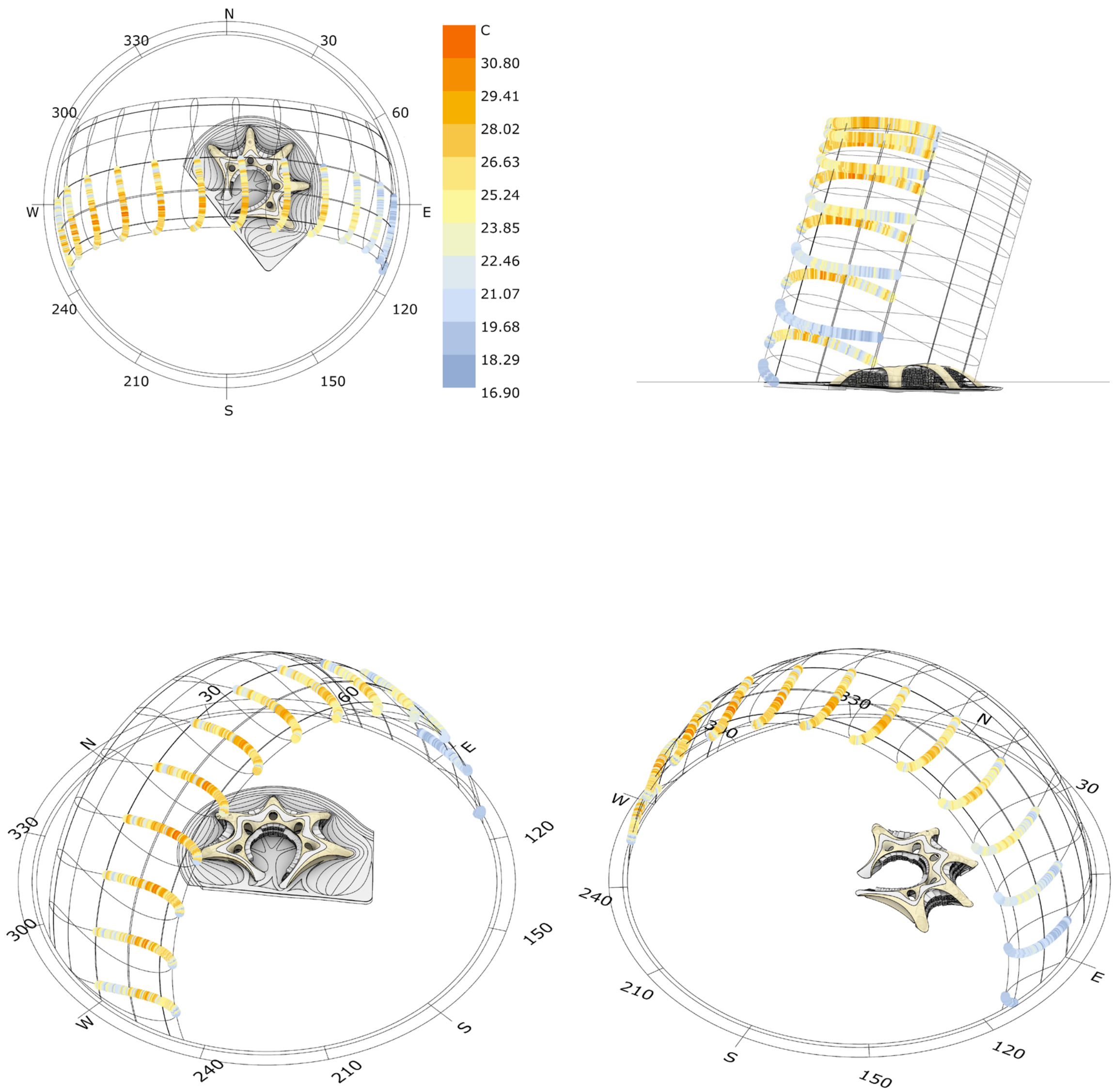
Bioclimatic Strategies

The bioclimatic strategies were set from the first steps of the project, using mainly the Grasshopper add-on Ladybug. The program performs environmental analysis, being a great ally of architects.

In Brasilia, the main bioclimatic strategies aim to prevent overheating. That way, it is desirable to avoid façades facing west, avoiding the exposure to the afternoon hot sun rays. As the enjoyable morning sun rays, as well as the cool breeze, comes from the east, this direction should be prioritized. The north façades are the ones with continuous sun exposition during the day, while the south elements are the ones receiving only defused light. The Brise-Soleil is an excellent strategy for preventing direct sunlight from entering internal spaces. Its orientation is crucial for optimal behavior, being desirable vertical elements for the façades facing north and horizontal for the façades facing east and west.

Summer

Sun Paths

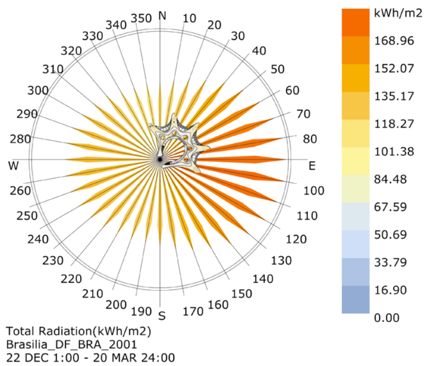


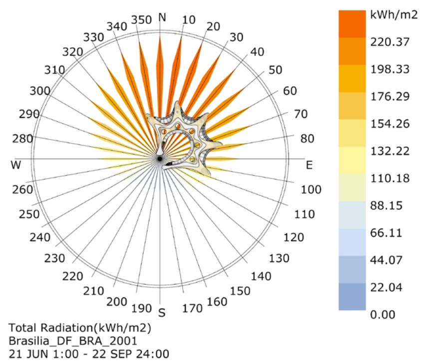
Summer **Winter**

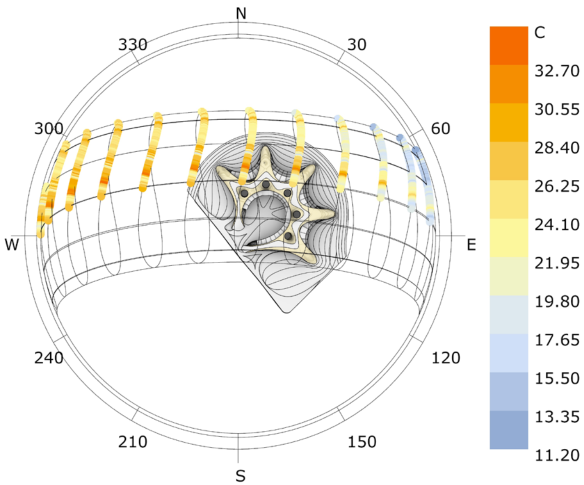
Total radiation charts

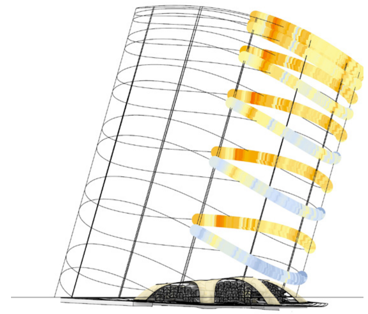
Winter

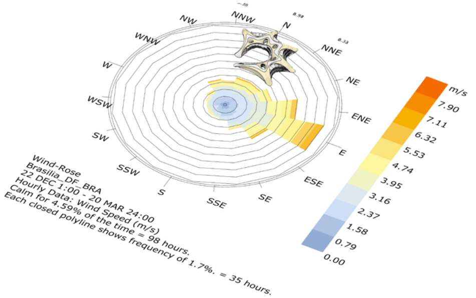
Sun Paths

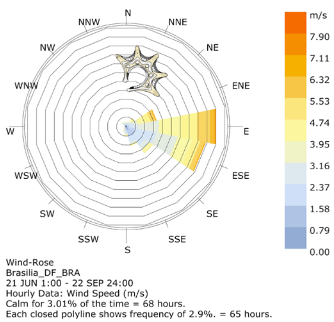


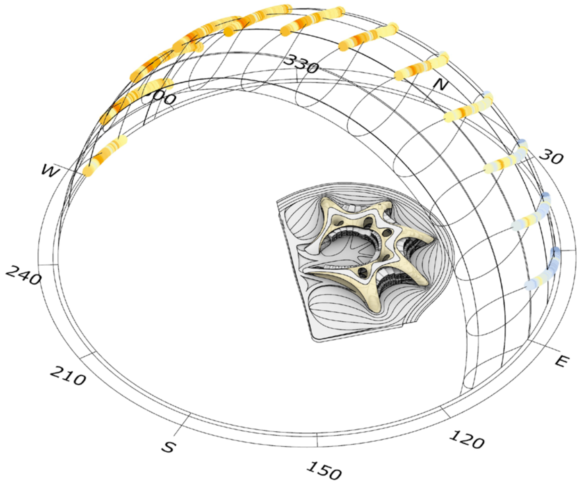


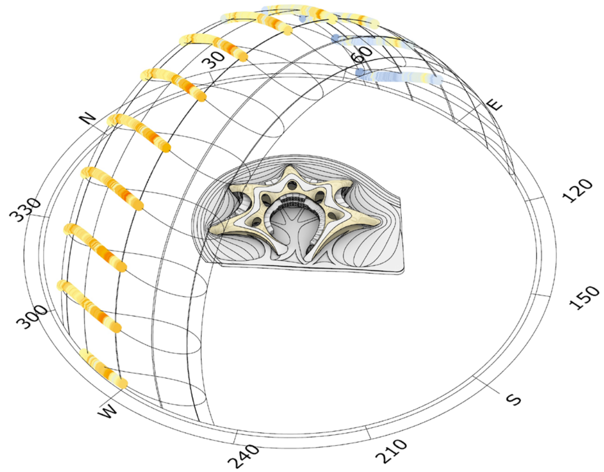










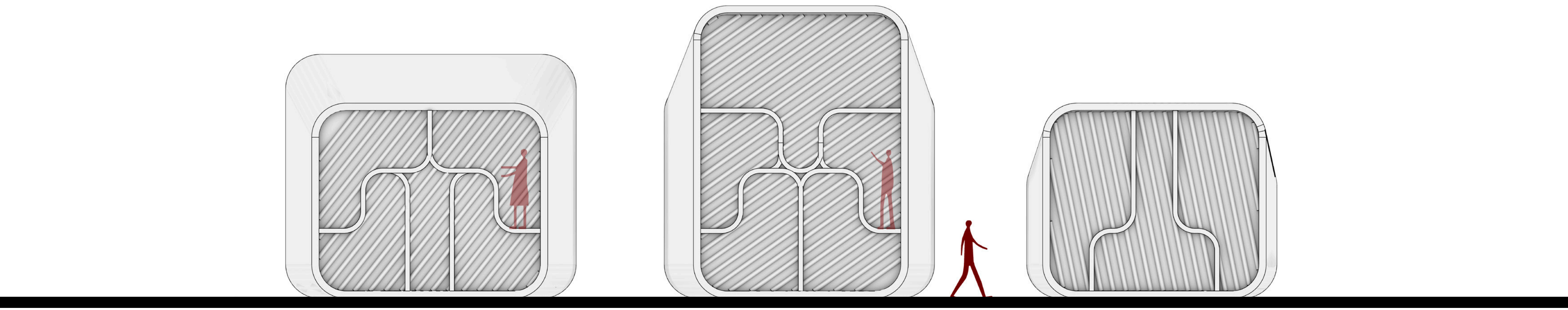


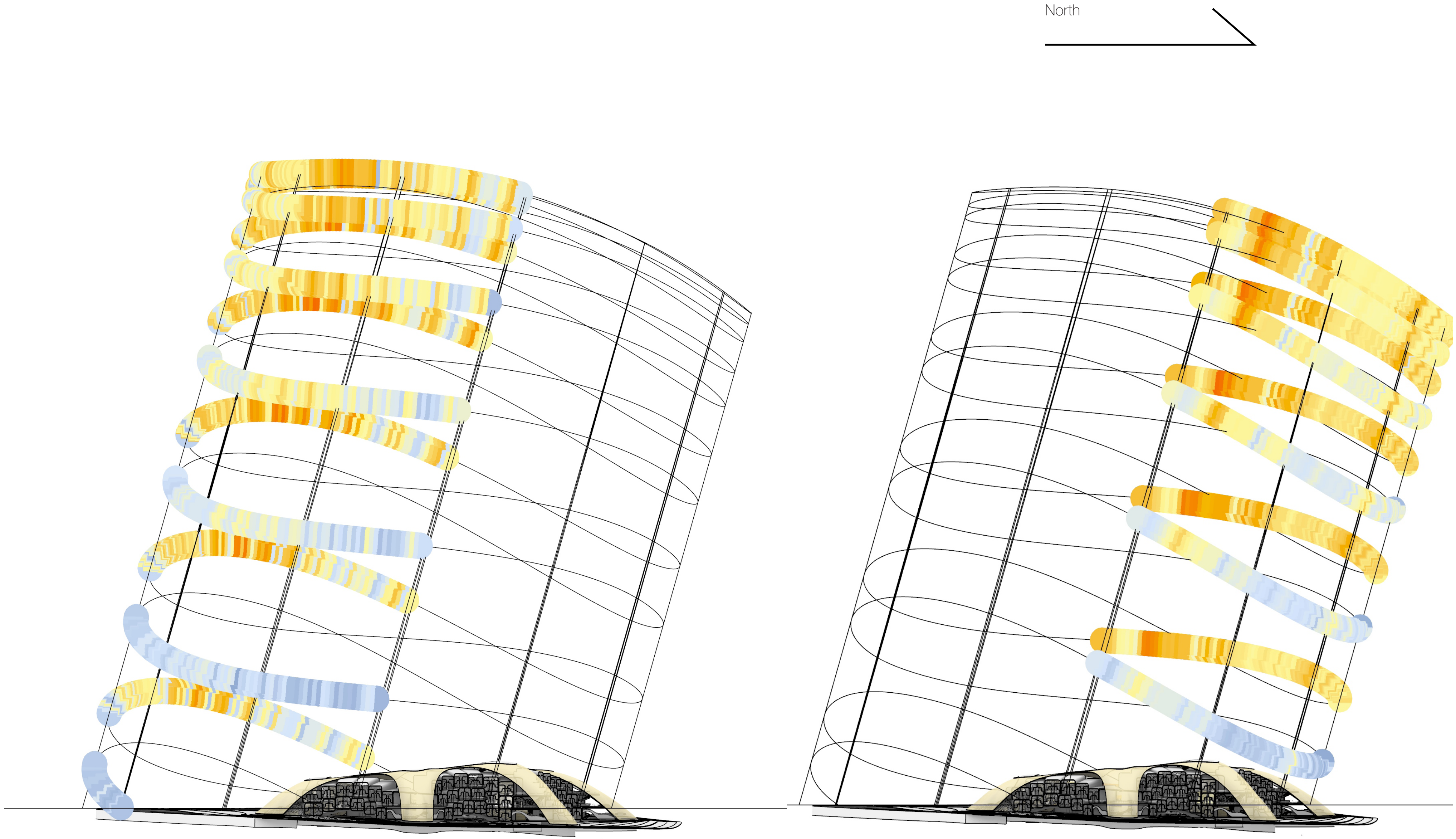
Angular Brise-Soleil

The circular shape of the building prevents it from having many façades facing one undesirable direction, but it also requires special attention when orienting the shading system. After analyzing the structure with the aid of Ladybug, a definition was created in which the Brises-Soleil inclination was defined by the angular deviation of the normal vector of each Façade and the north vector, and then rotated of 90 degrees. This way, closest to the north direction, more vertical the elements should be.

Shape and Material

Another strategy resides in the physical properties of the structure. Reinforced concrete, the material of both shells, has a high thermal mass and can store the heat gained during the day and release it during the evening. Also, structures in vaults have been used for millennia in arid and hot regions because of their ability to minimize heat from radiation, and at the same time providing vertical ventilation.
Considering that roofing is responsible for the higher thermal gain, mainly in equatorial and tropical regions, this strategy is very promising.




North

10. Shells

The last decades were characterized by the exploration of possibilities that digital tools brought and as a result, an evident change in form and expression started to appear, but those new forms were often empty of structural rationality. The advances in fabrication processes, mainly with the introduction of new technologies as robotic arms and CNC machines have shifted the feasibility of the virtual and by doing so, new constraints were added in the design phase.

As a performance-oriented design, the goal is to think the creative process as a holistic and integral process, from the beginning of the conception to its materialization and fabrication, considering the material intrinsic behavior as strong constrains. In such a holistic approach form, structure and material must be thought combined.

This integration is what Oxman and Oxman (2014) call “Vitruvian Effect”. They argue that the growing bond between the virtual - computer- and the real - architecture - shows itself as a “continuum from design to production, from generation to fabrication”. This way of concept architecture resets a new “continuous logic of design thinking and making” and creates an integration of “science, technology, design and architectural culture” (Oxman & Oxman, 2014, pp. 8).

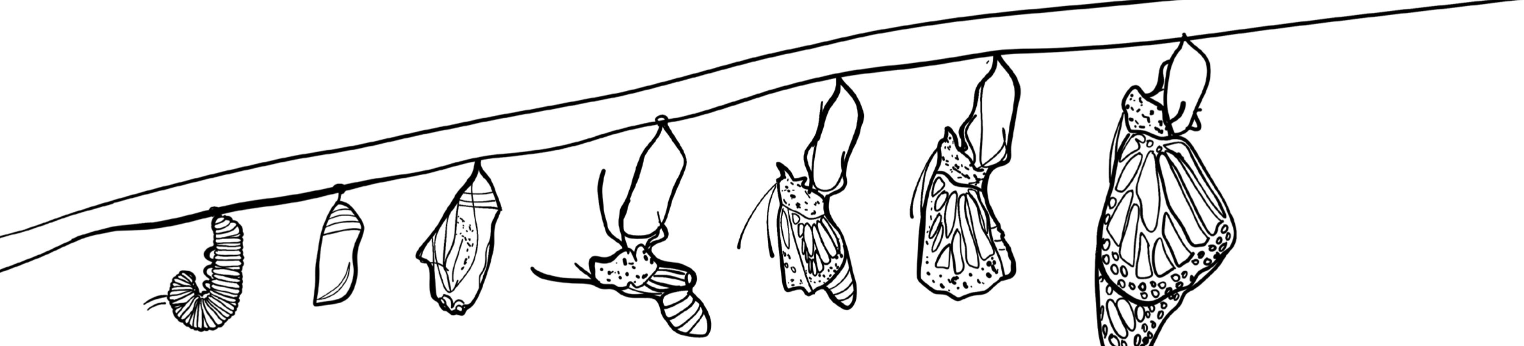
Considering that the project will take place in the city of Brasilia, Brazil, some constraints must be set to make the project feasible. The first constraint to be considered in the project is the lack of advanced technological materials in the construction sector, being the most used supplies the concrete and ceramic bricks. To use those primary materials to do a digitally informed architecture is an interesting constraint, due to their compressive mechanical performance.

Taking into account the excellent compression response of the materials mentioned above the first ideas of the project started to flourish. Based on methods of form-finding present in the work of Frei Otto, Gaudí, Heinz Isler, and other great architects and engineers from the last century, the idea of a shape that responds optimally to compression efforts sets ground. Funicular structures can overcome vast spans with minimal use of material, being also known for their inherent durability.

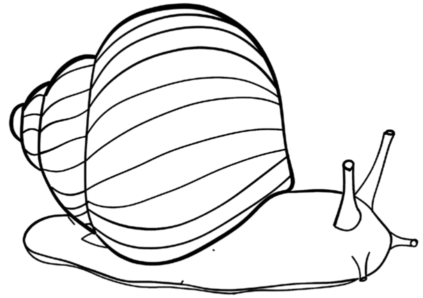
The pursue of linearity has become one of the most significant characteristics of Modernism, and it is still today one of the main fetishes in architecture. To reach large spans with horizontal elements became possible only with the development of the reinforced concrete, and yet such horizontality tends to bend. The horizontal component works in compression at the upper part and tension at the lower, resulting in inefficient use of material.

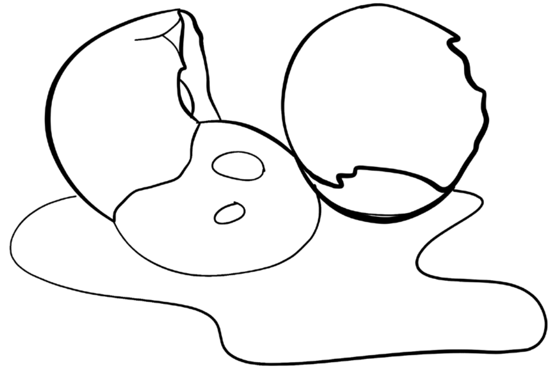
Compression-only structures present a huge advantage regarding the use of materials, being able to save up to 70% of the material, meaning a lighter and more sustainable output, reducing energy costs from fabrication and transportation (Aravena, 2014),

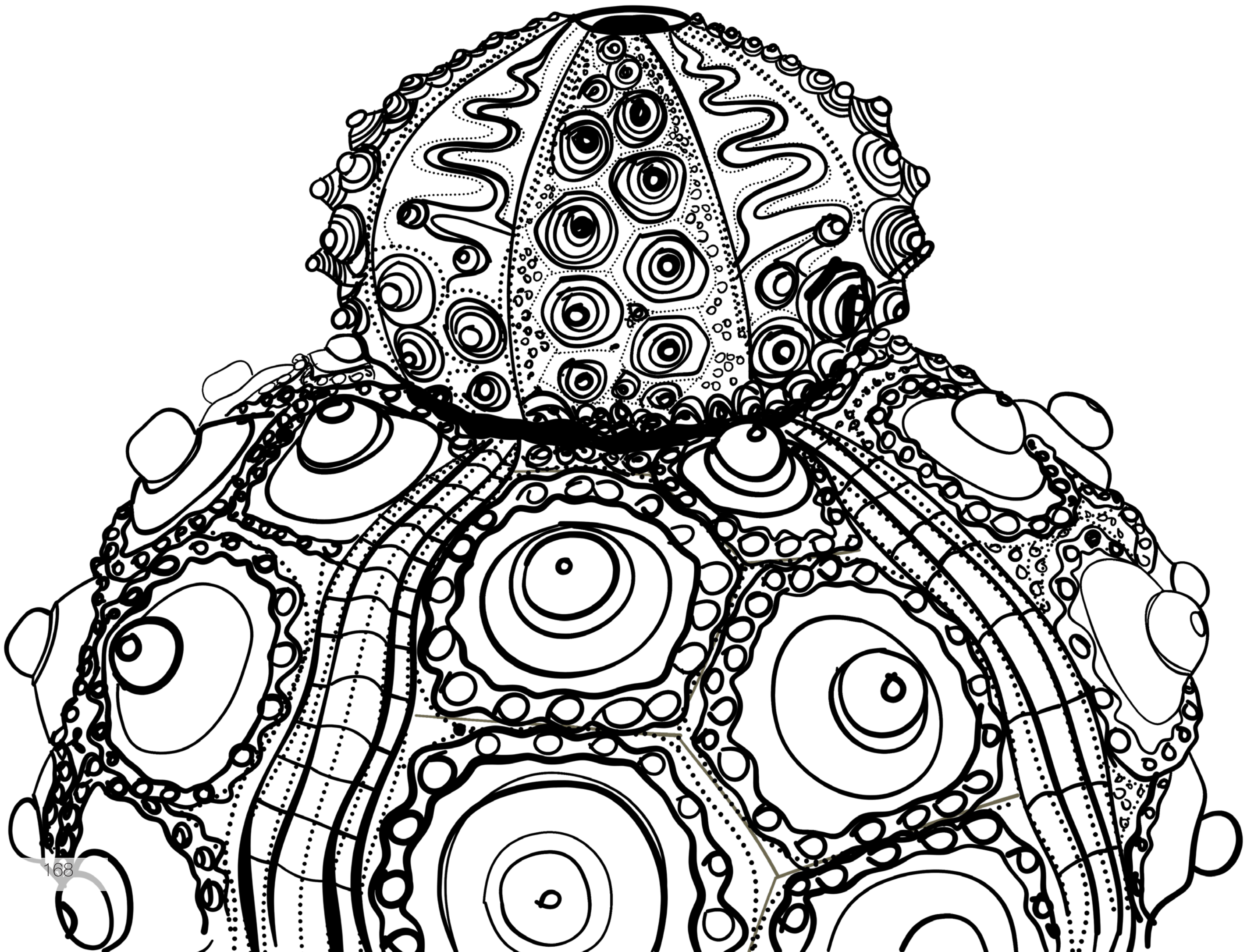
With the advancements of digital tools, the process of form-finding has become more accessible, easier and faster. One massive constraint in the past was the difficulty in calculating the structure’s stability, relying mainly on physical models to simulate the system’s behavior. Nowadays, we have different computational methods to analyze this kind of funicular shell, and the one used in this specific project is the Trust Network Analysis (TNA).



Brainstorming: The Biomimetic Approach

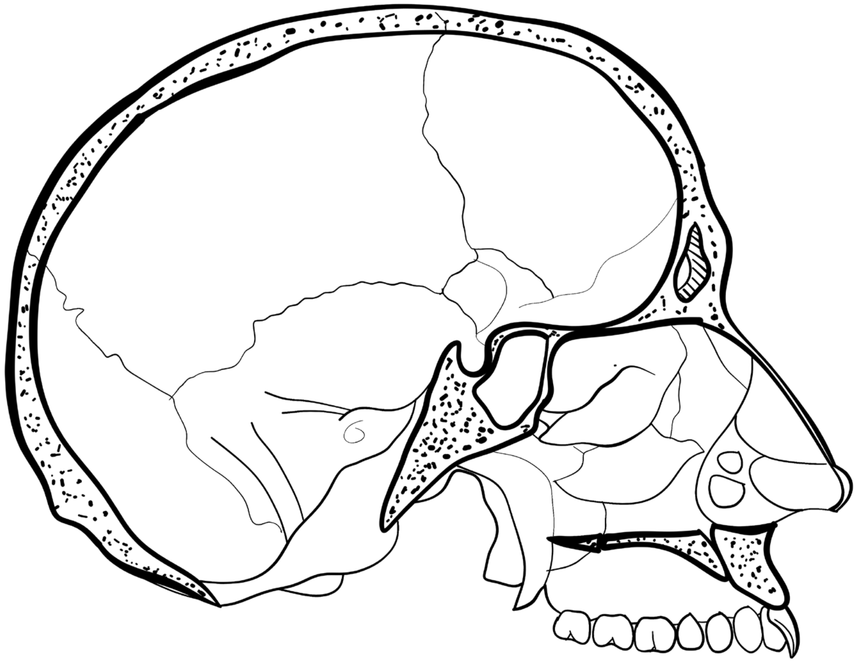
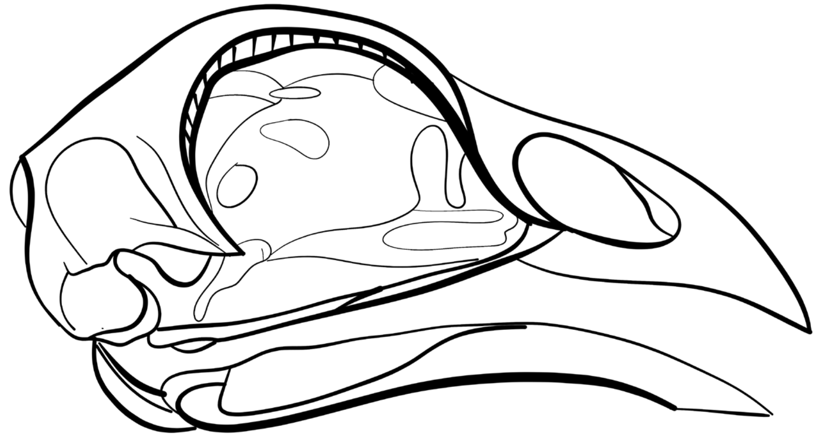
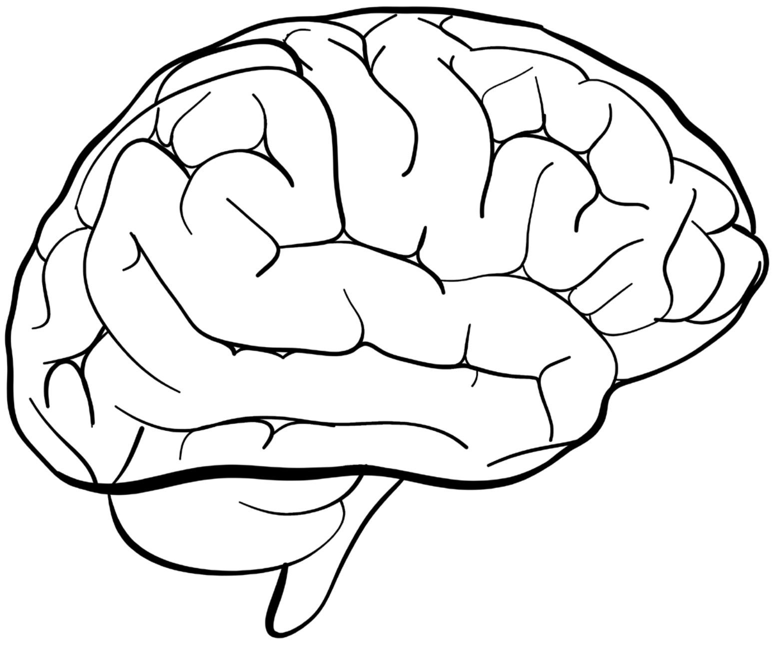
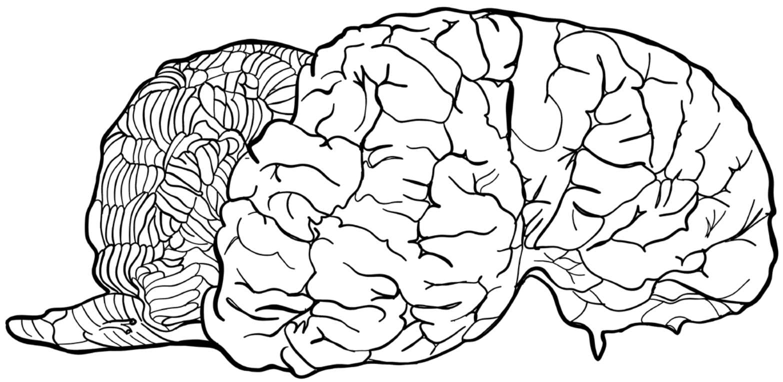






Shell structures

Present in nature as protection systems of vulnerable and soft organic tissues. Shows optimal response to compressive efforts, using minimal ammout of material.

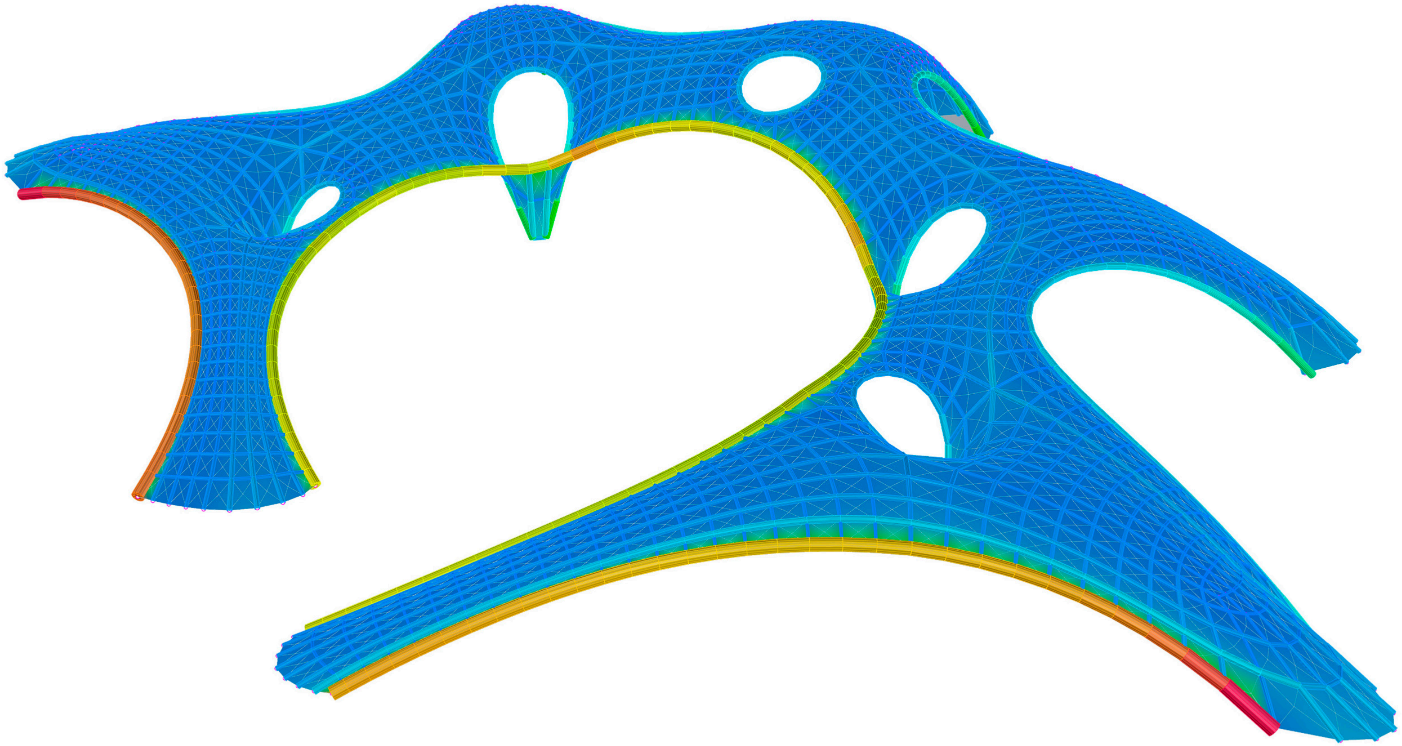





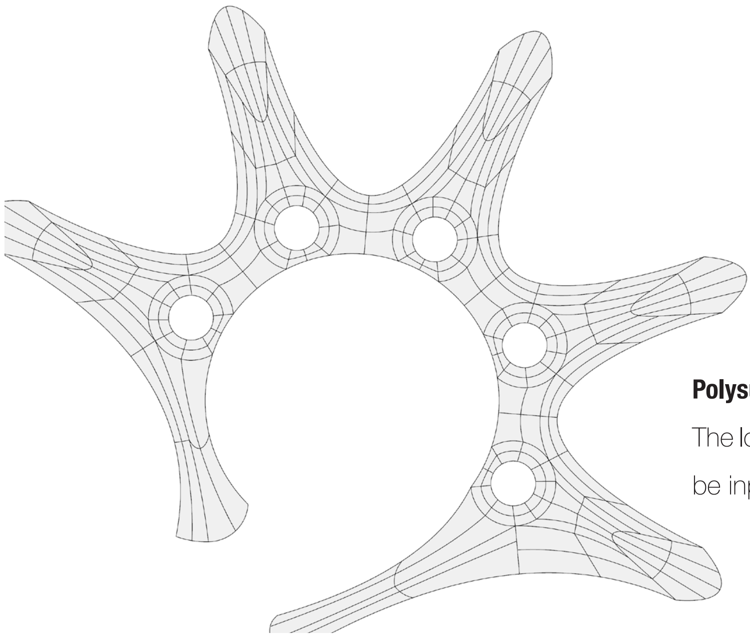
RhinoVAULT

RhinoVAULT is a Digital Form Finding plug in for Rhinoceros®, already explained in the first part of the present work. It was chosen among other digital engines because of its visual interaction with the dual graphs, the form and force diagrams.
Many tries were made before arriving with the final form, and meanwhile a lot of structural knowledge was gained throughout the process. Working with a tool that gives you instant visual feedback, both in form and in force diagrams has a strong educational effect.

The first input given was a polysurface with the isocurves aligned with the force path desired, the support points and the guide curves for the edges. In the menu, the user can set the numbers of interactions desired in order to reach horizontal and vertical equilibrium. The procedure of finding equilibrium is based on a swarm approach, in which each node interacts with it surrounding elements, establishing a optimal form. In this process, the user can also interact with the process by manipulating the nodes from each diagram, always having a automatic alteration in the dual graph.

Top Vault



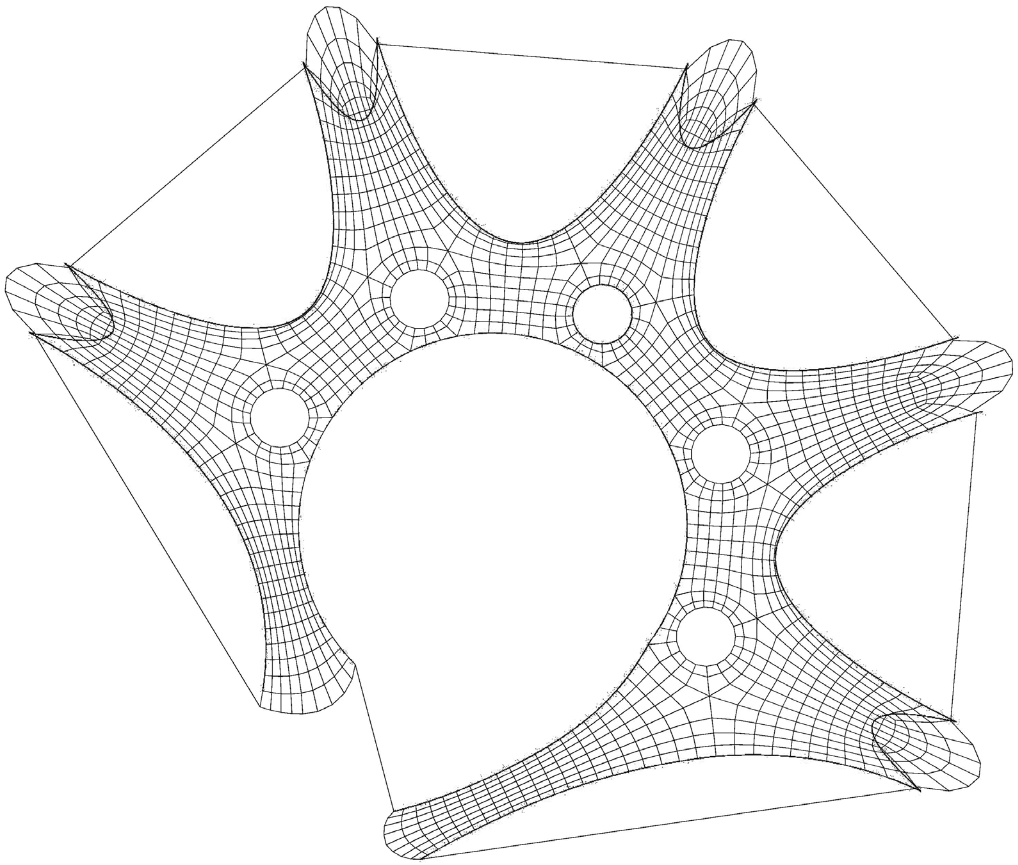


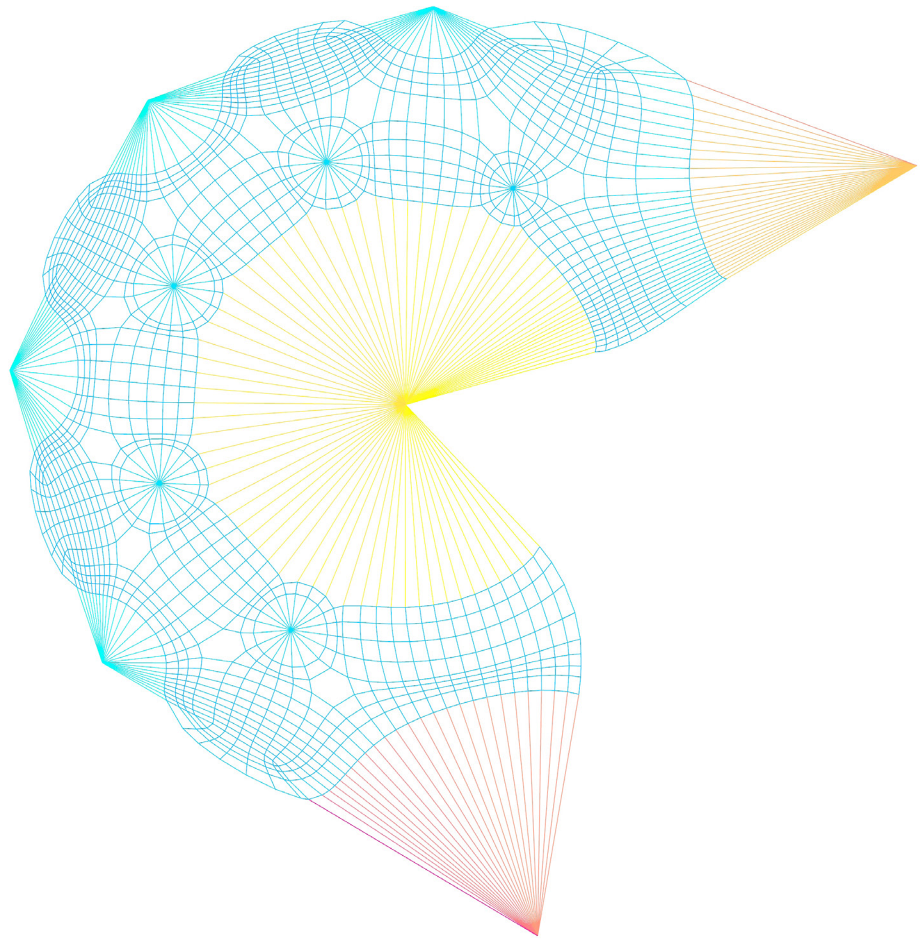
Polysurface input

The logics of the flow of forces must be inplicit in the isocurve paths.

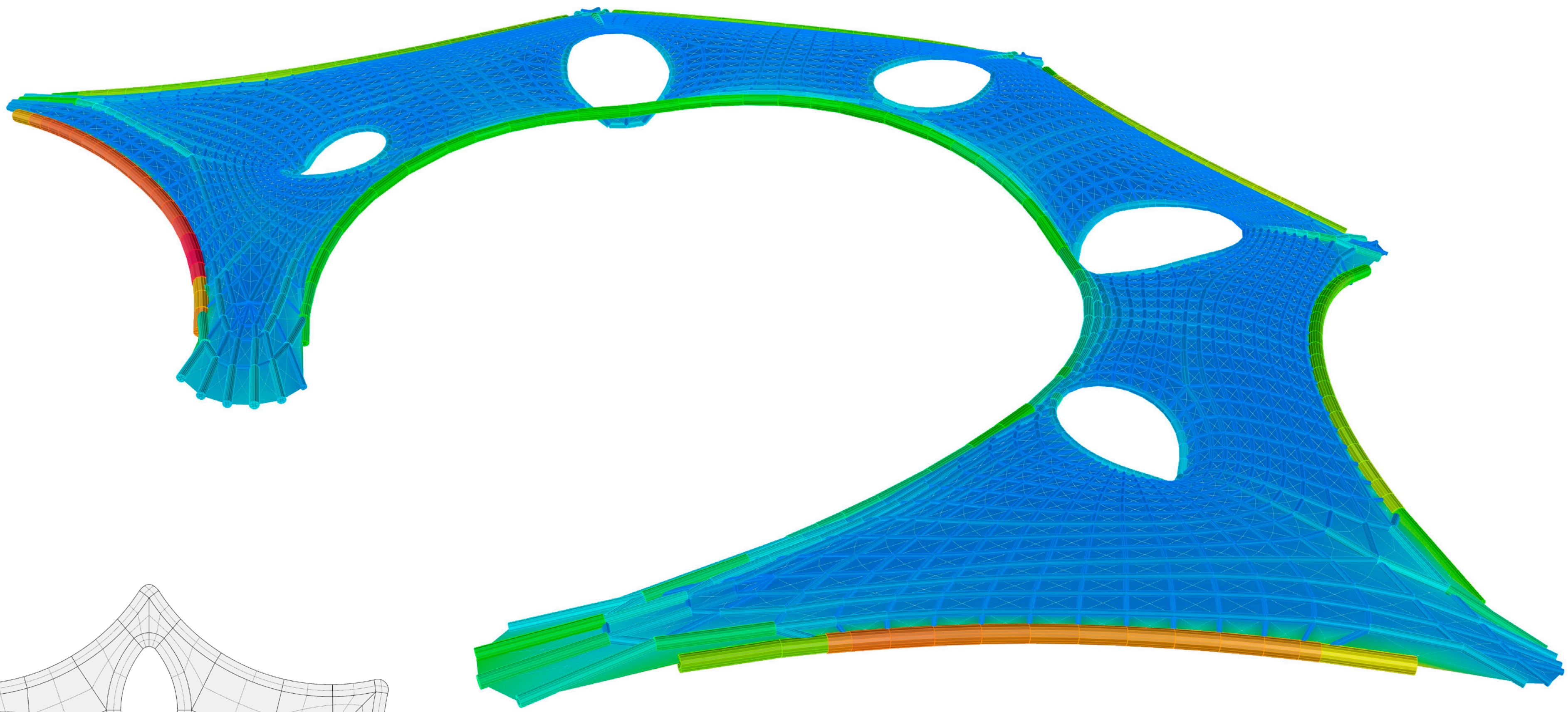
Dual Graph:

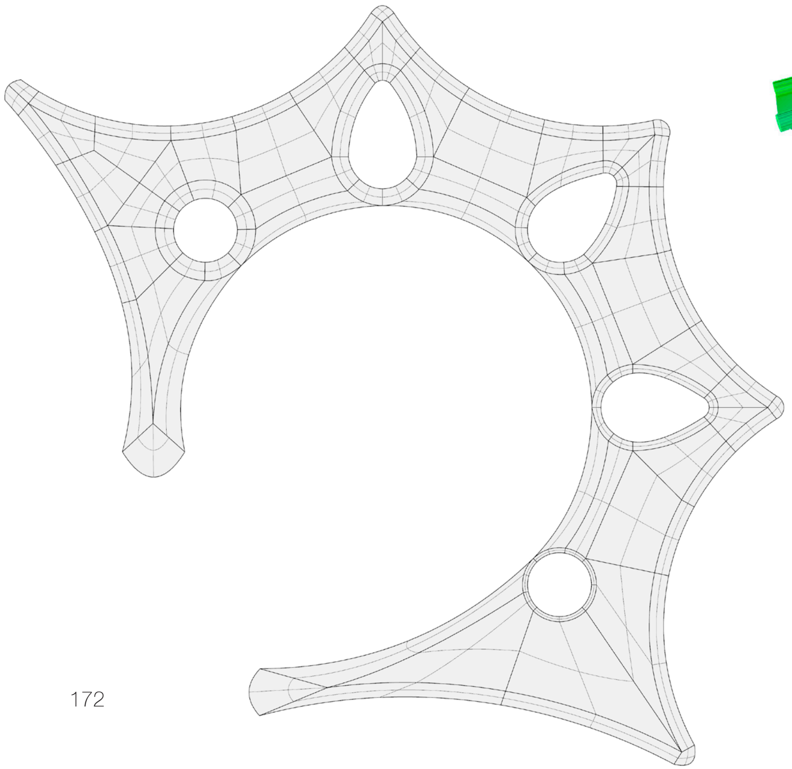
Form and Force diagrams are correlated and codependent.





Bottom Vault



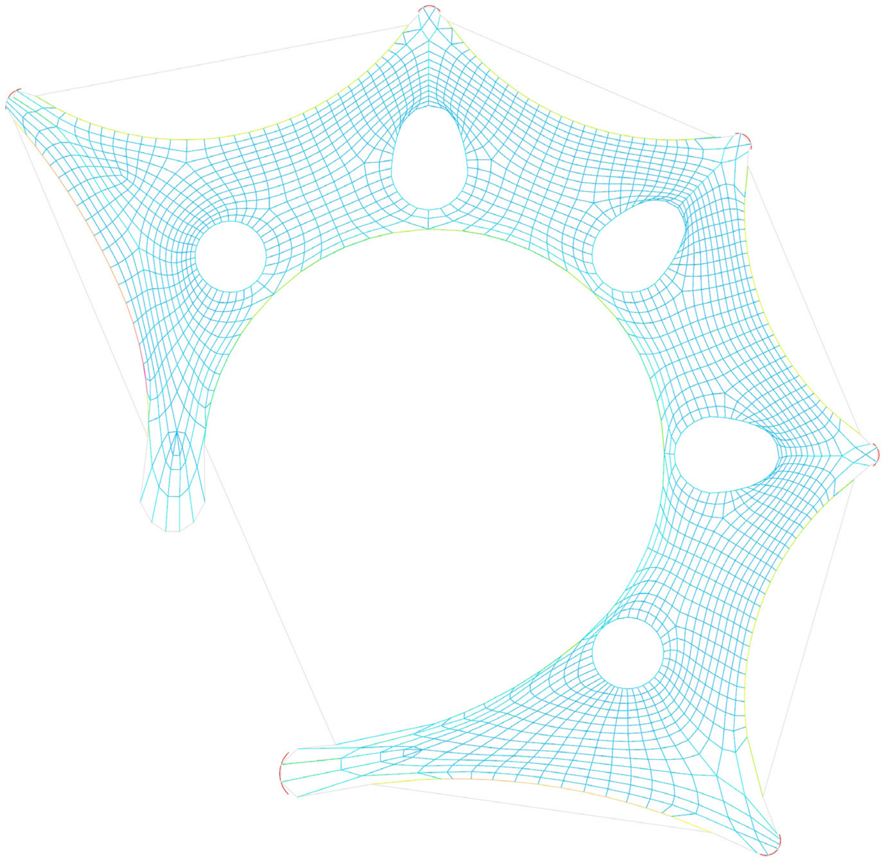


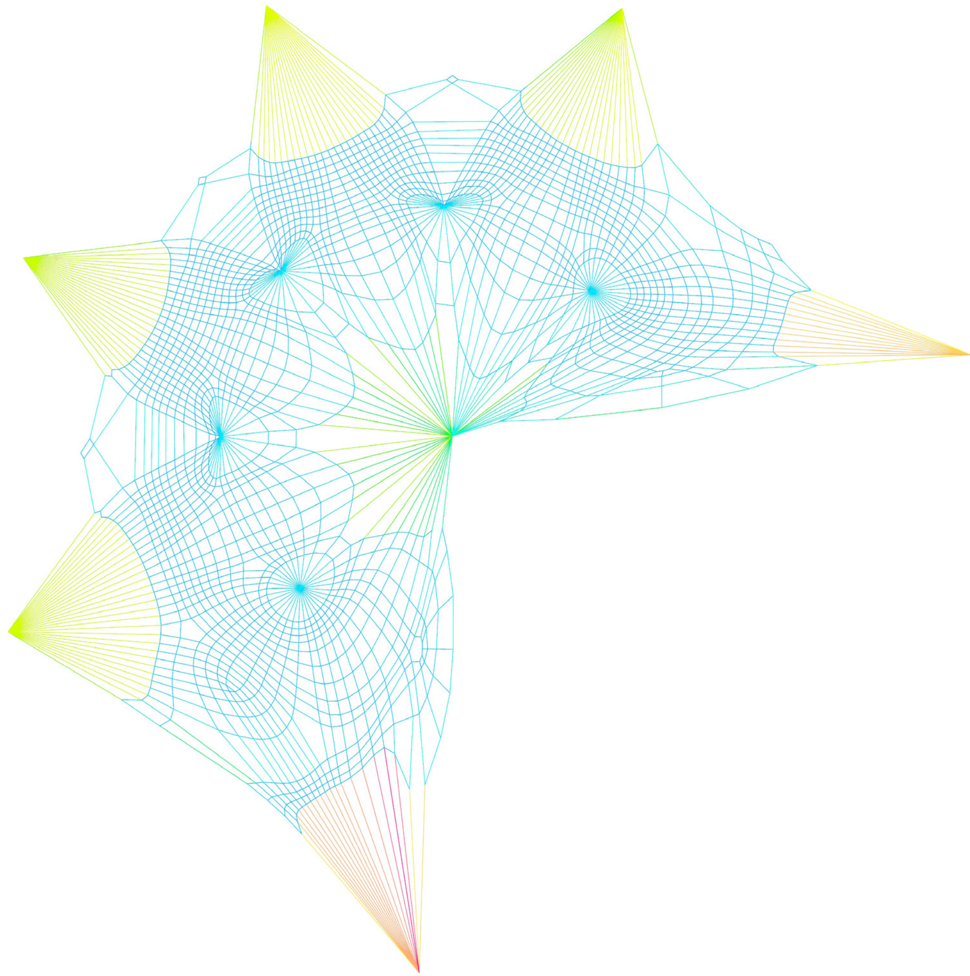
Polysurface input

The logics of the flow of forces must be inplicit in the isocurve paths.

Dual Graph:

Form and Force diagrams are correlated and codependent.



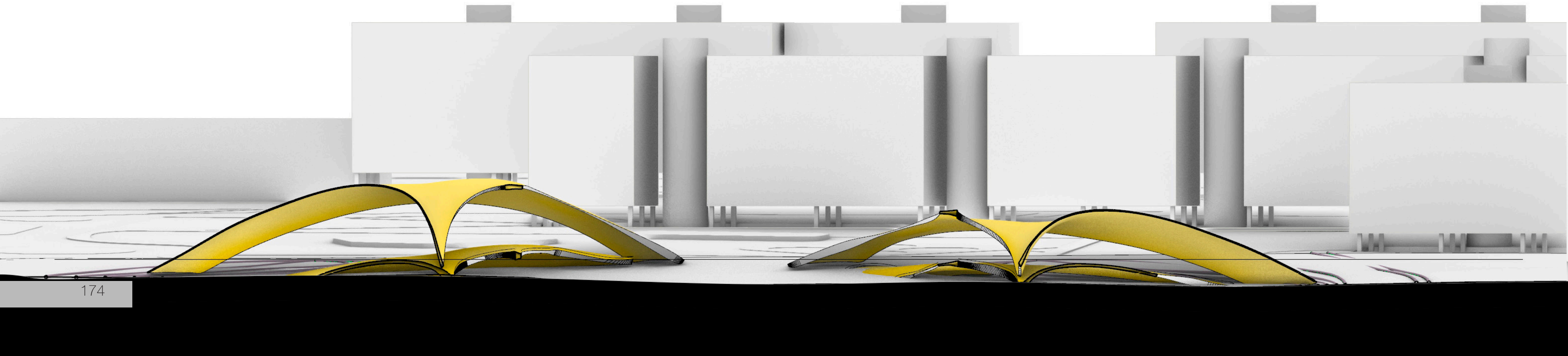


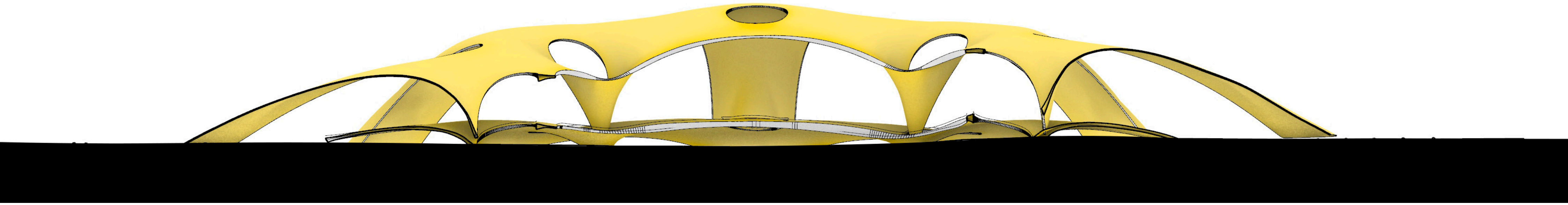
Karamba3D

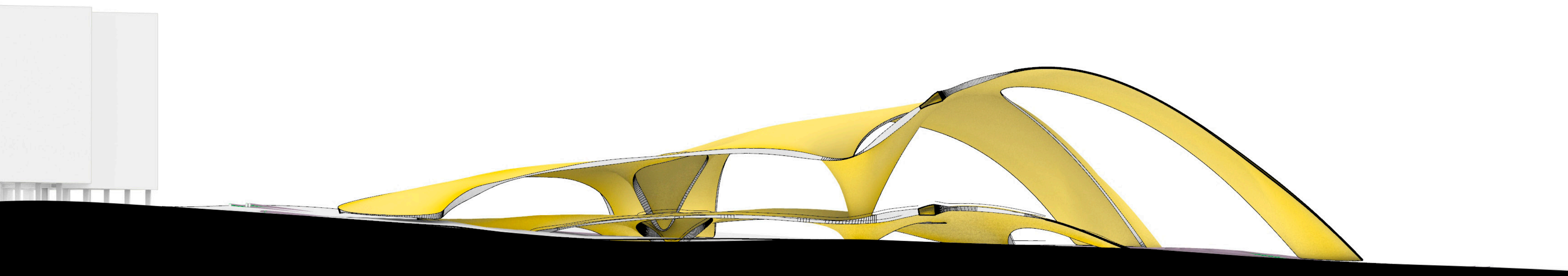
Digital tools empowers the architect with the structural knowledge necessary to propose optimal shapes, resulting in more coherence in the final project. Karamba 3d is one of these tools, working with parameters inputed by the designer, giving as output a full structural analysis since the first steps of the design. It works entirelly inside Grasshopper, and it is able to generate optimal structures as well as analysing forms created by other engines.

To analyse the present shells, it took as input the meshes generated by RhinoVAULT, along with parameters such as material, loads, support points, type of section and the size range of the elements. It gave as output the optimal cross section in each point of the mesh, the force lines acting in the form and the utilization distributed along the structure.

The resulting cross section and mass calculation corroborated with the theory of Form-Active and the results obtained with RhinoVAULT. It numerically proved that the deeper the funicular shape is, better it performs. The Upper shell, besides being taller and larger superficial area, it has a thinner cross section, a lower utilization percentage and a almost the same mass.







Karamba3D

Top Shell

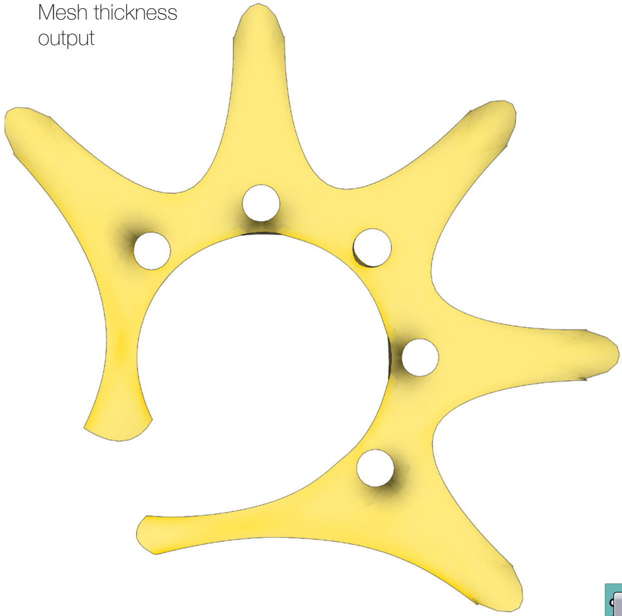
Analysis input:

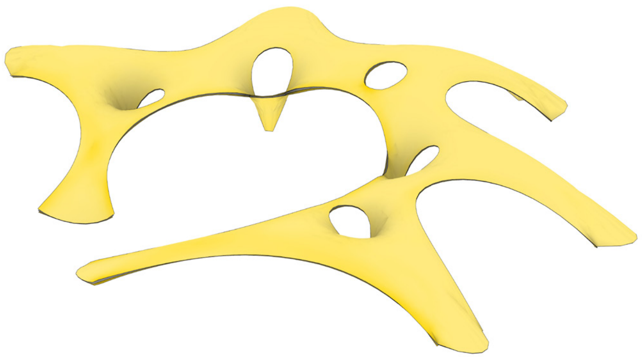
- Mesh
- Support Points in the Mesh
- Section Range: 10 to 200 cm
- Loads: Gravity + 700kgf/m^2
- Material: Reinforced Concrete B550 -EN

Analysis output:

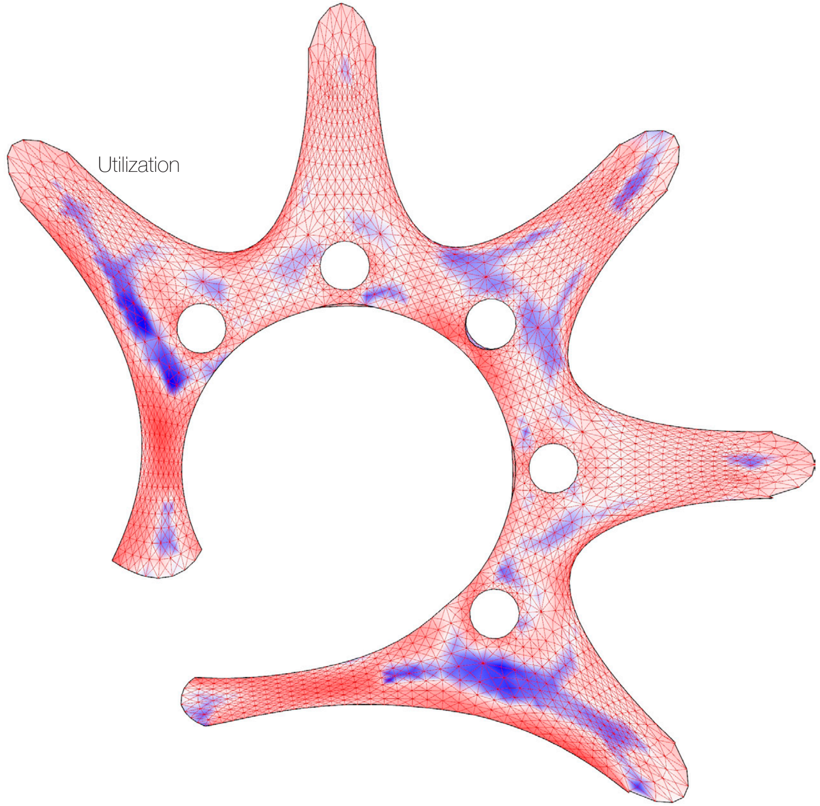
- Mesh Cross Section
- Cross section range: 10 to 110 cm
- Principal Stress Lines
- Utillization of each part of the shell up to 23%
- Total mass: 6480 ton

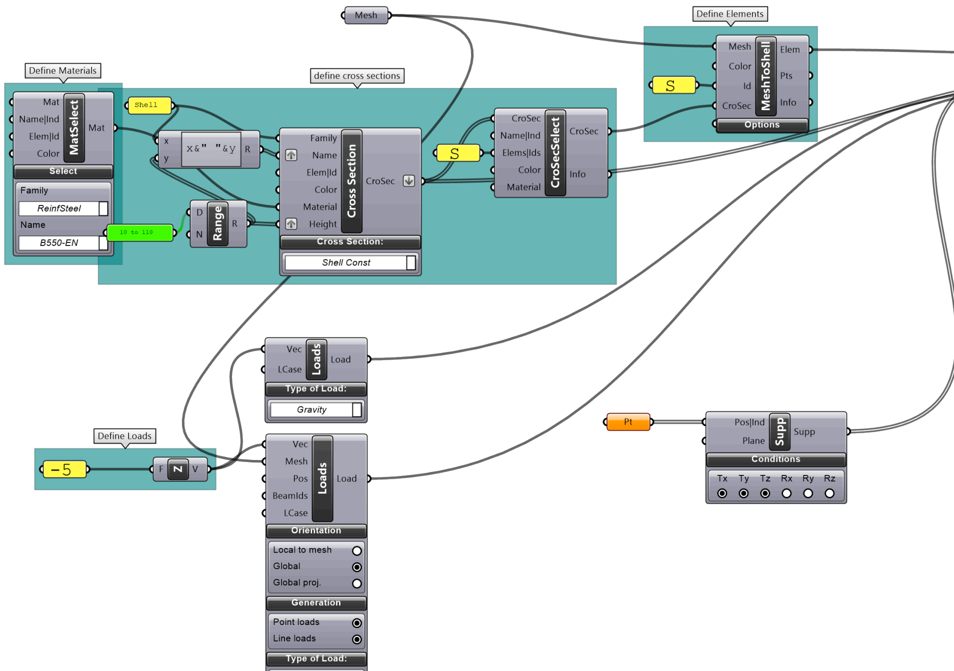
Mesh thickness output



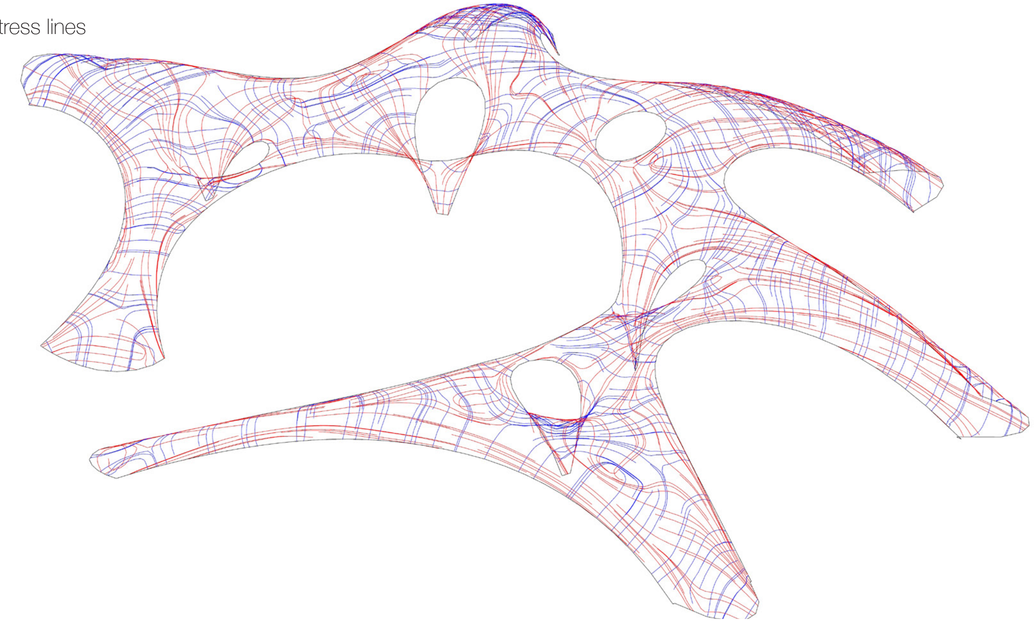


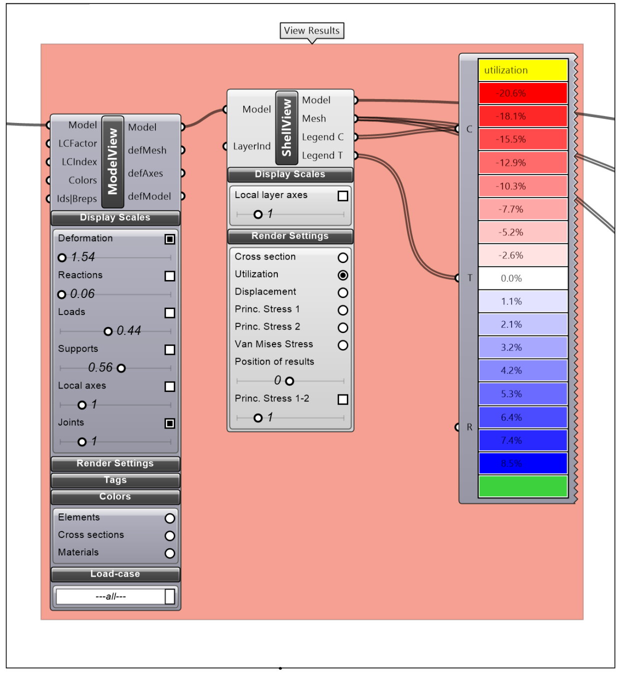
Utilization

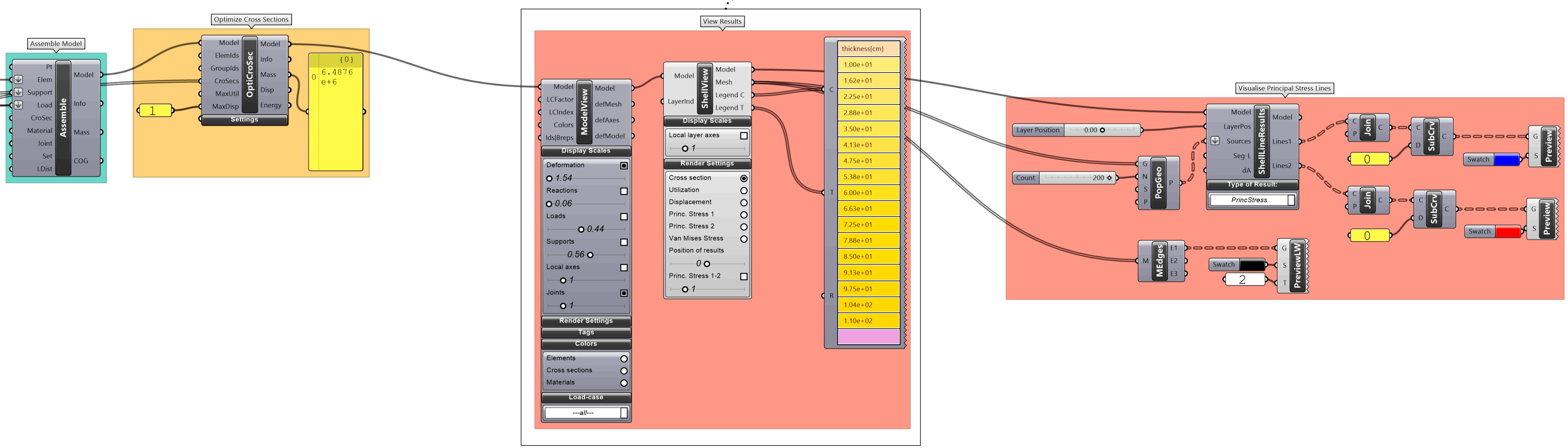




Stress lines







Karamba3D

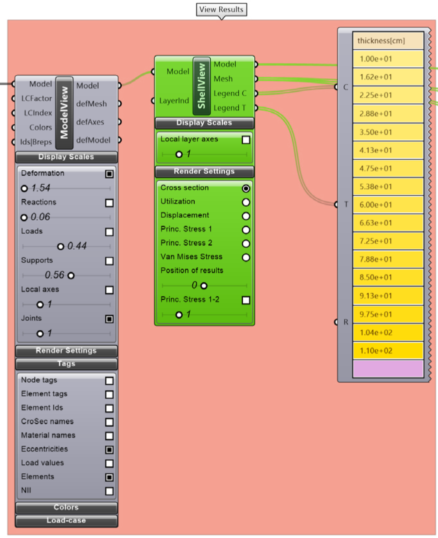
Lower Shell

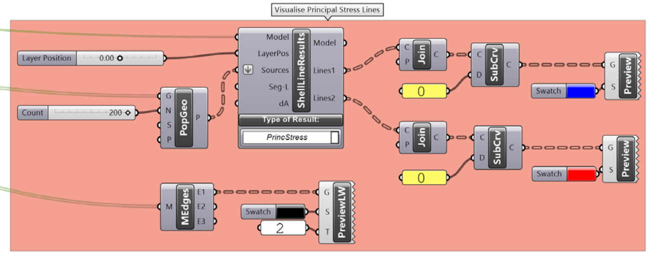
Analysis input:

- Mesh
- Support Points in the Mesh
- Section Range: 10 to 200 cm
- Loads: Gravity + 700kgf/m^2
- Material: Reinforced Concrete B550 -EN

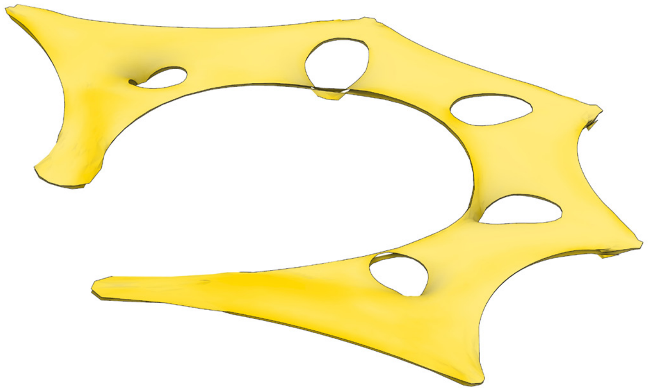
Analysis output:

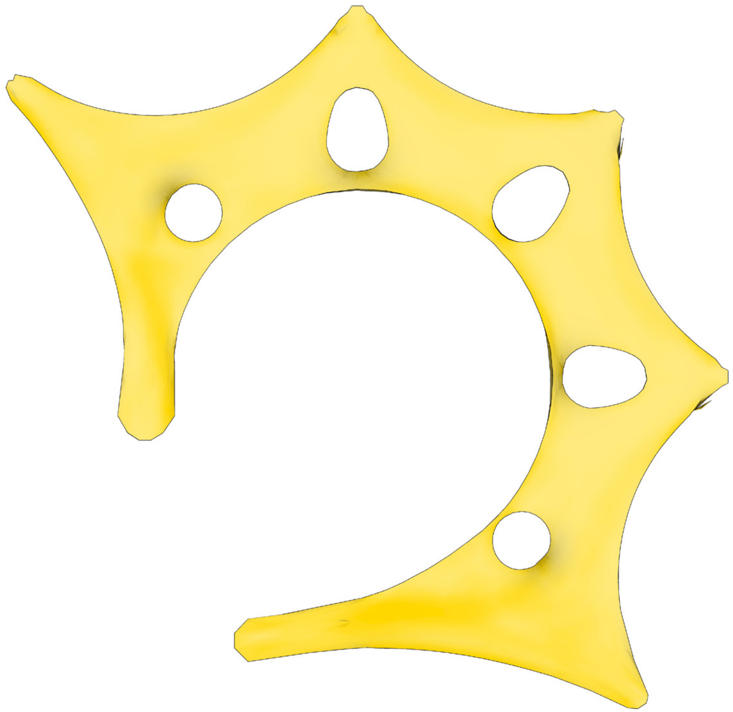
- Mesh Cross Section
- Cross section range: 10 to 110 cm
- Principal Stress Lines
- Utillization of each part of the shell up to 27%
- Total mass: 6200ton

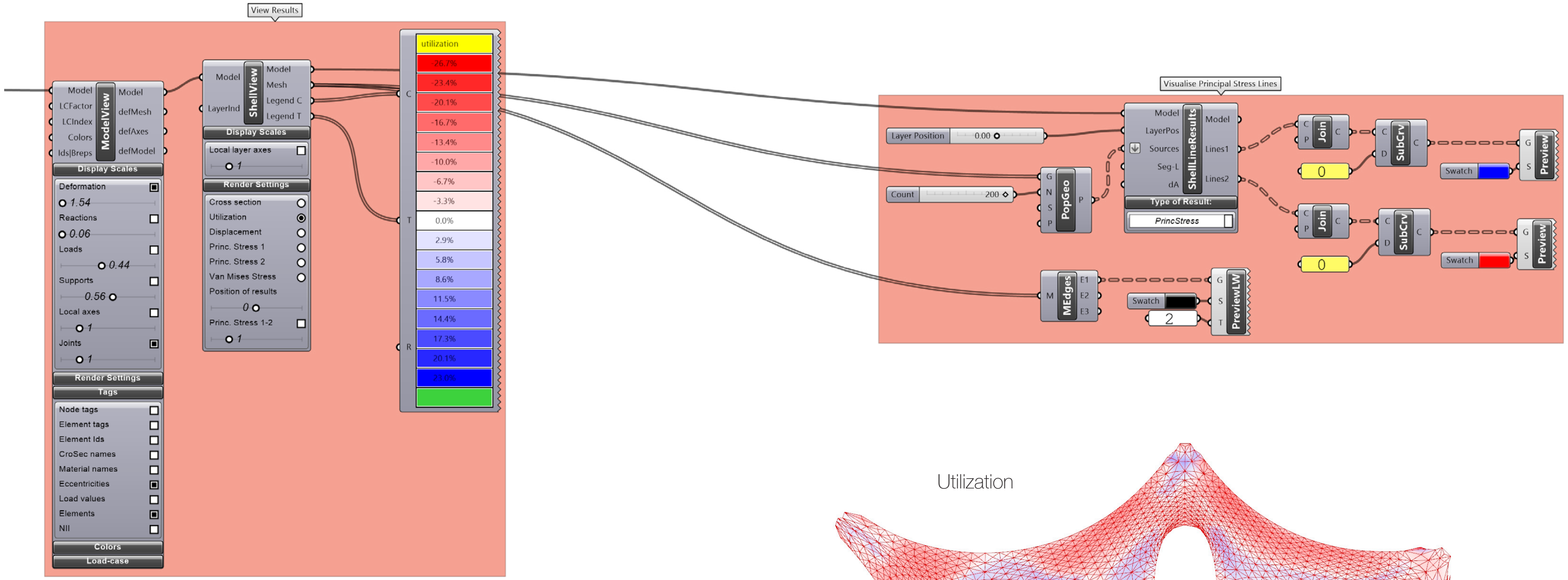


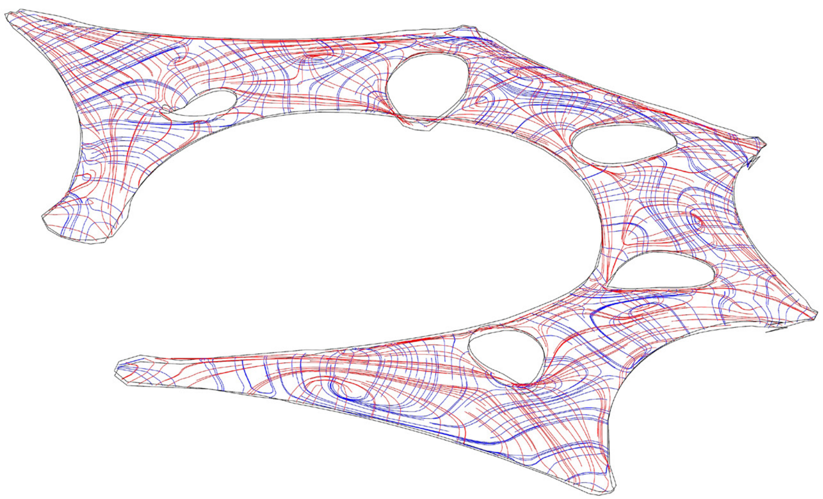


Mesh thickness output

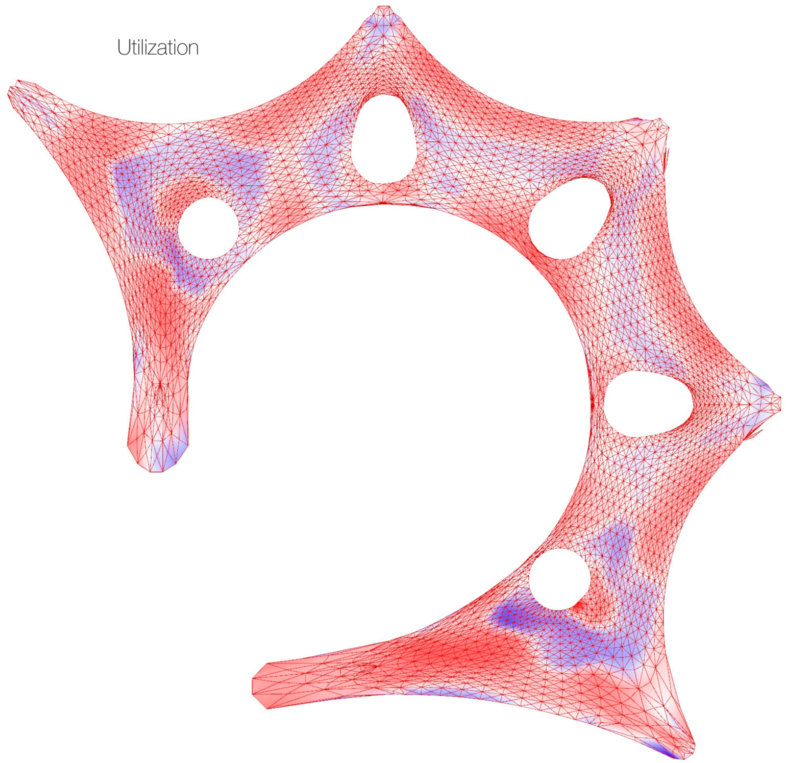






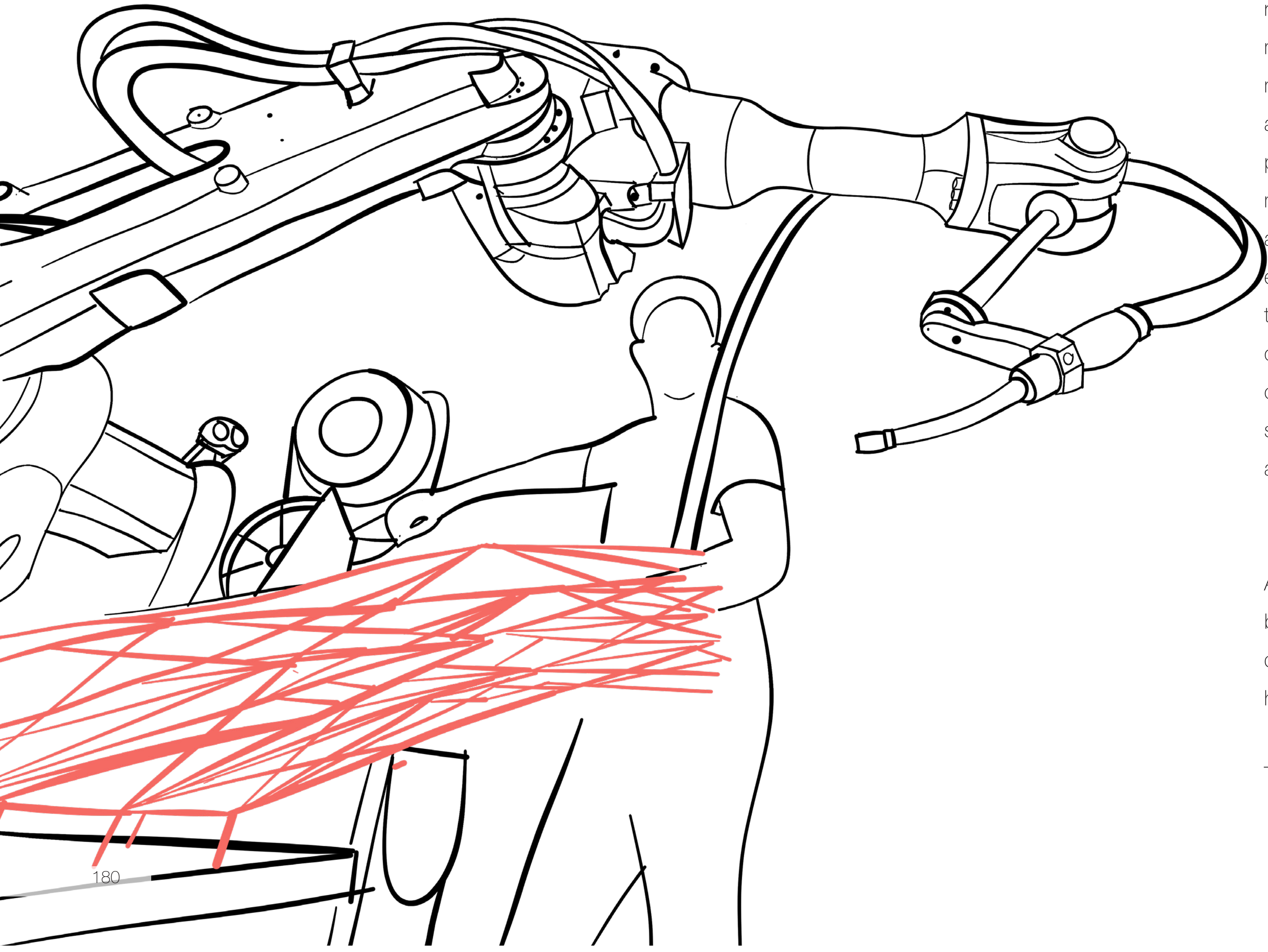


Stress lines



Utilization

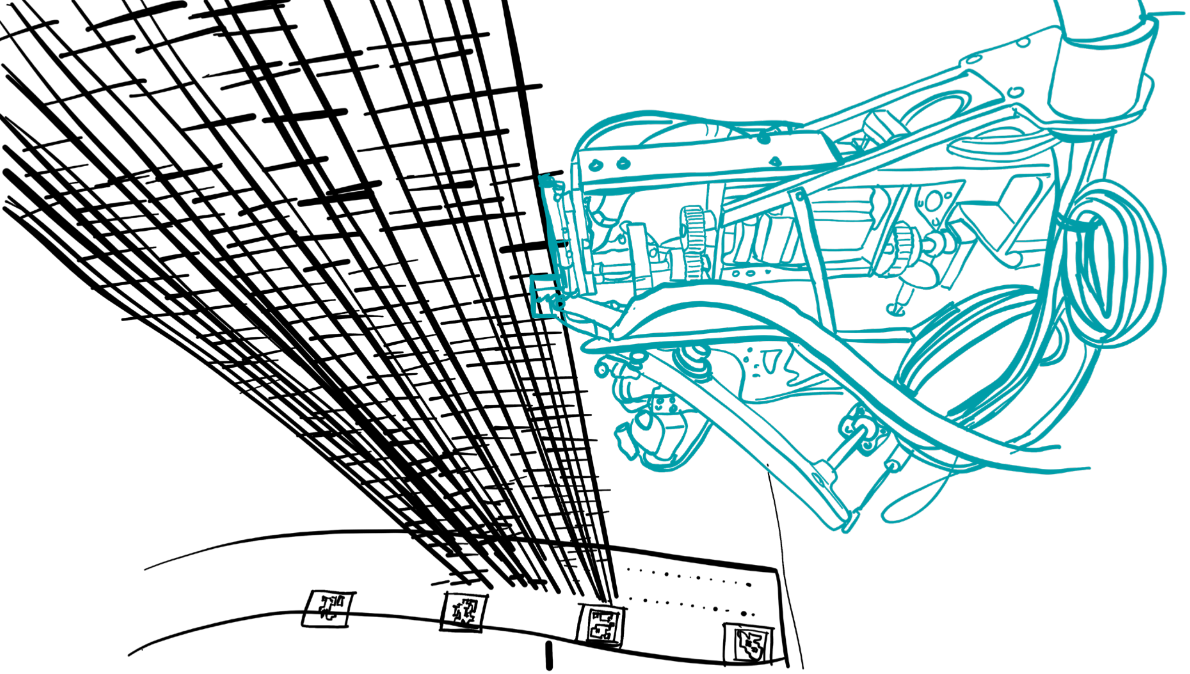
Fabrication



The fabrication process is based on the technology developed by ETH Zurich, called Mesh Mould. It is a digital fabrication technology that combines formwork and reinforcement, using a robotic arm to manipulate the steel reinforcement. The manipulations done are bending, welding and cutting the rebars. It is a complex process that demands a competent and multidisciplinary team since it combines areas such as robotics, material technology, engineering and architecture. Considering that the costs of the formwork of doubly curved structures can cost more than 75% of the total cost of the construction, this strategy shows great advantages. (Hack et al., 2017)

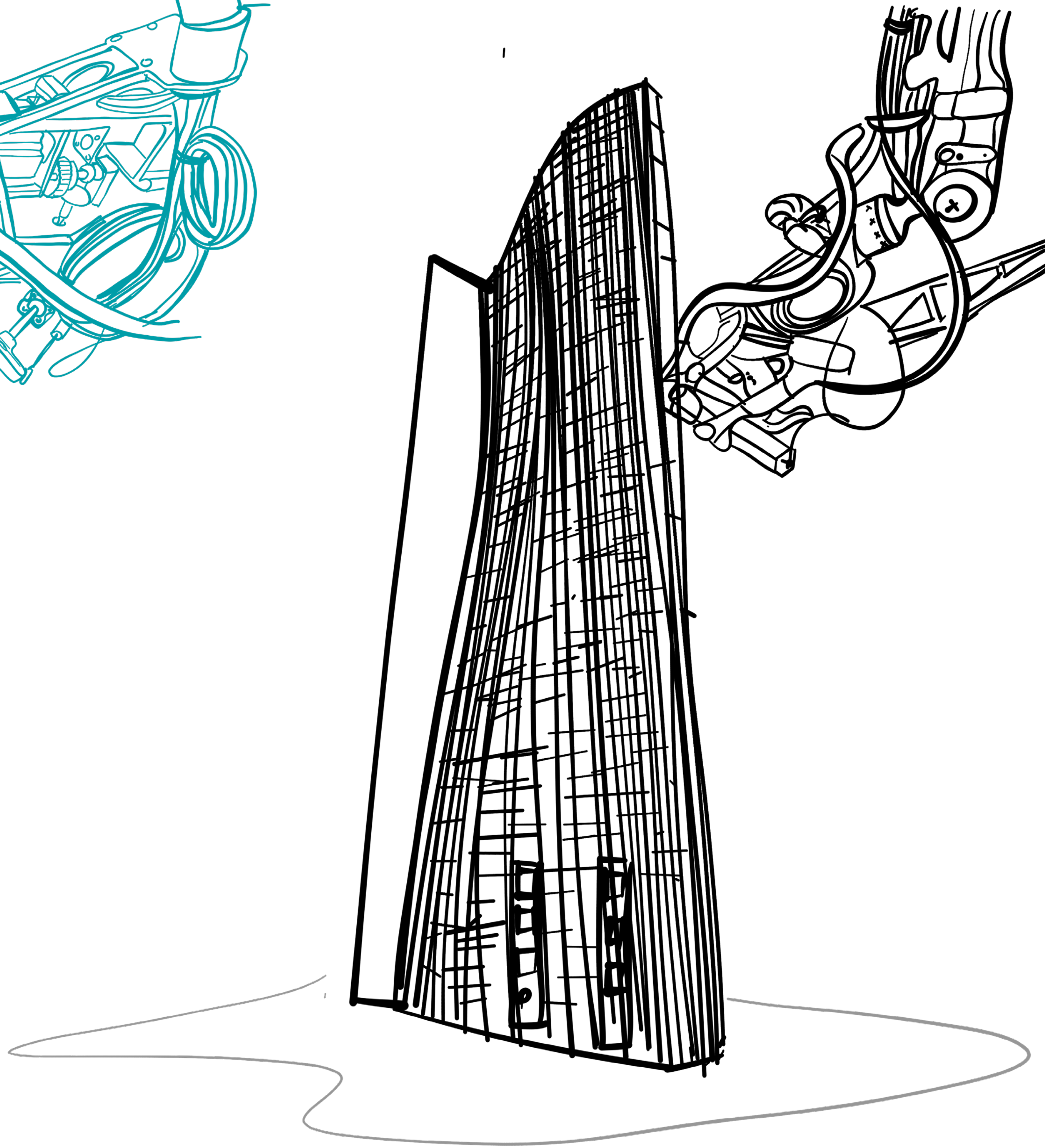
All the following images were handrawed based on the process created and demonstrated on the website: http://gramaziokohler.arch.ethz.ch/

The first step is to



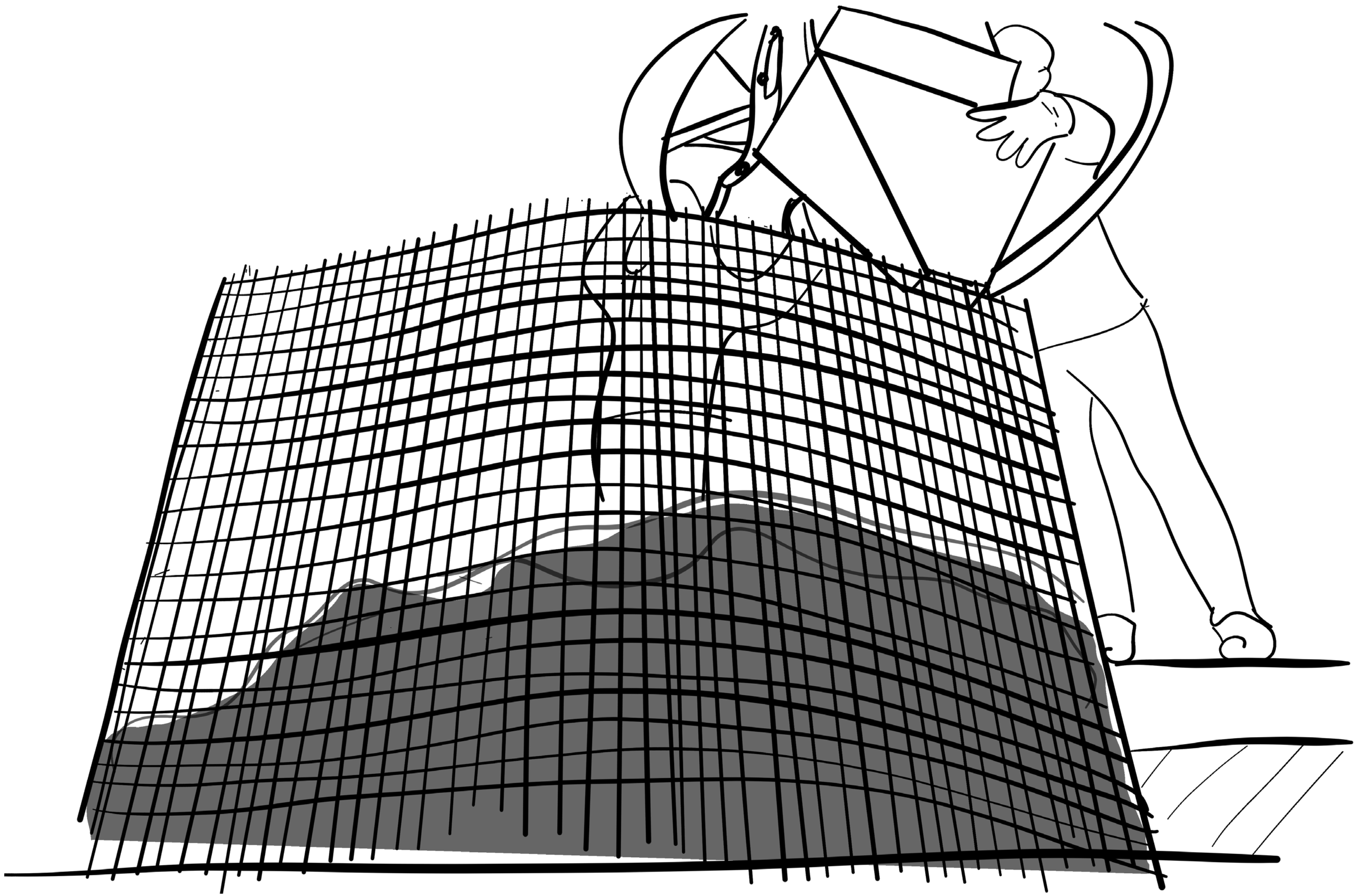
First Step

Prefabrication of the mesh mould



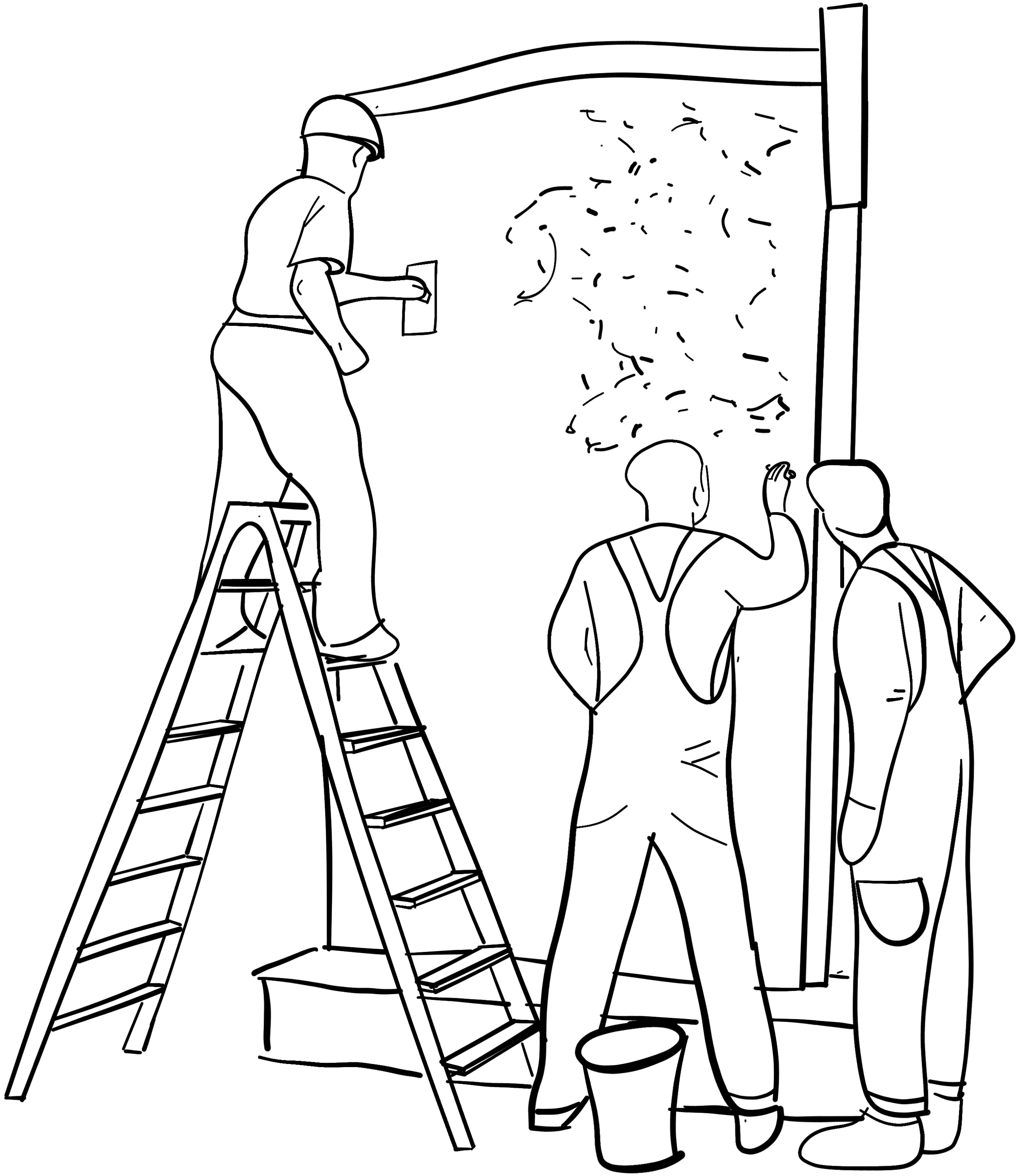
Second Step

Pouring the concrete manually.



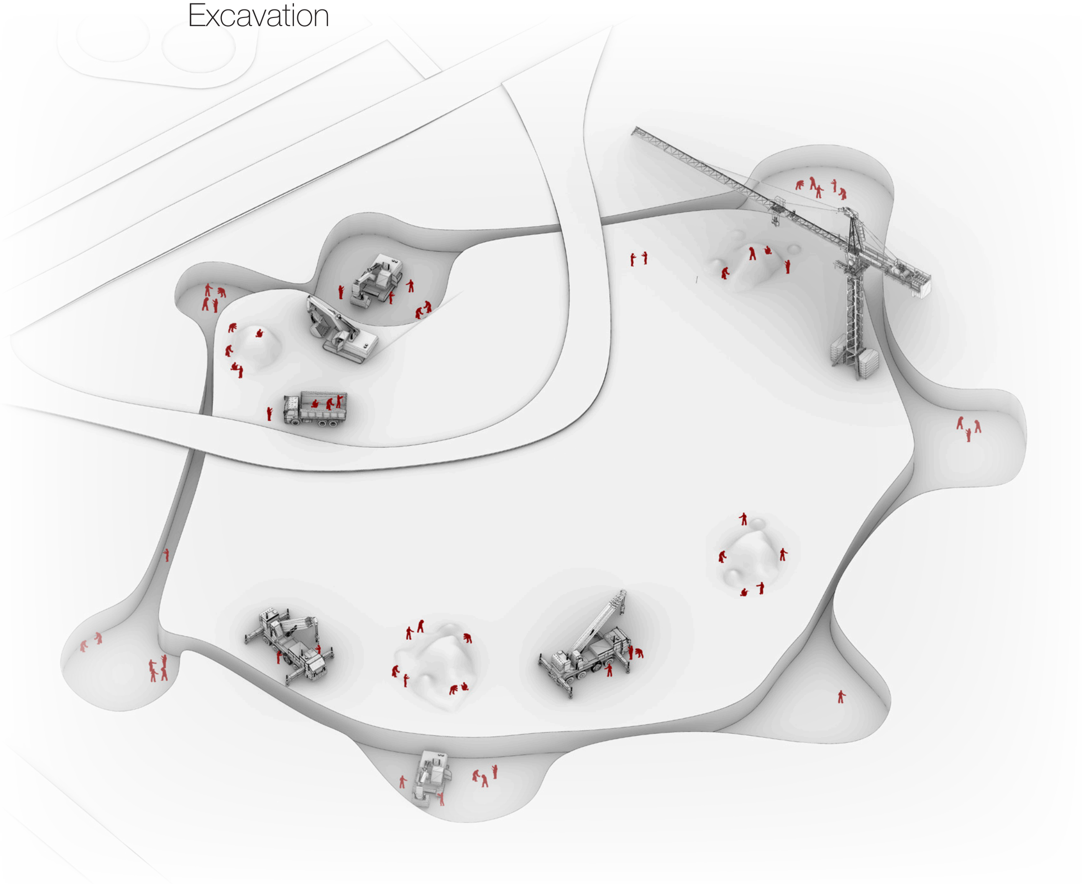
Third Step

Finishing the surface by smoothing.

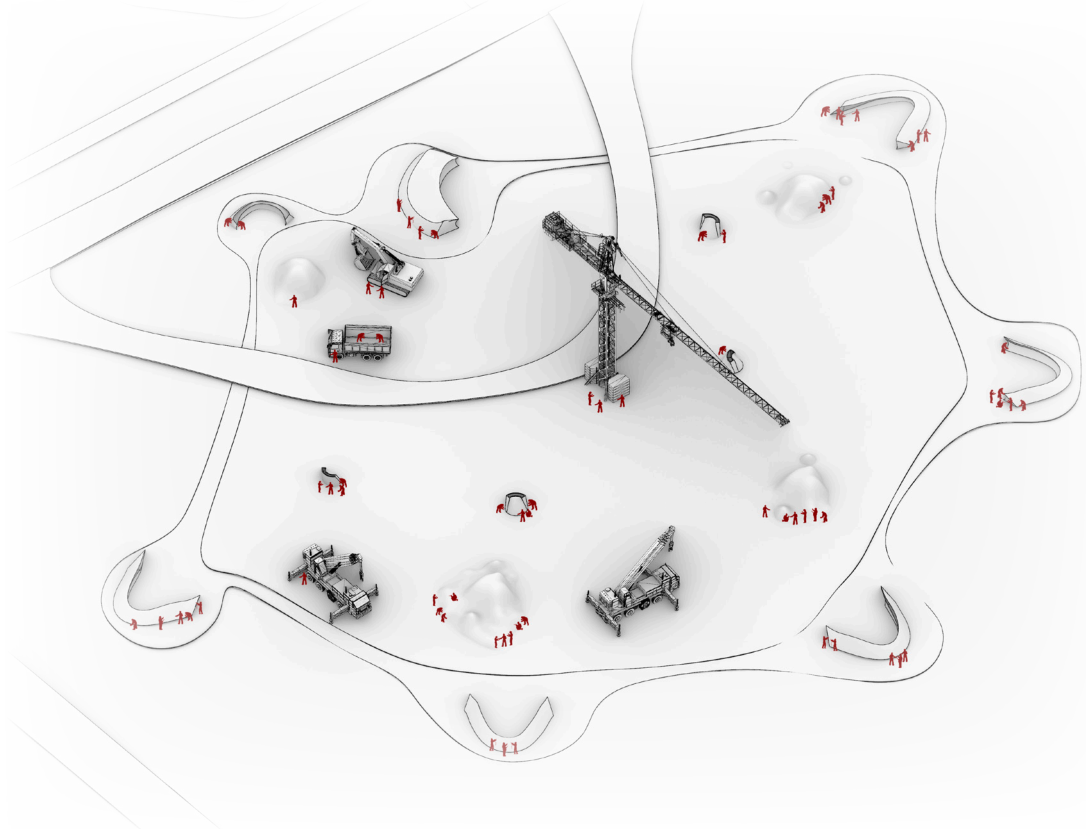


Assembly

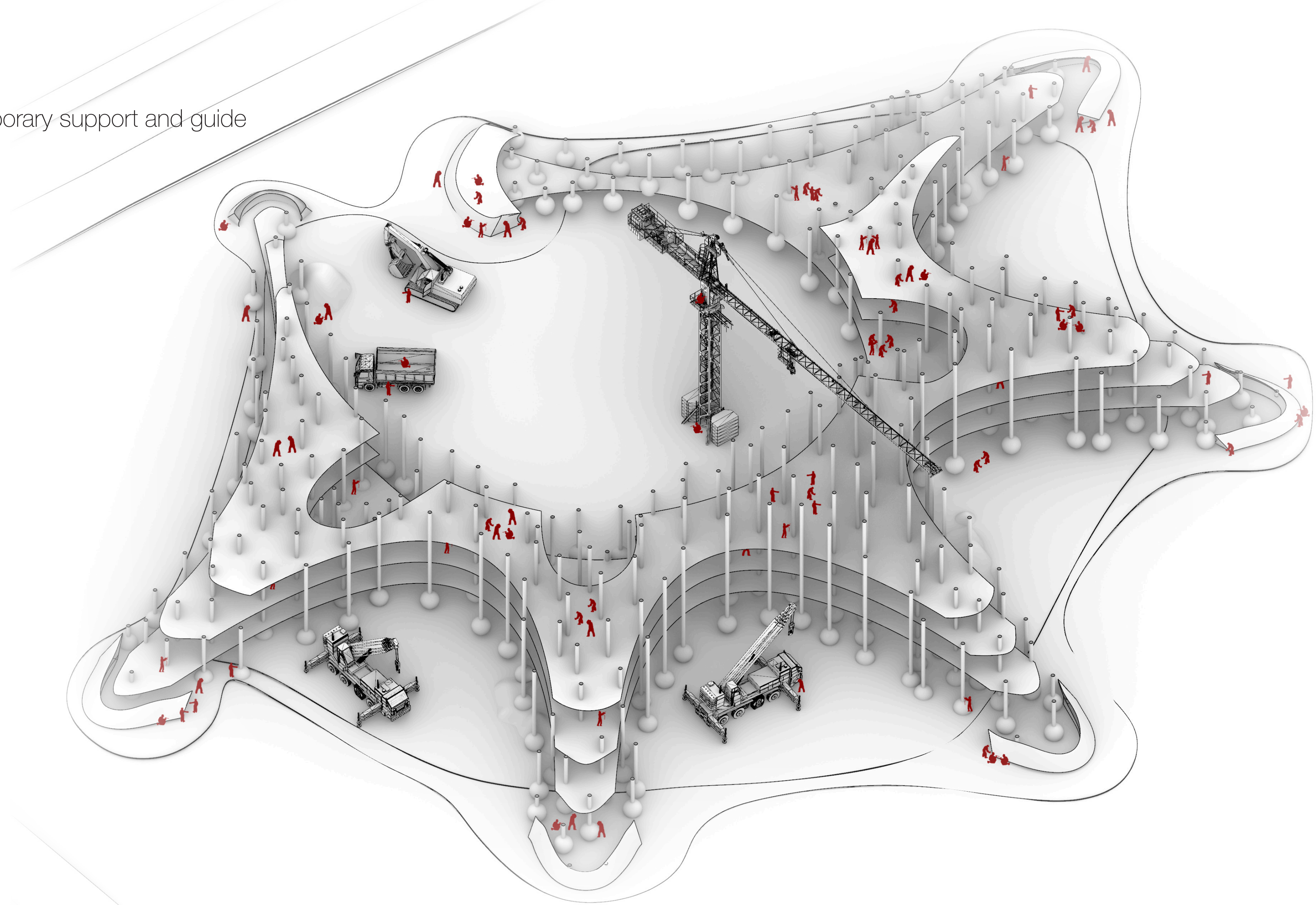
Excavation



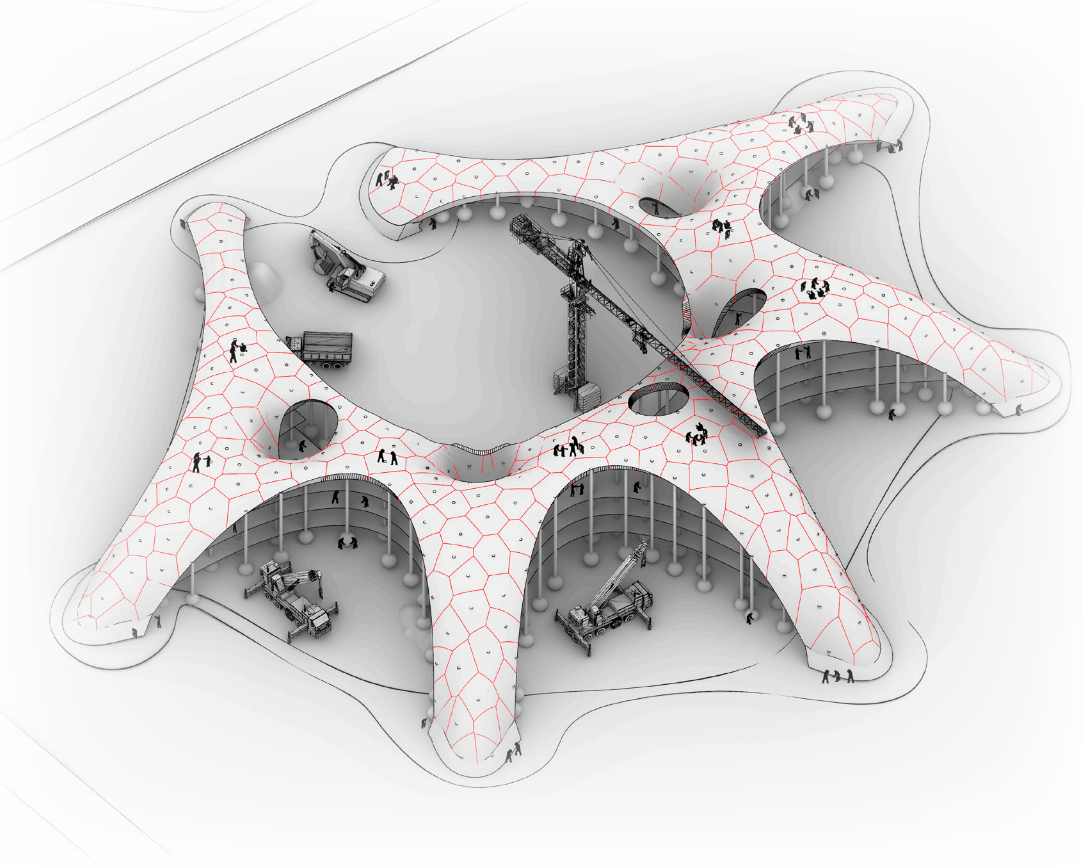
Foundation



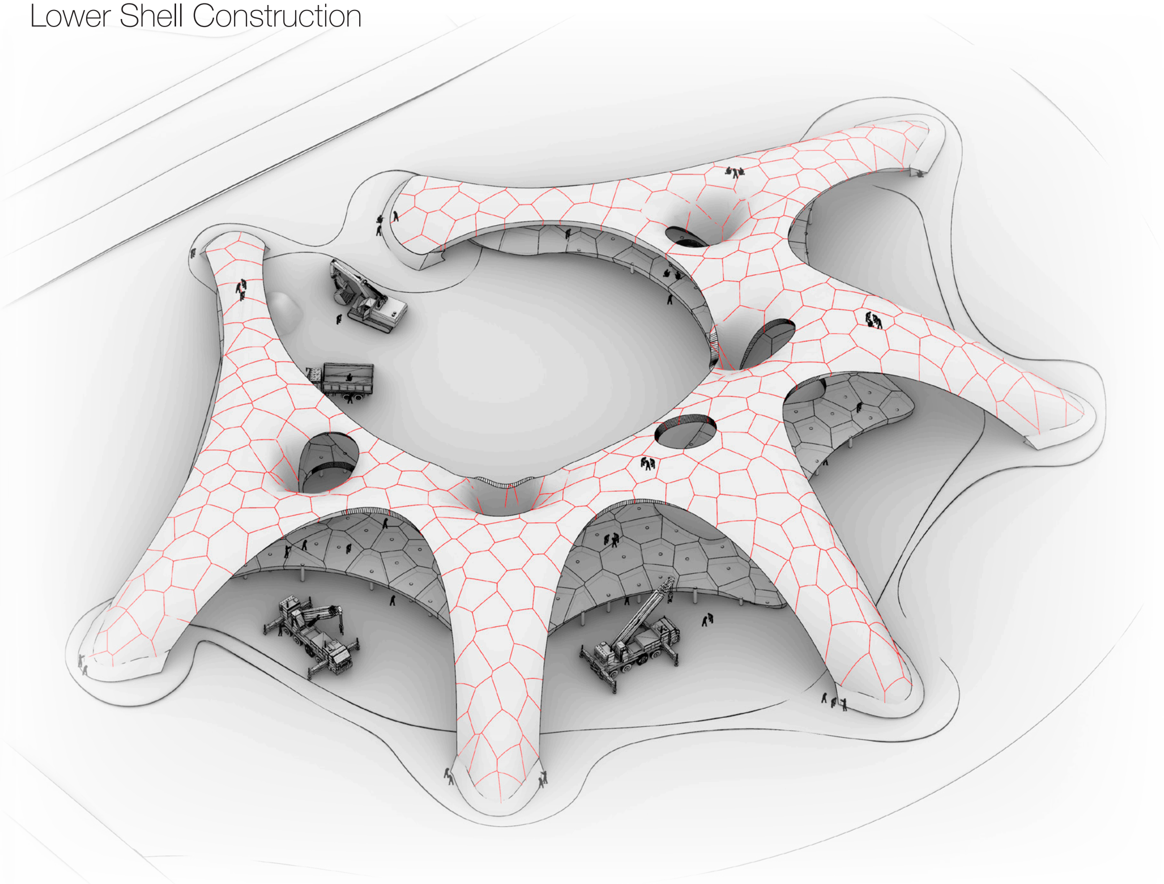
Temporary support and guide



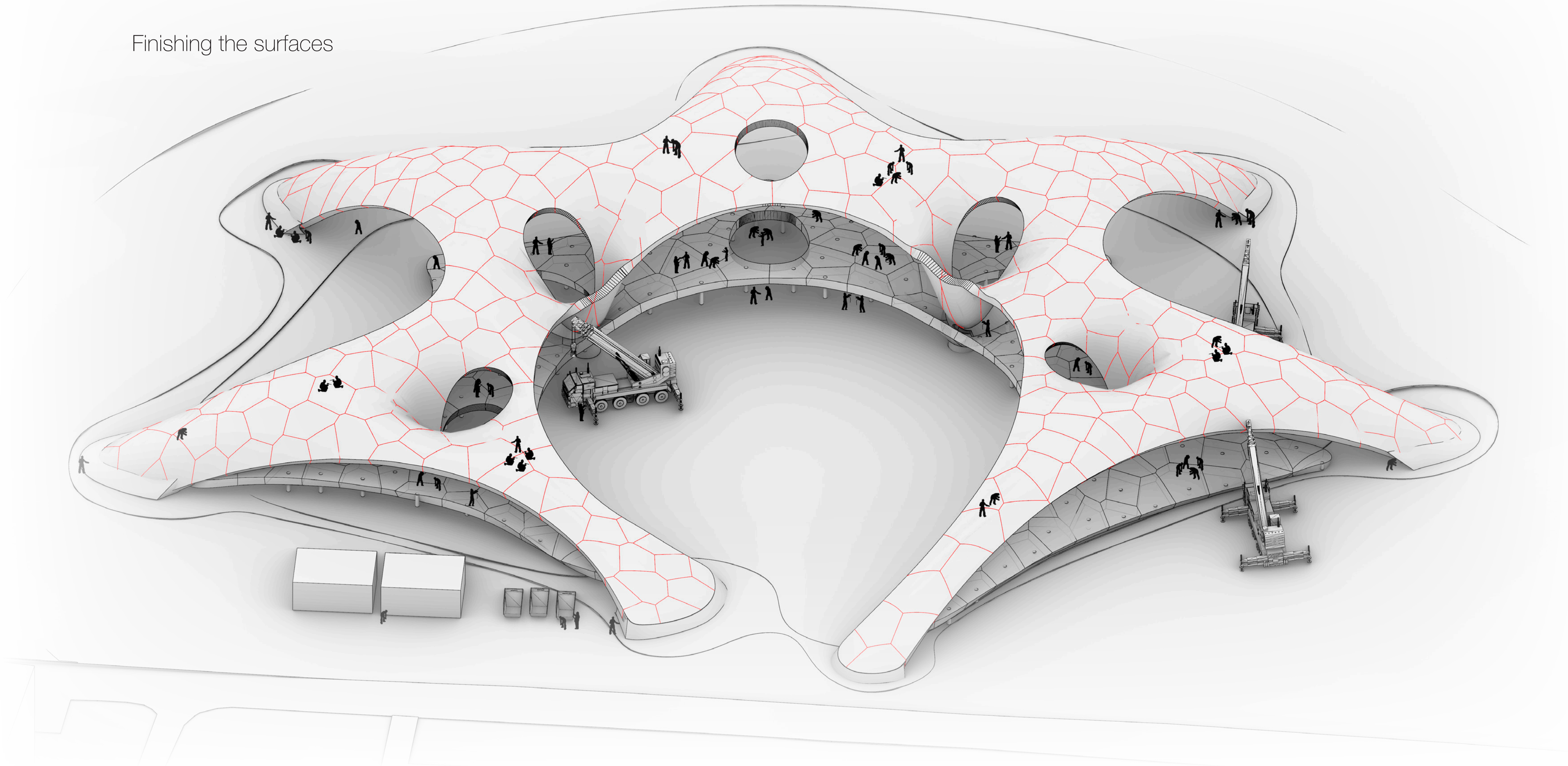
Upper Shell Construction



Lower Shell Construction

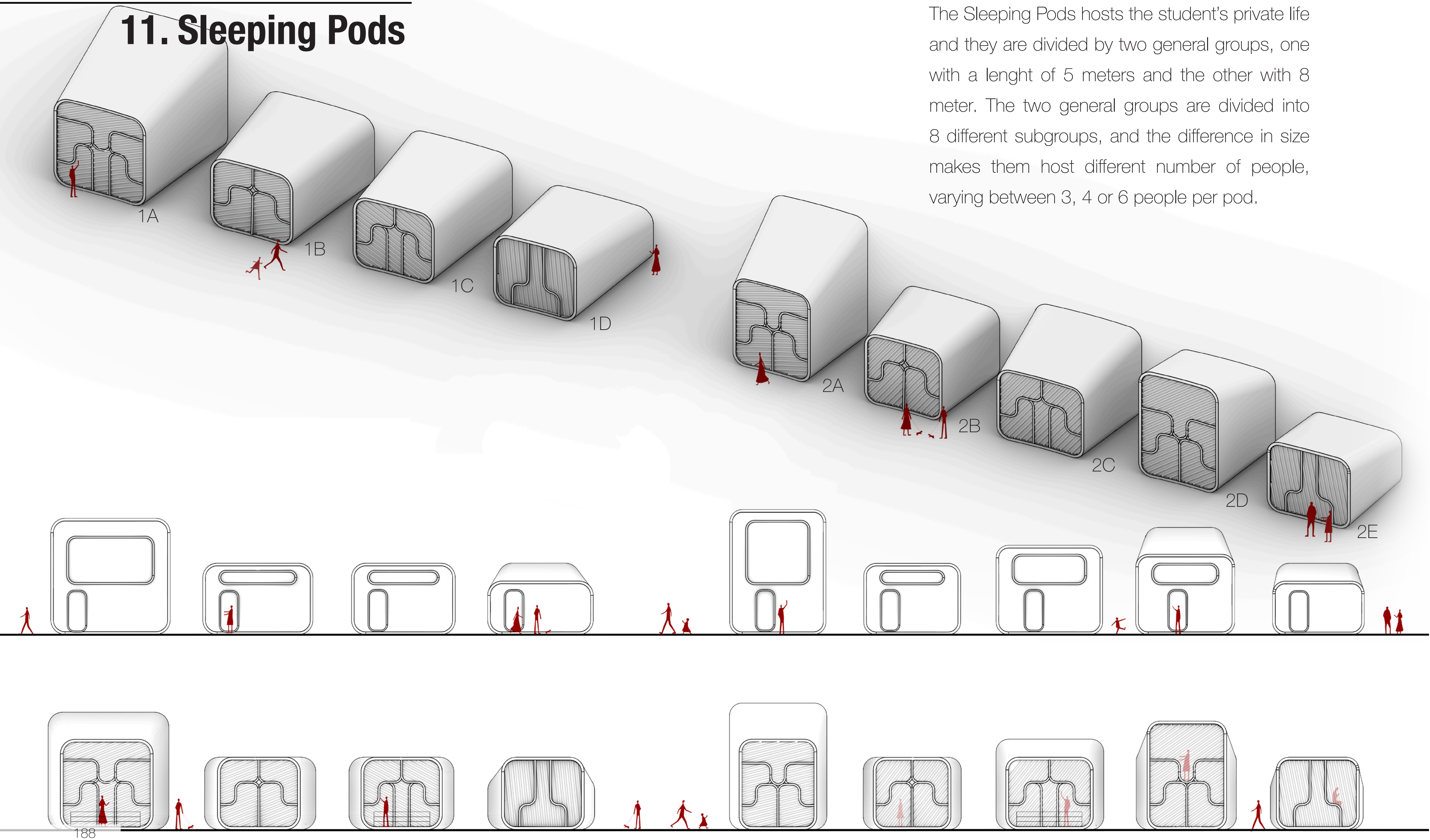


Finishing the surfaces



11. Sleeping Pods

The Sleeping Pods hosts the student's private life and they are divided by two general groups, one with a lenght of 5 meters and the other with 8 meter. The two general groups are divided into 8 different subgroups, and the difference in size makes them host different number of people, varying between 3, 4 or 6 people per pod.



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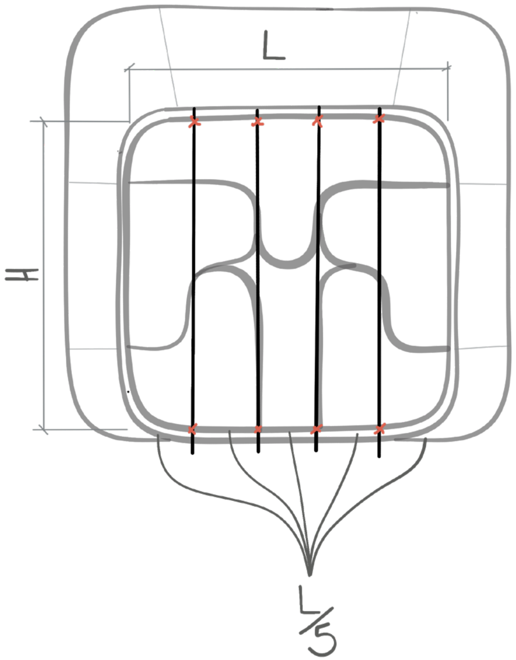
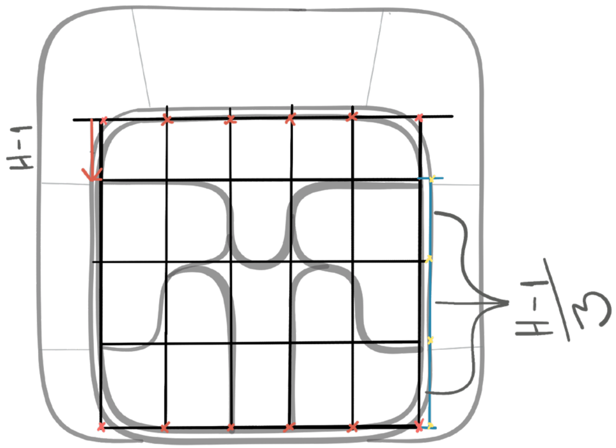
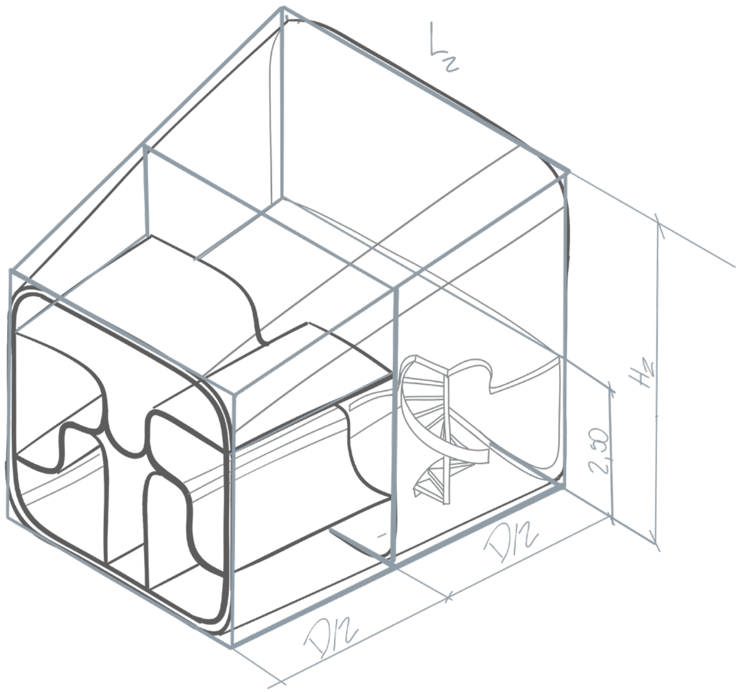
The strucures were generated from a few pre-determined inputs: the curve edge of the lower shell, the maximum height of the upper shell, the vertical displacement of each row and their offset from the line below. Although they are all differentiated among them, they also obey some minimum dimensions.

That happens because their private subdivision must have a horizontal projection of at least 2x3m and a minimum height of 2.5m. The elements were segregated algorithmically by height, their depth and the fact that they had or no a balcony.

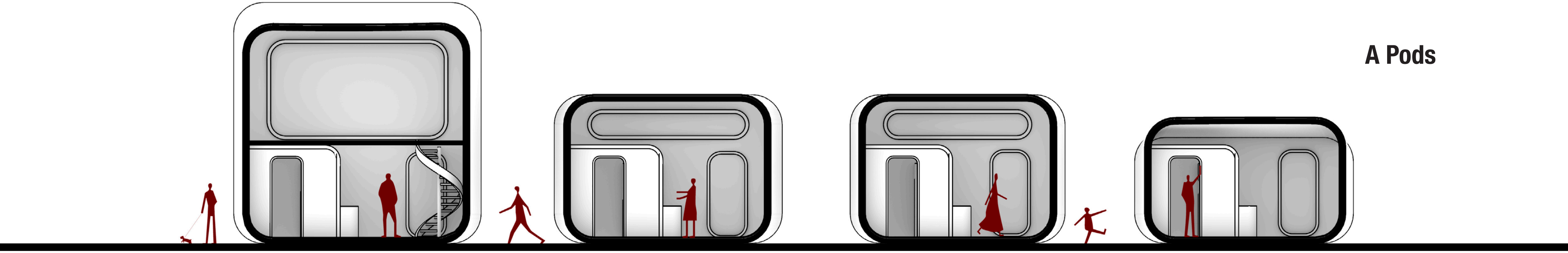
Inside each pod, there is one bathroom, a small kitchen with think, small fridge, a microwave and some extra space that could serve as a storage place for the residents or a cozy chilling area.

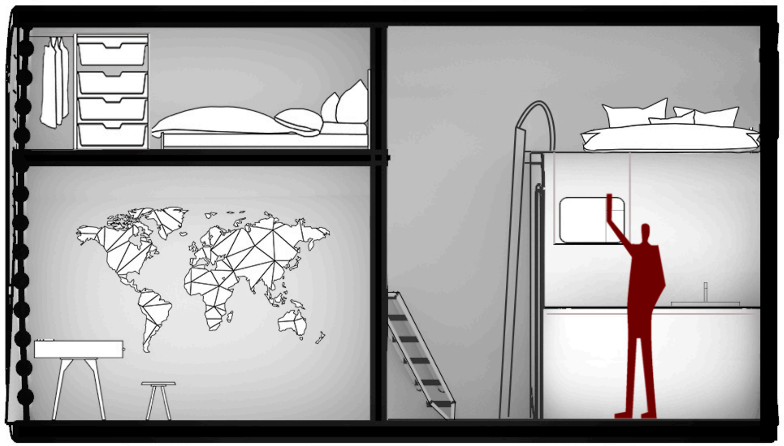


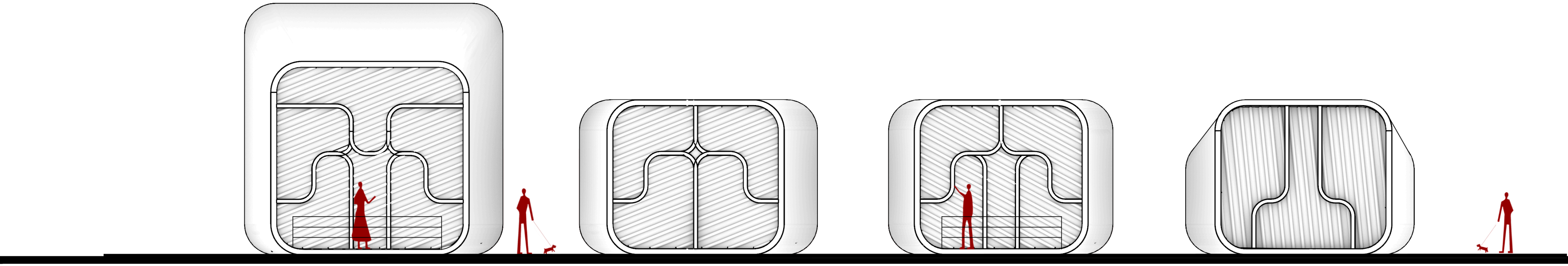




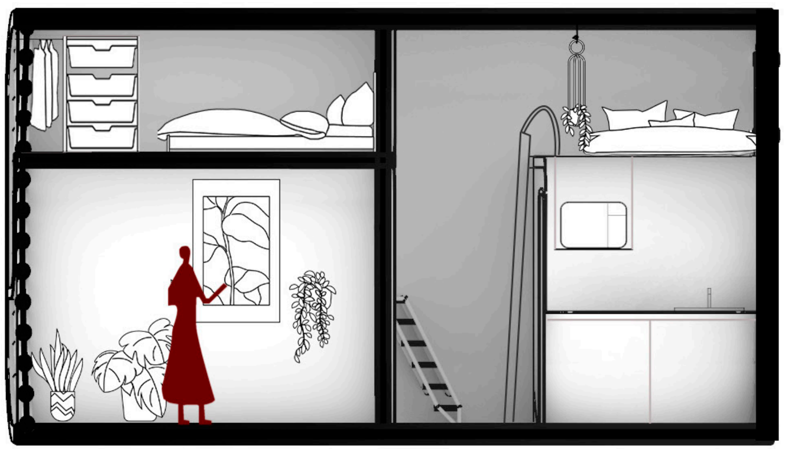
A Pods



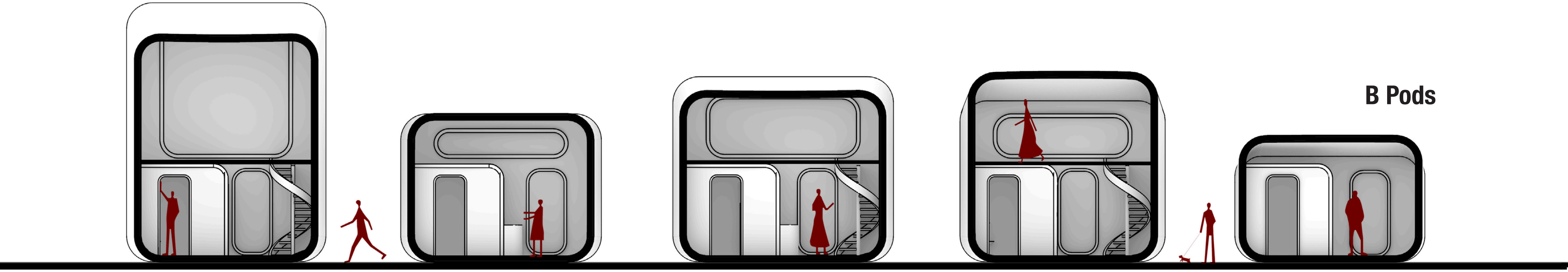


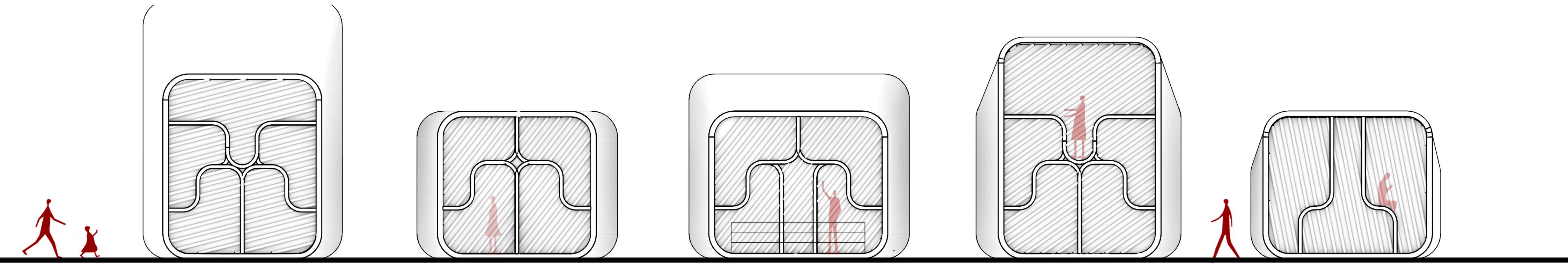


A1	A2	A3	A4
6 people	4 people	4 people	3 people
20 pods	25 pods	17 pods	1 pods
120 people	100 people	68 people	3 people

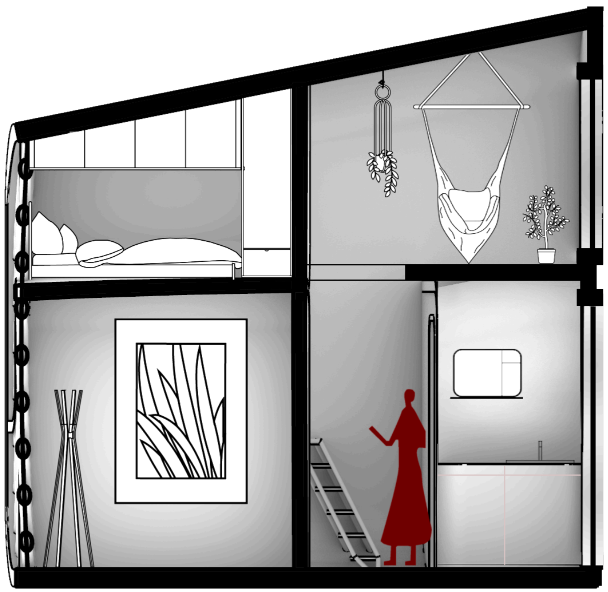


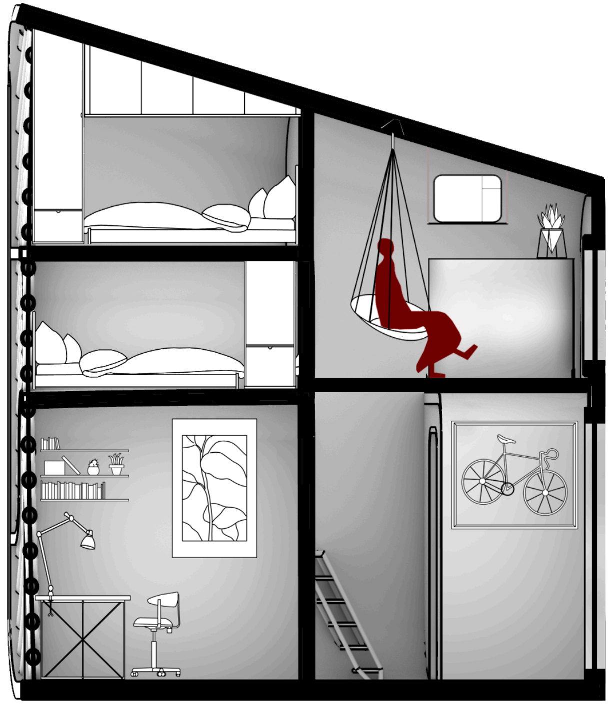
B Pods





B1	B2	B3	B4	B5
6 people	4 people	4 people	6 people	3 people
2 pods	4 pods	4 pods	13 pods	1 pods
12 people	16 people	16 people	78 people	3 people

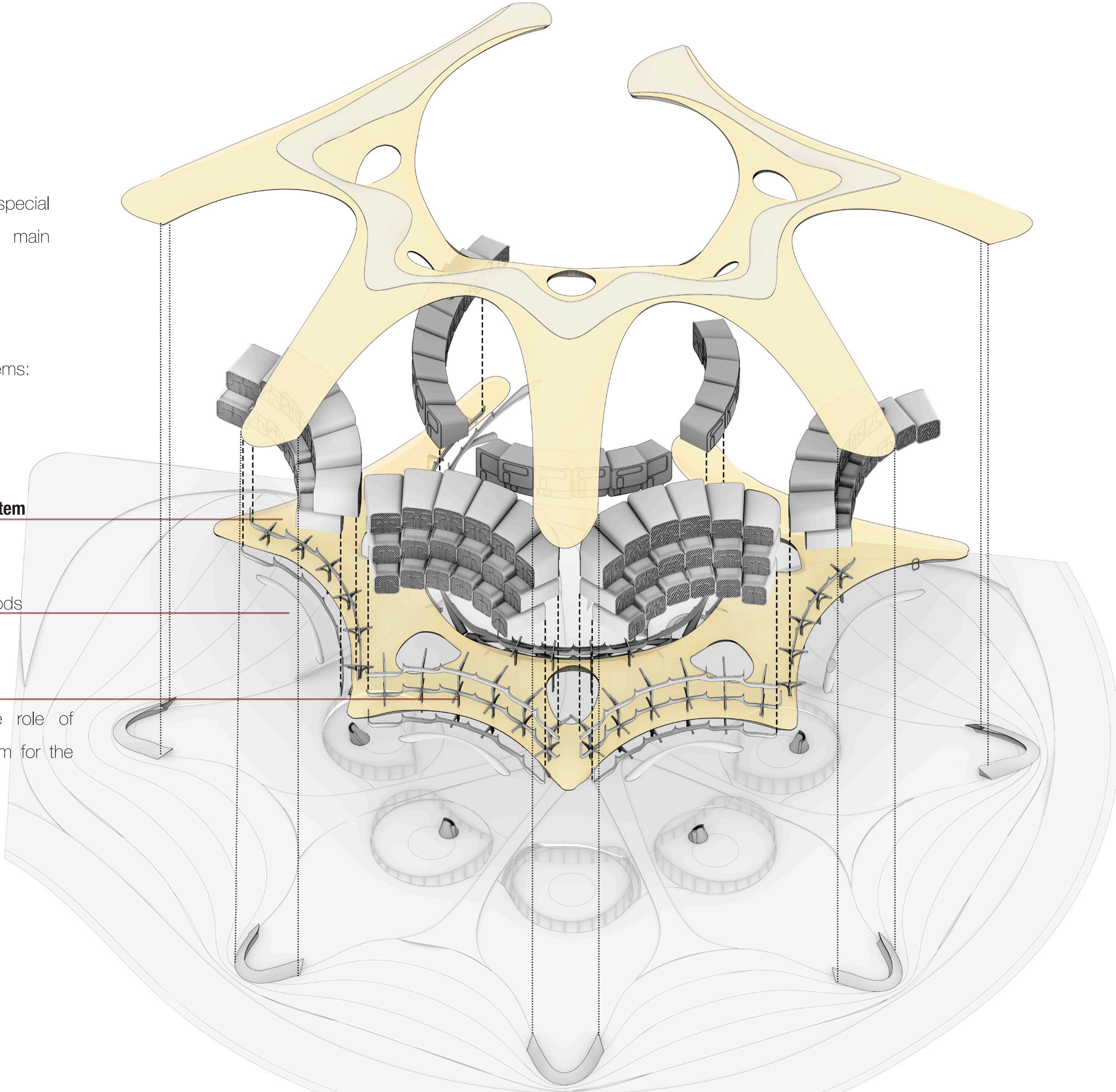




Structure

The sleeping pods have a special structure, detached from the main canopy.

They are supported by three systems:



Distributed load by stacking up system

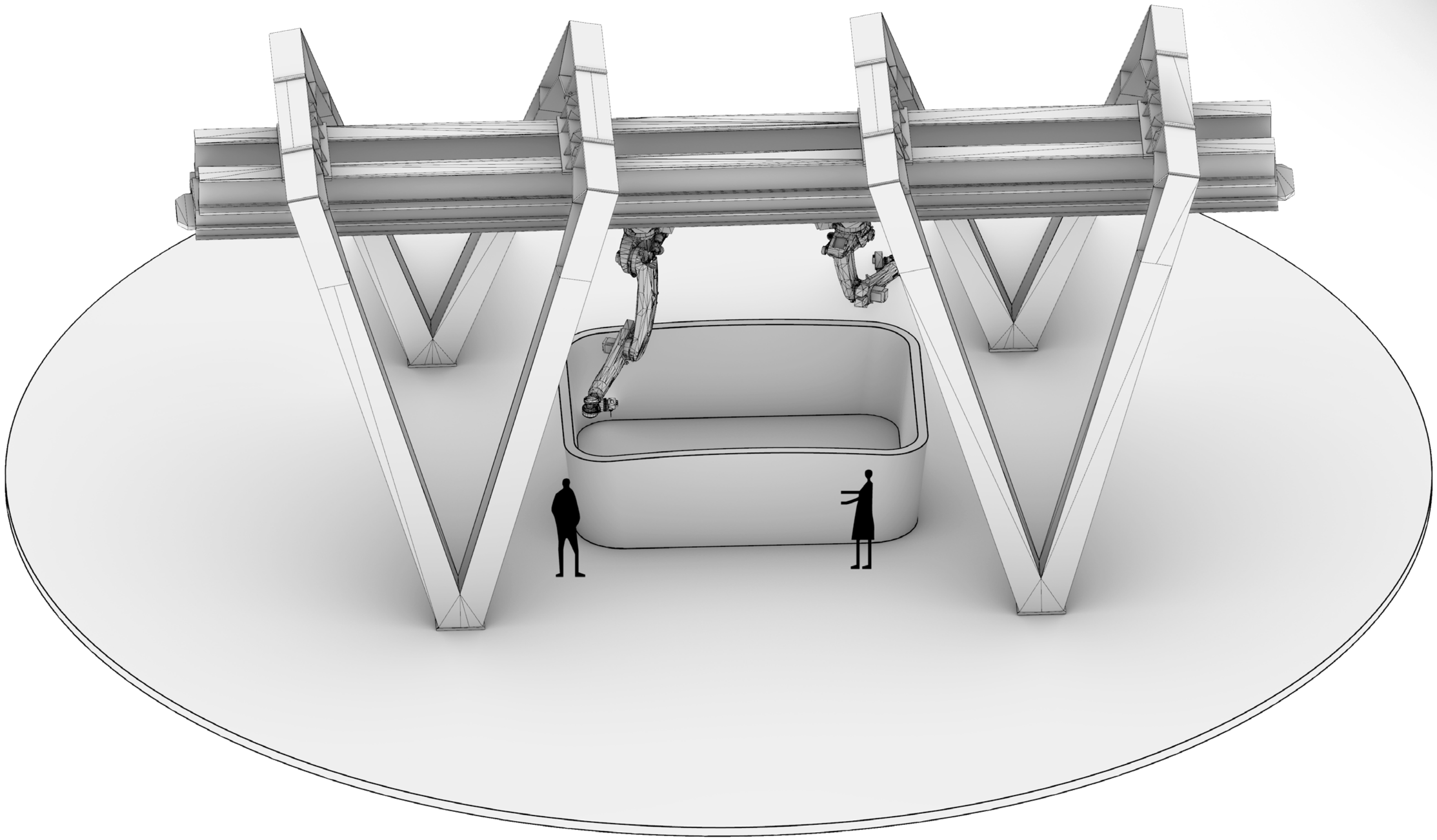
Arch-shaped structures - level 0 pods

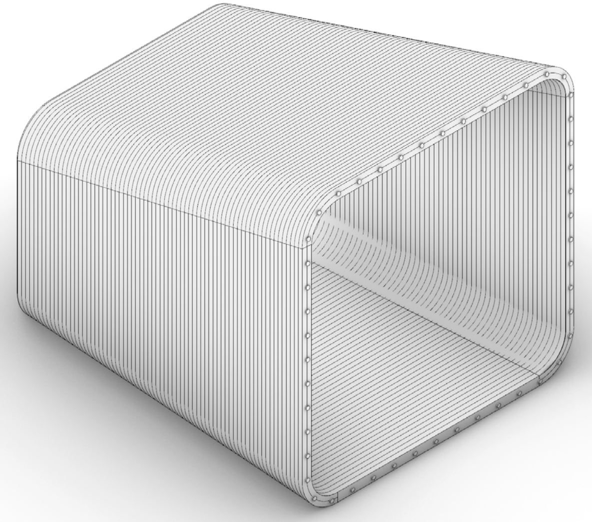
Crossarm-brace pillars

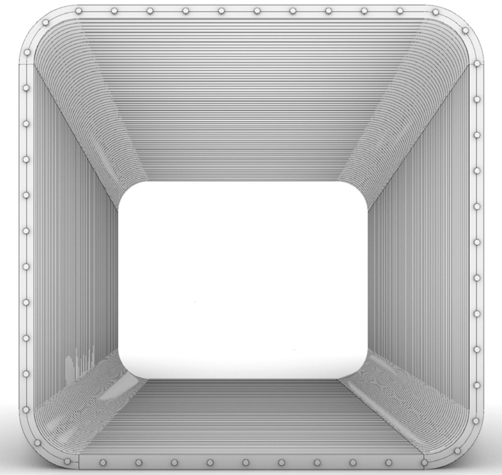
This last one make a double role of supporting both the curved beam for the sleeping pods and the staircase.

Fabrication

The pods were thought to be structured with a metallic frame covered by a fiber reinforced polymer 3d printed by a wide range robot. There materials assures the lightness and stiffness needed for these elements.

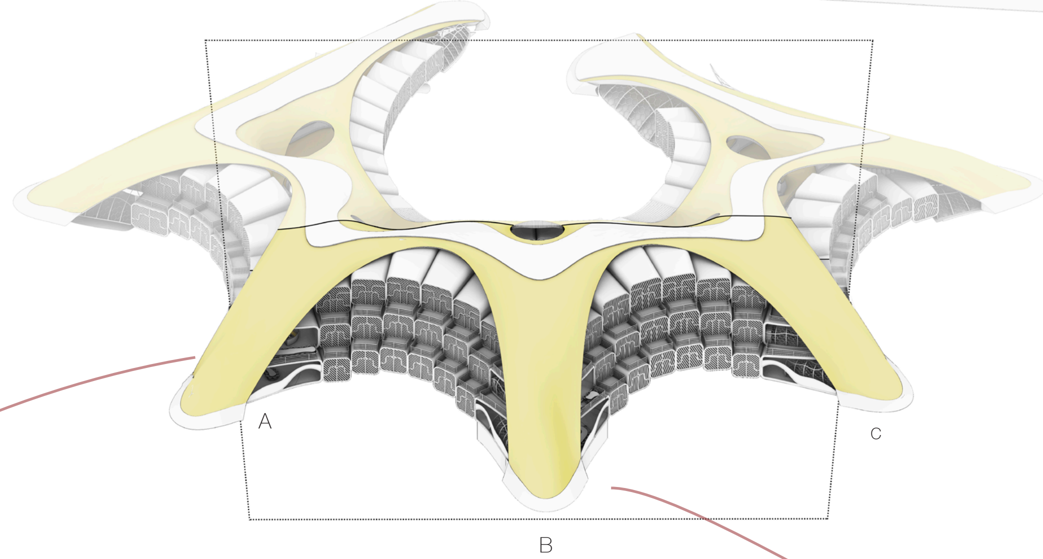


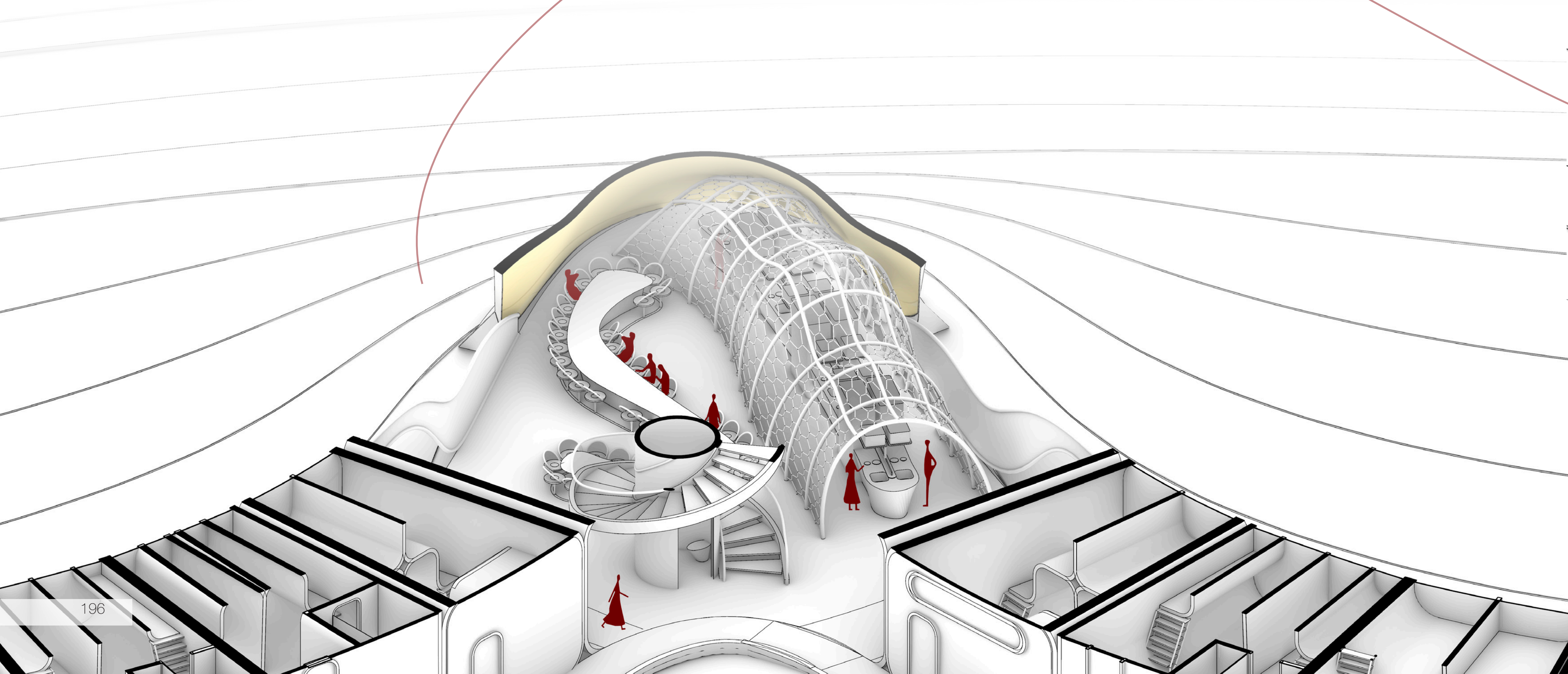


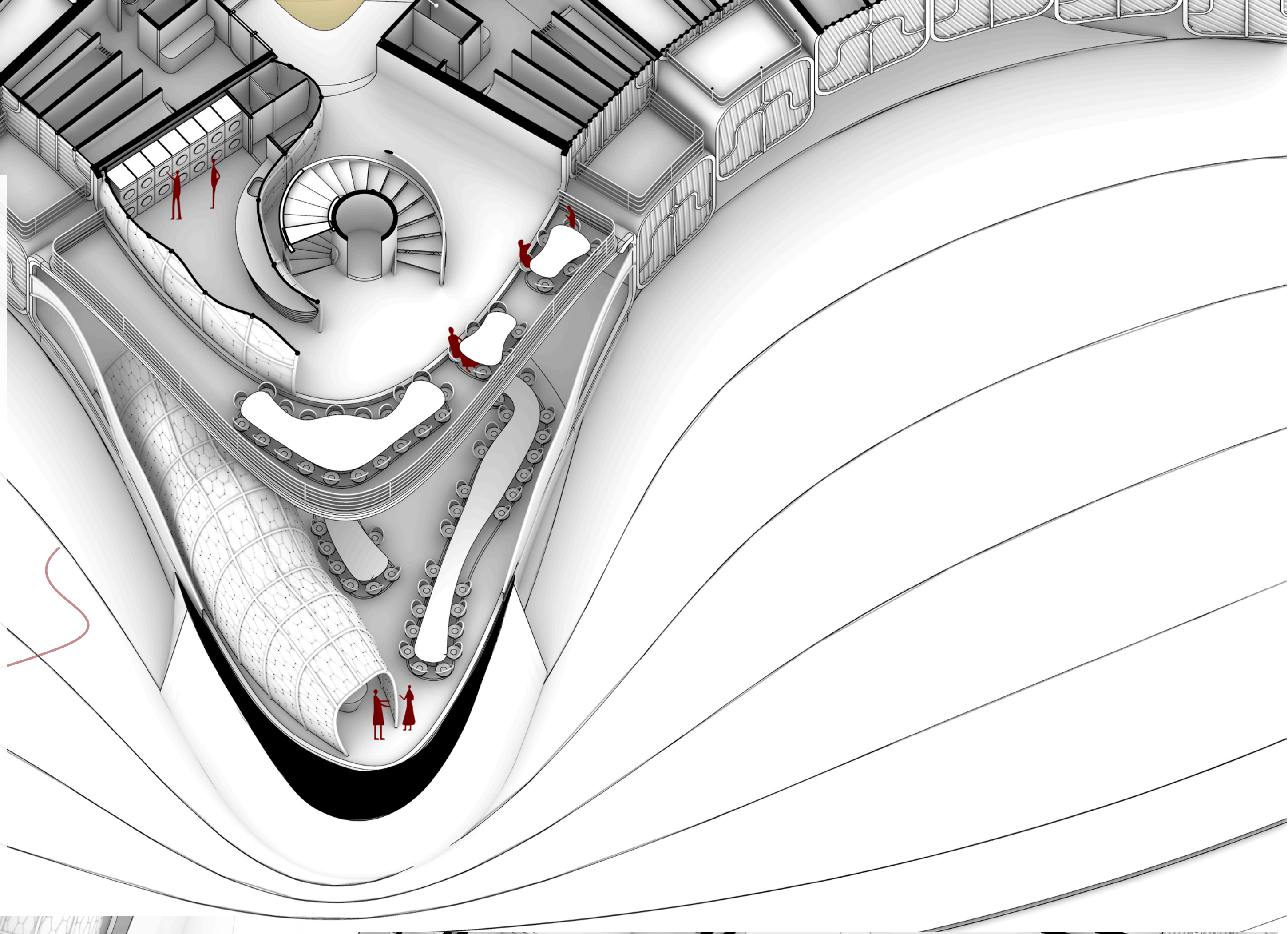


12. Shared Spaces **Nodes**

There are three main nodes in the project. They play a crucial role in the articulation of the flows by hosting essential functions of the project, as Shared kitchens, Laundry area as well as the vertical circulation.
Regarding the vertical circulation, there are proposed one in each node, with the node "B" having a lift





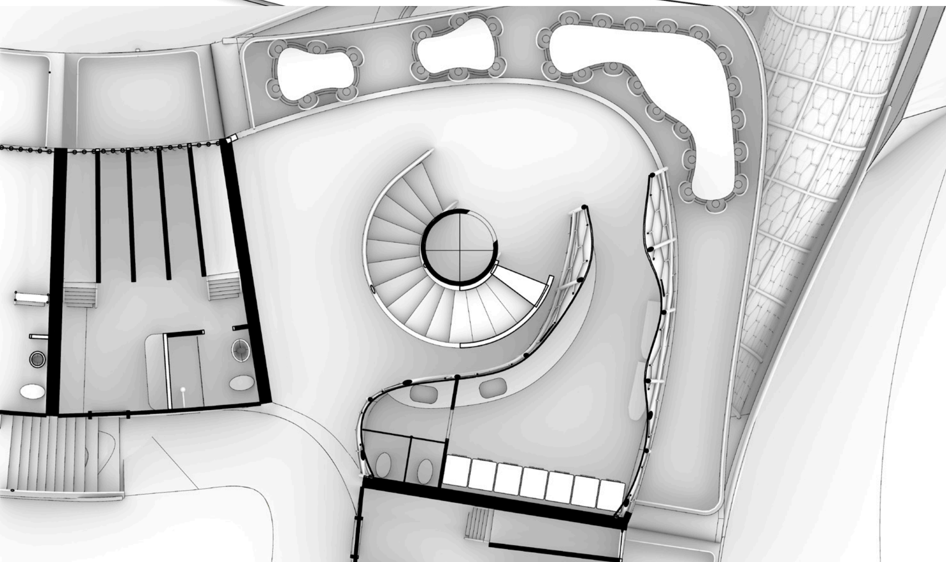


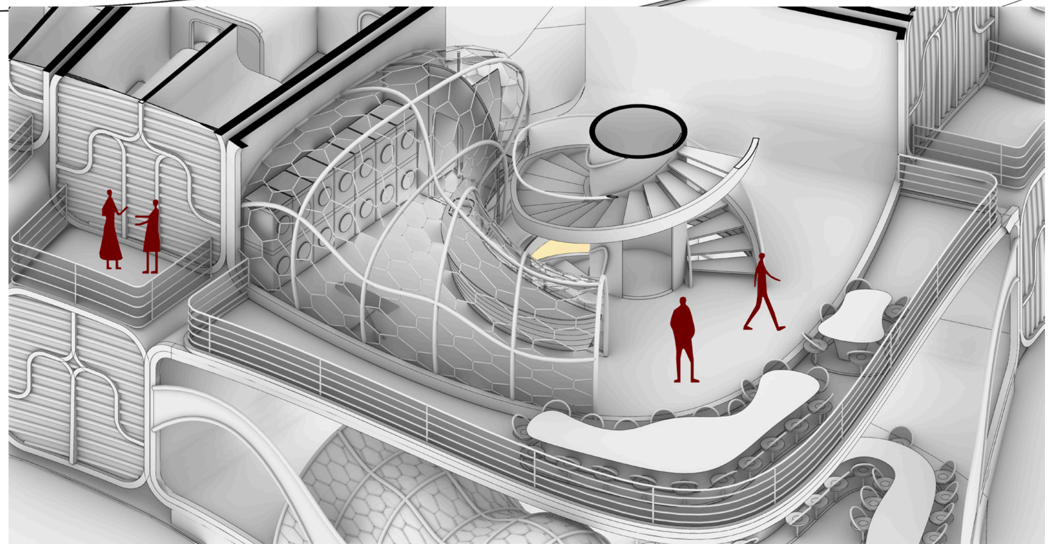
Laundry

They are located in two of the three nodes, the B and C. There is a number of one machine for each 20 people. This area is also designated to storage and support for the maintenance of the shared areas.

Parameterization of the space

All soft spaces were created from the same logical sequence - definition. In such algorithms, two initial curves were given and from them were manipulated parameters such as number of divisions the height of points, as well as the degree of correlation between such points. By such points new curves were interpolated, and by such curves were generated the surfaces.



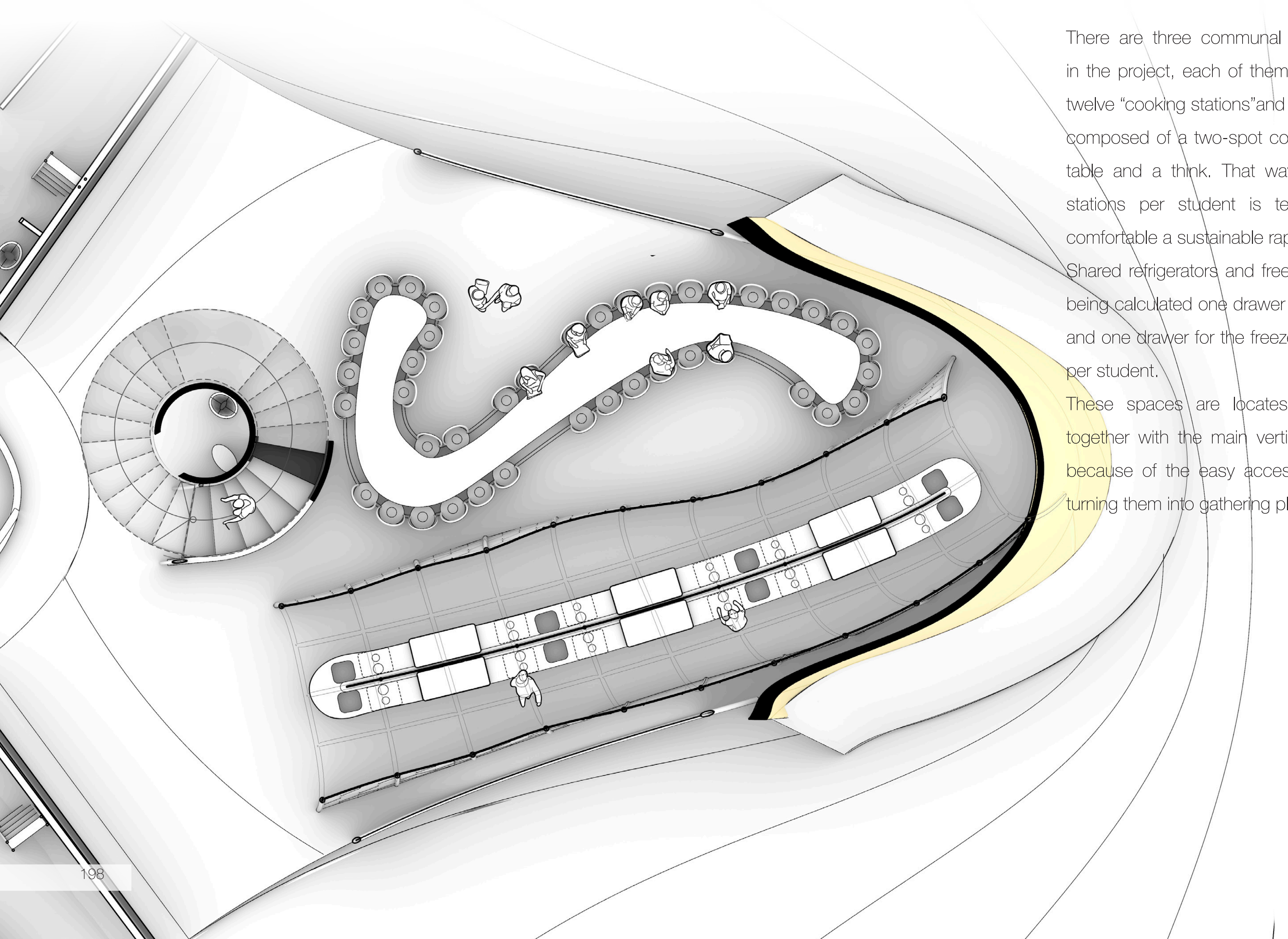


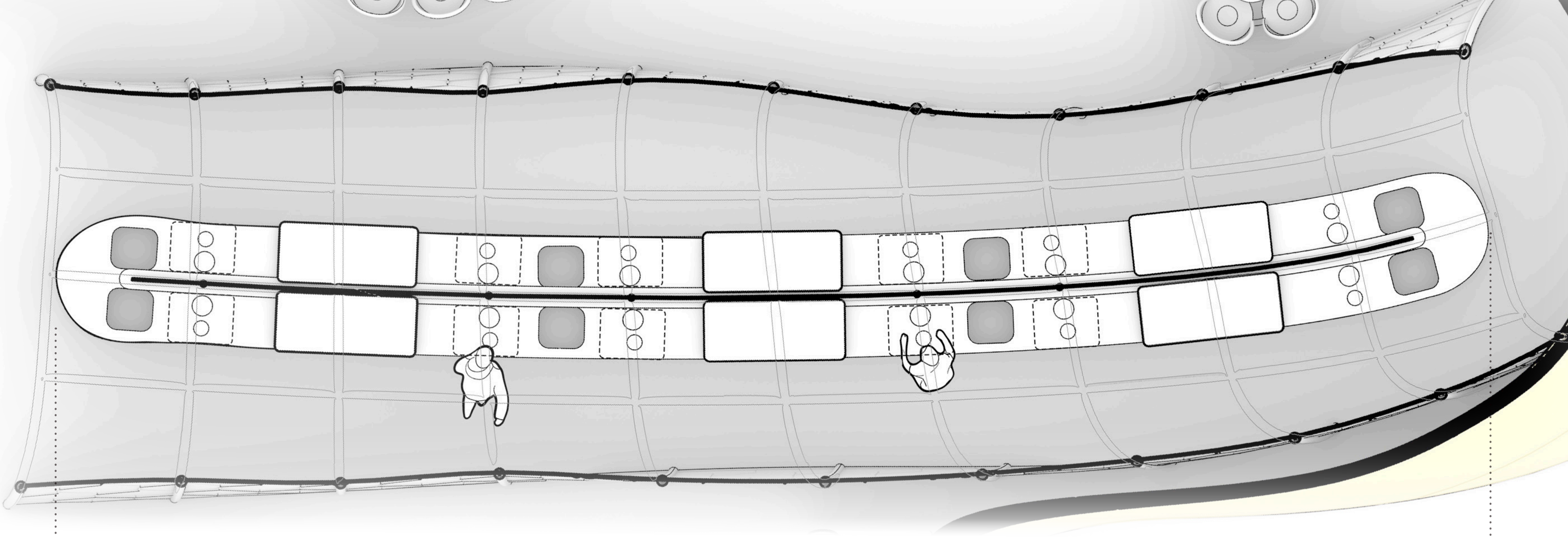
Kitchens

There are three communal kitchens planned in the project, each of them is equipped with twelve "cooking stations"and these stations are composed of a two-spot cook-top, a working table and a think. That way, the number of stations per student is ten, considered a comfortable a sustainable rapport.

Shared refrigerators and freezers are planned, being calculated one drawer for the refrigerator and one drawer for the freezer (50cm x 25cm) per student.

These spaces are locates in the corners, together with the main vertical flows. That is because of the easy access of such areas, turning them into gathering places.

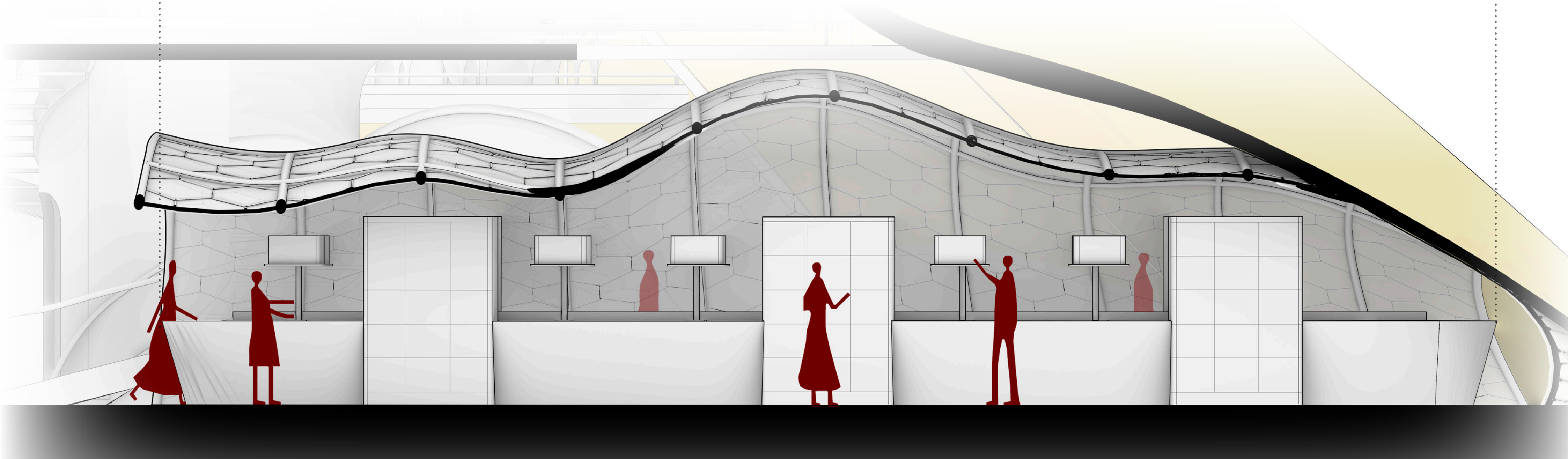




Floor Plan - Shared Kitchens

0 1 2 3

Elevation View - Shared Kitchens

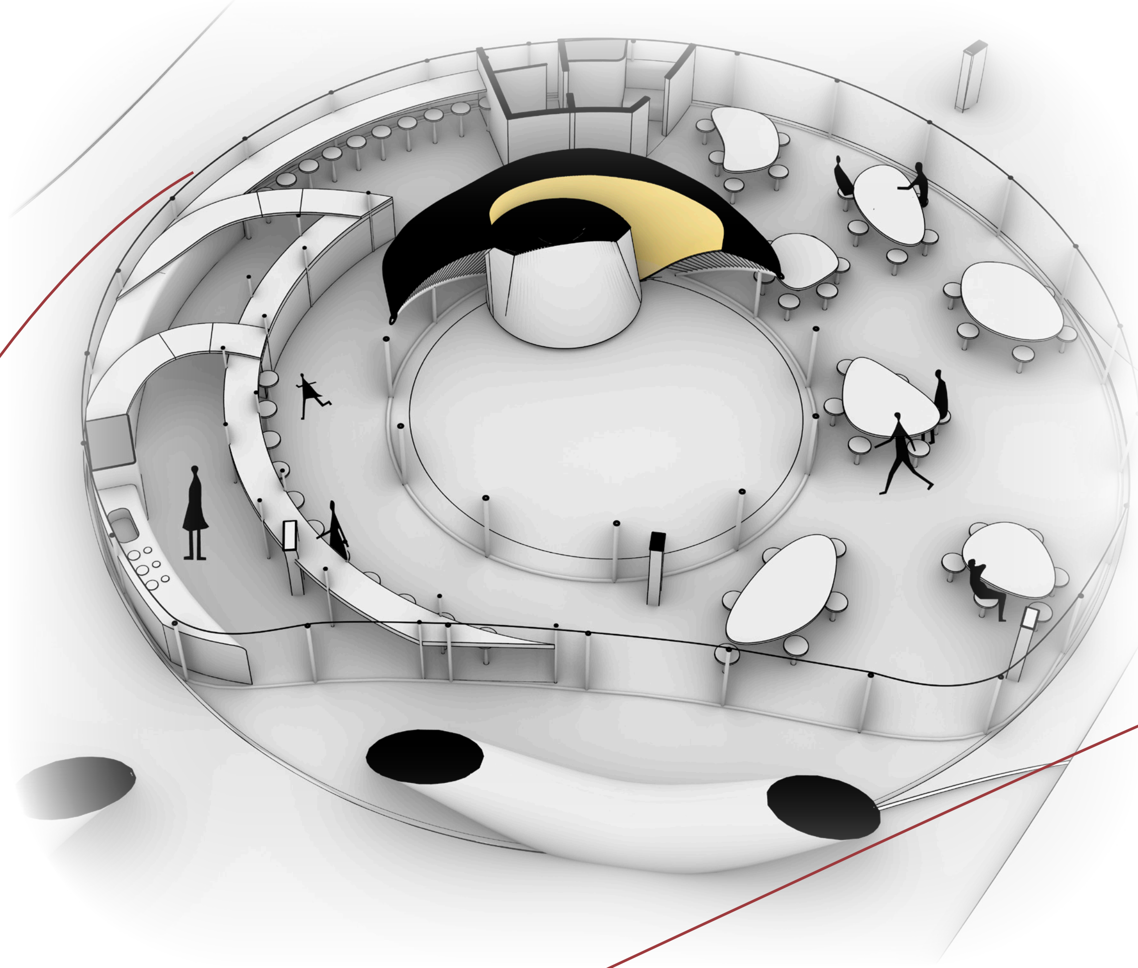


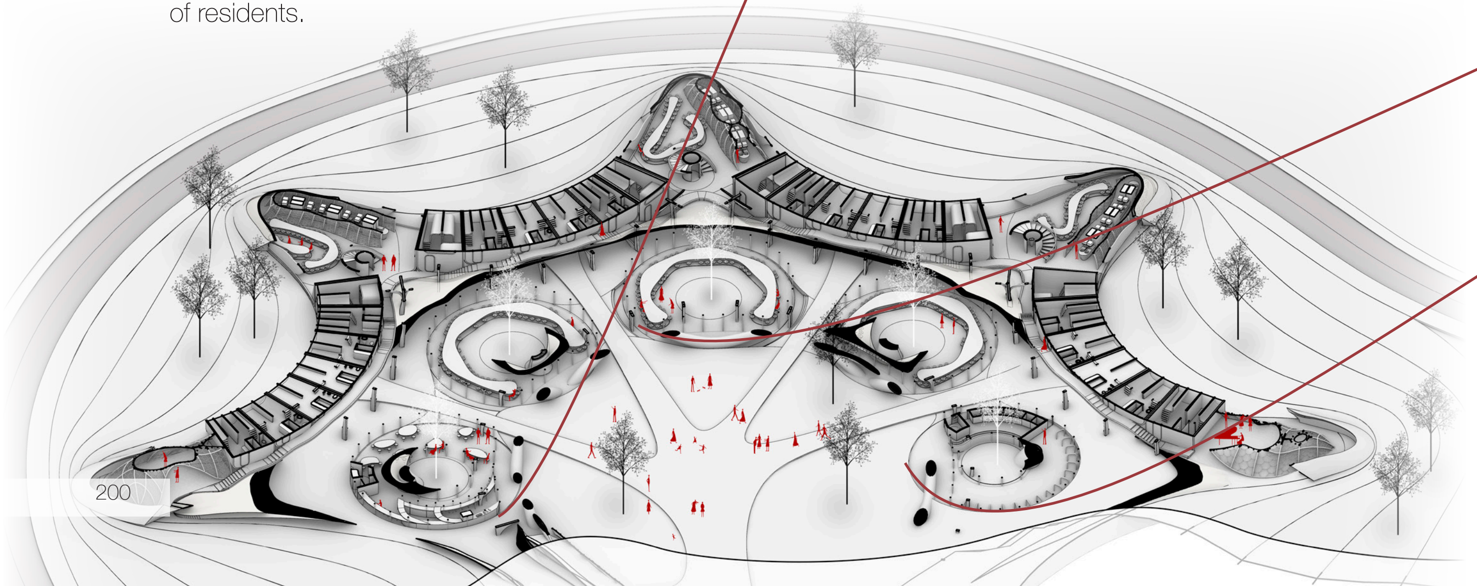
Public spaces

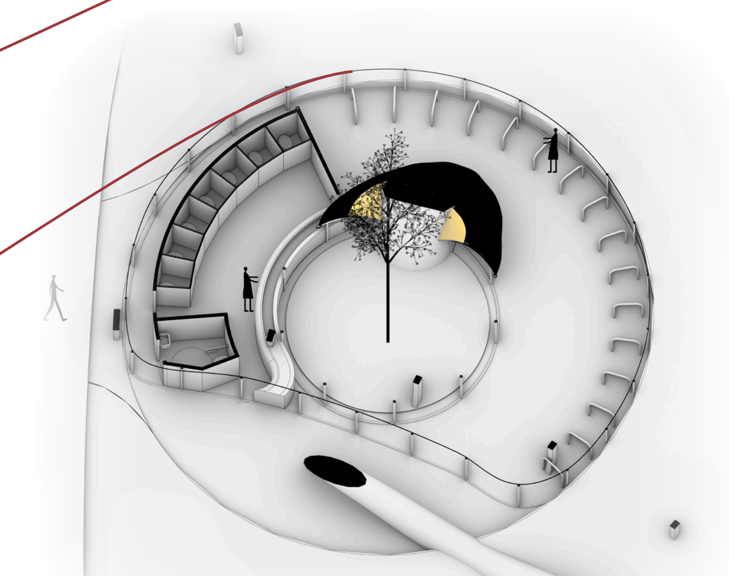
Pilotis

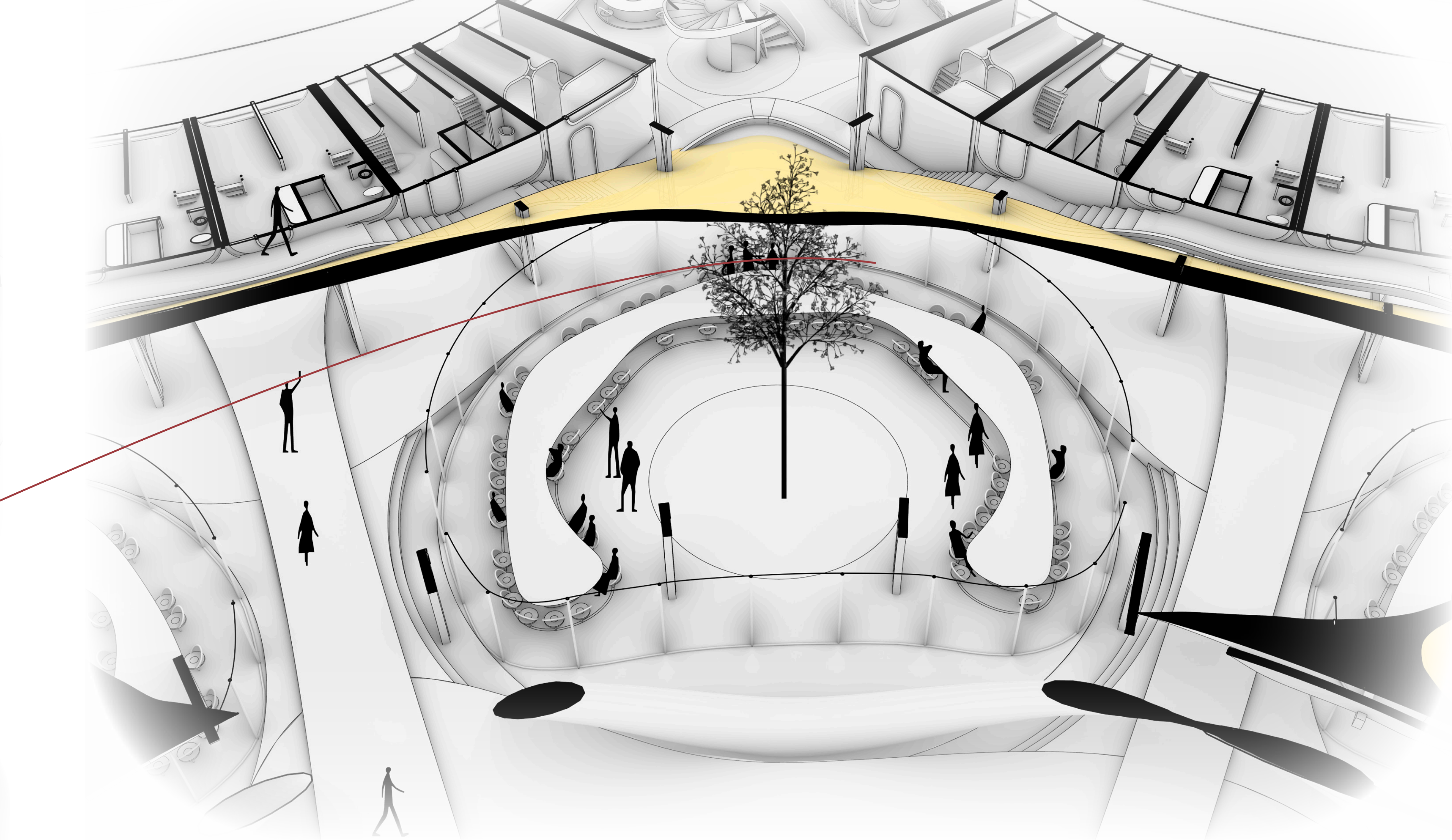
The programme has public spaces for the entire academic community to benefit from the facilities. In addition, bringing outsiders into the area will benefit the inhabitants themselves by increasing the social density of the area. The Pilotis of the buildings, as in all Brasilia, are public, and in these spaces were foreseen spaces for shared study, aiming at undergraduate students of the university itself. In this area, there is also a cafeteria to support all residents and visitors, as well as toilets.

The only private part of the area is the bicycle rack, which is for the exclusive use of residents.









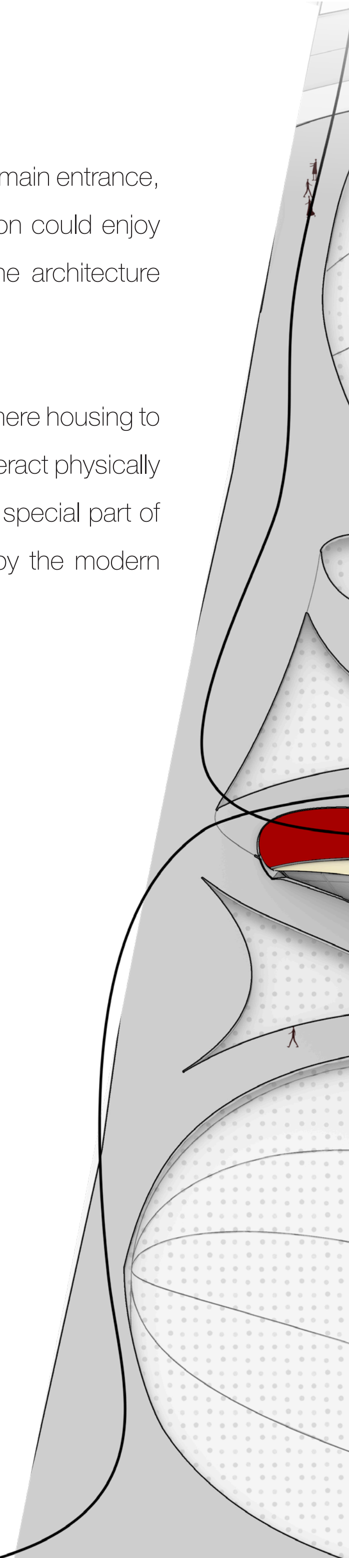
Public spaces

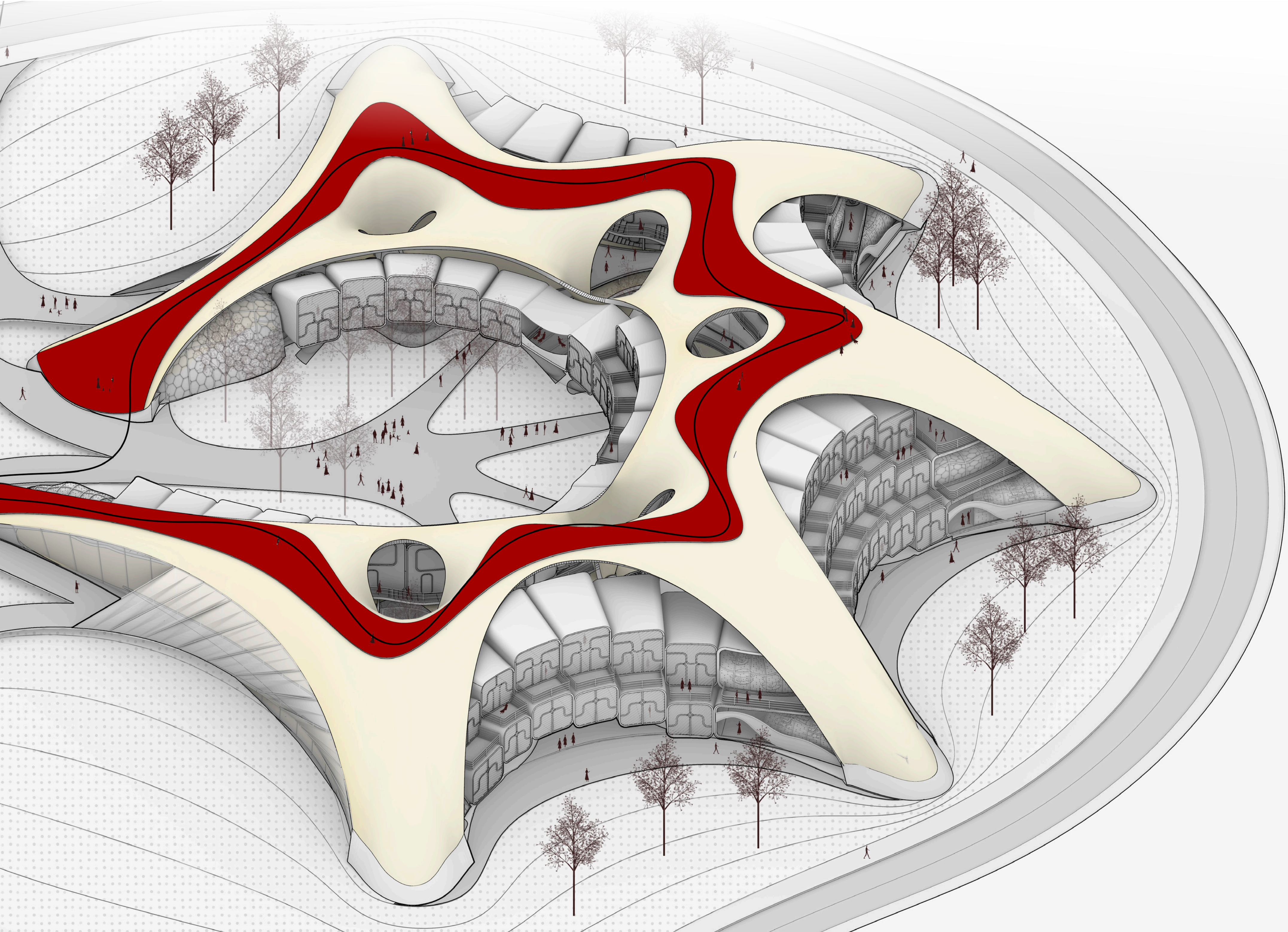
Vaulted Promenade

Due to the gentle curvature of the Top Shell from the main entrance, it was created a path on which the whole population could enjoy the experience of walking on it, interacting with the architecture while delighting the view and the cool breeze

.

This experience shifts the building character from a mere housing to an entire tactile experience. This way, people can interact physically with the architect's intention, turning this area into a special part of the city, driving away from the austerity imposed by the modern architecture predominant in Brasilia.





Conclusion

Having a holistic view of architecture is imperative in the XXI century. Digital tools can combine different fields of knowledge, generating buildings with better structural, social and bioclimatic performance. They also empower architects with a broader view of the whole conception of the project.

The model shifted from a tool for representation to a mechanism of generation. With the model, it is possible to visualize the building's performance instantaneously, generating a pool of the possibilities from which the designers should rely on their choices. Such tools are now numerically proving what pre-digital architects had empirically done by interpreting the constraints imposed by nature.

Although it may seem to be the golden answer for all architectural problems, it comes with some constraints. For optimal use, the architect should acquire a whole new range of expertise and also work with a cohesive interdisciplinary group.

To sum up, in terms of sustainability, it is necessary to shift the use of parametric architecture for optimal performances, linking together different areas, propitiating an environment of shared knowledge.

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