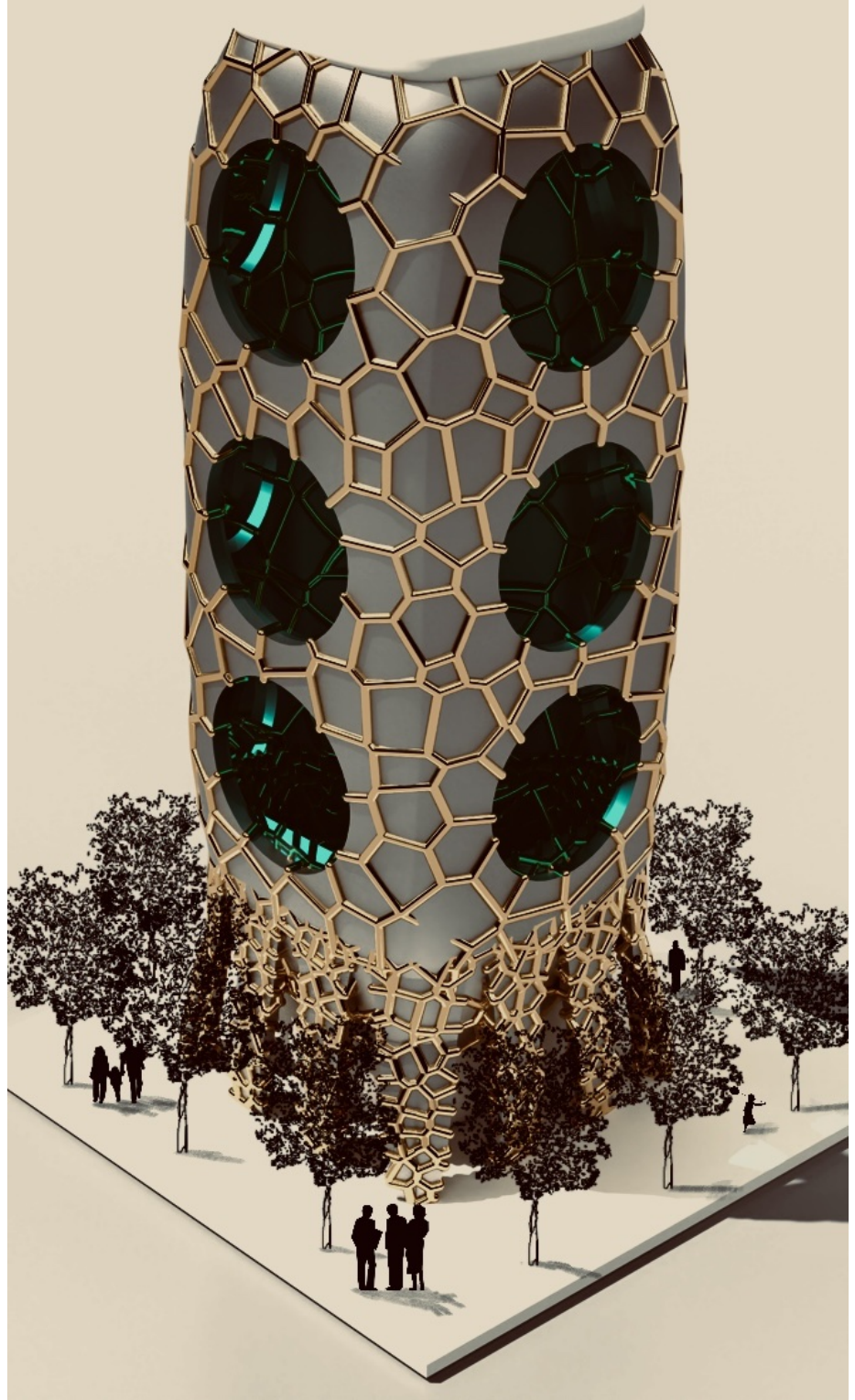


THE_USE_OF_3D_PRINTING_AND_LATTICE_BASED_STRUCTURES_IN_ARCHITECTURAL_DESIGN_

Razvan Ruxanda | Miami University
2023-2025



THE USE OF 3D PRINTING AND LATTICE BASED STRUCTURES IN ARCHITECTURAL DESIGN

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Spring 2025

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A Study on the Application of Additive Manufactured Lattice Structures in Architectural Design

By: Razvan Ruxanda

Miami University, Spring 24

Thesis Statement

Using additive manufacturing to generate lattice-based structures in the implementation of architectural design and construction.

Hypothesis Introduction

Architectural design can use this method of fabricating materials to create optimal lattice-structure that could produce an array of slender members resembling efficient, lightweight, macroscale structures found in framed buildings.

Relevance and Thesis Argument

The aim of this thesis is to investigate/explore the form generation through the print path creation achievable by additive manufacturing. So rather than having the form dictated by traditional building methods, let the printing process dictate the form. In this way, the architectural form is all parametrically generated, which is a function of the print path, not of the initial form.

Current additive manufacturing technologies can assemble lattice structures with length scales ranging from tens of centimeters or larger. In the paper written by Mark Messner "Optimal Lattice-Structured Materials," lattice materials have shown to have excellent stiffness/strength-to-weight scaling,

outperforming natural materials. However, there are currently no methods for producing optimal structures that consider the full space of possible 3D lattice.

In the paper written by Messner, methods for optimizing lattice-structured materials', mesostructure, which is a structure or superstructure of intermediate size or complexity, is described. The materials consist of arrays of slender members, similar to bridges and frame buildings in terms of their efficiency and lightweight.

The design principles of efficient, lightweight macroscale structures, used in applications such as buildings and bridges, are applied to mesoscale material construction. Considering their excellent strength-to-weight scaling and stiffness, lattice-structured materials can be used for lightweight structural applications. Three main points are noted as reasoning for the use of this construction methodology.

[1]. Additive manufacturing technologies can now assemble lattice structures on small scales to much larger scales.

[2] Commercially available technologies can assemble metal lattices with length scales on the order of millimeters all the way up to feet.

[3]. On these scales it becomes reasonable to treat the structures as effective materials with an architectural lattice which can be of intermediate size or complexity.

The role of homogenized modeling in lattice materials is to capture the macroscale, effective response while neglecting the fine details of the mesostructure deformation. In terms of macroscale material design, designed lattice structures are excellent frameworks. Additive manufacturing processes offers a designer control over the printed material mesostructure, which in turn controls the effective material response.

There also is a research paper written from various research institutions in China which studies various truss-lattice cell structures for various applications in additive manufacturing. The paper is called Architecture design of periodic truss-lattice cells for additive manufacturing. In this paper, the authors investigate a novel design strategy of various truss-lattice cell structures which propose different lattice unit cell configurations, including triangular prism (T), quadrangular prism (Q) and hexagonal prism (H). They do this by considering the tight spatial arrangement that pertains to each shape and manufacturing constraints. According to their findings, additive manufacturing can be used to fabricate complex components with multiple scale three-dimensional lattice cells, which have superior mechanical and physical properties. This also ties into looking at how the printing process can exhibit characteristics which decrease the material usage and the carbon footprint, while increasing the surface area efficiency.

What is additive manufacturing?

In order to understand additive manufacturing, let us first define it. Additive manufacturing is a process of creating 3D objects by adding layers of material on top of each other. It is also known as 3D printing and has become increasingly popular in recent years due to its ability to produce complex parts quickly and accurately. Additive manufacturing is also cost-effective, as it eliminates the need for costly tooling and production costs. It is also a more sustainable process, as it produces less waste than traditional manufacturing methods.

This method of production has not been around for many years as other methods of production such as traditional metal casting. The first cast

was done around 3200 BCE of a copper frog. (Olsen 2020) Now let's look at some of the key moments in additive manufacturing. Wyn Kelly Swainson patented the process of fusing solid plastic on top of liquid plastic in 1997 by directing a laser onto a tray submerged in liquid plastic. Stereolithography was patented in 1986 by Chuck Hull, which is a 3D printing technique that uses a laser to fuse small particles of plastic, metal, glass, or ceramic powder together. The first organic bladder was 3-D printed in 1999. This was the first 3-D printing of organic material. French artist Patrick Jouin created the first functional furniture using 3-D printing in 2005. Moreover, in 2015, Europe built the first printed house using additive manufacturing. (Linke 2017) All of this to say that traditional casting and forging methodologies have been around a lot longer than any method of additive manufacturing.

The next process is to understand how one goes from design development to production. To create an object using additive manufacturing, someone must first create a design using computer aided design, or CAD, or take a scan of the object someone wants to print. That design is then imported into the 3-D printers software, where it is analyzed for printing defects or any other support material that may be needed while printing. The 3-D printer then begins creating the object immediately. It can take anywhere from a few hours to a few days to complete this process. Printing depends on the medium, the shape complexity, and any additional prints that may be needed while the main piece is being printed.

There are issues with this kind of manufacturing as any new method of production is still being perfected and simplified. Additive manufacturing is more expensive and takes longer to create large lot sizes. One of the biggest challenges is making sure that the final part has good properties, such as reducing the number of defects that could form.

Although there are some setbacks to this process and large scale implementations have not been fully realized. There are some distinct benefits to additive manufacturing which cannot be found in other manufacturing processes. A number of benefits will be realized, such as removing

intermediate steps from the supply chain and obtaining a single part much more quickly.

By manufacturing something additively, you can also make objects with functionally-graded materials, meaning different materials can be used inside and outside the object.

"Imagine you want something that has high conductivity, but also is abrasion resistant. On the outside, you have the abrasion-resistant materials, like ceramics, and on the inside, you have the conductive materials, like metals. Creating something like that is quite difficult to do with conventional manufacturing. With additive manufacturing, you produce — layer by layer — pretty much any geometry you want to create. You can create 3-D entities that are much more complex and have different material properties."

-Thomas Roemer, senior lecturer in operations management at MIT Sloan

Roemer also believes that the two biggest advantages to additive manufacturing are creating complex geometries and producing small lot sizes. A subtractive manufacturing method is also available. In this process, layer upon layer of material is removed until the desired outcome is achieved. There are some setbacks to this kind of process. Objects with awkward angles or too small dimensions can be difficult to subtract materials with subtractive manufacturing. This barrier is eliminated by additive manufacturing. In addition, this means that manufacturers can make an object lighter by eliminating weight. A final product's functionality can be affected by its weight, which is especially important in the aerospace and automobile industries.

Typically, additive manufacturing produces 3-D objects with a fixed geometry. In 4D printing, 3-D objects can be created that can change or transform over time, without requiring the intervention of a human. 4-D printing has a variety of applications. One area in which self-configuring materials would be useful is extreme environments, such as space. Biomaterials are another example. As cost decreases and the manufacturing process accelerates, additive manufacturing will be used for a broader range of applications - some companies are already using additive

manufacturing to manufacture everything from houses to food.

Despite all the advantages of additive manufacturing, traditional manufacturing is still currently faster and less expensive. There is also a case for a hybrid model of manufacturing, where additive manufacturing would be used initially, but traditional manufacturing would take over once lot sizes increased.

Previous Structural Innovations

To better understand how different structures can be implemented in the manufacturing process, let's examine previous structural innovations in the field of architecture.

A notable example of this kind of structure is the Geodesic Dome designed by Buckminster Fuller. To demonstrate the difference in strength between a rectangle and a triangle, Buckminster Fuller would apply pressure to both structures. In contrast to the rectangle, which would fold up and become unstable, the triangle can withstand the pressure and is much more rigid - in fact, the triangle is twice as strong as the rectangle. By applying this principle, Fuller was able to create a new architectural design, the geodesic dome, which was based also upon his principle of "doing more with less." Fuller discovered that a spherical structure created from triangles would be extraordinarily strong.

By using the "doing more with less" principle, the sphere encloses the greatest volume of interior space with the least amount of surface area, thus reducing materials consumption and costs. According to Fuller, when the sphere's diameter is doubled, its square footage is quadrupled and the volume is increased eightfold.

An important project which would push Fuller to patent the term design of the Octet Truss in 1961, is a key component in understanding the structural and functional properties of space filling shapes.

That project, which launched in 1951 and was to be completed a year later, was to produce a geodesic cotton-mill for the North Carolina State College. One of the challenges in designing the cotton-mill was the development of a flooring-structure capable of supporting 200

pounds per square foot. This is important because the development of what Fuller would call the Octet Truss would be developed. This truss was made by the use of grids consisting of combinations of octahedra and tetrahedra.⁷

When grids made up of the Octet Truss units were stacked on top of one another, they produced the space-filling "Isotropic Vector Matrix".

"Being a geometry of equal vectors and equal 60° angles, it is possible to extend this equilibrium array infinitely outward from the center point of the VE, producing what is called the Isotropic Vector Matrix (IVM). Isotropic means "all the same", Vector means "line of energy", and Matrix means "a pattern of lines of energy".⁸

As a result of this assembly of isotropic vector matrices, its triangular nature was inherently resistant to compression. In 1953, Fuller tested an Octet Truss made from 170 aluminum struts at the University of Michigan. The entire frame only weighed 65 pounds, but it could support a total weight of 6 tons.⁷

Another important figure to look at is Felix Candela and his Hyperbolic Paraboloid designs. There are two types of shells according to Candela: the proper shell avoids bending stresses and is doubly curved. This shape can be described as having a saddle curve. This curve can be better described as a set of arches following one directional path with another set of cables or inverted arches in the other, perpendicular, direction. And the improper shell, which carries the load through some bending action upon the material used.

In a shell structure, the thickness is generally much smaller than the width and length. It is important to avoid bending stresses since they can cause ruptures or buckling. To reduce or eliminate bending, it is necessary to give the material a curvature, so that it is shaped like a shell. If properly designed, the structure can span much greater distances and the bending is minimized or eliminated. By using membrane stresses to carry the load, a proper shell ensures that the stress, in tension or compression, is distributed evenly throughout the thickness of the material. Stress equals a force acting on an area.⁶

For shell structures to distribute their own weight adequately, they must be designed with the proper shape, thickness, and material. There is a possibility that in some parts of the shell, high concentrations of forces can be caused by incorrect geometry. The concentration of these elements can cause the material to crack or even collapse completely. In contrast, a properly designed shell is able to distribute forces evenly due to its correct geometry. Whenever there are unavoidable high concentrations of forces (such as when a structure is fixed to the foundation), a structure should be thickened to minimize the stress on the structure.⁶

"Of all the shapes we can give to the shell, the easiest and most practical to build is the hyperbolic paraboloid." -Candela, "The Hyperbolic paraboloid," 226

A hyperbolic paraboloid (also called a hypar) has the additional property of being defined by straight lines. The boundaries, or edges, of the hyperbolic paraboloid can be straight or curved. Developing the edges of the hypar involves planes that "cut through" the surface. In order to create his designs, Candela used both straight and curved edges. A straight-edged hypar in the umbrella structure was used to create one quadrant (called a tympanum). The roof of El Altillio Chapel is composed of this single hypar, whose construction reflects the straight lines visible in the final structure. By arranging umbrellas in sequence, he was able to create a large roof covering using multiple hypars.⁶

Space Filling Shapes or an Isotropic Vector matrix such as the Octet Truss was revolutionary and marked the beginning of a new era in lightweight and efficient structural design. Fuller's invention is still used today in a variety of fields, from aircraft to architecture. And despite Candela's Hyperbolic paraboloid not being used in mass applications. There are very valuable lessons to be learned from his applications with paraboloidal shapes as compared to pure bending stress, compressive membrane stress and tensile membrane stresses.

Study 1: Optimal Lattice-Structure Materials

As discussed briefly in the introduction, the study done by Messner outlines three main findings.

1. A homogenized model for long-wavelength elastic and failure properties of arbitrary lattice materials.
2. A compact, intrinsically periodic parameterization of lattice structures design space.
3. A method for using the resulting parameters modeled to optimize traditional architecture design.

The model discussed represents;

"long wavelength limit of discrete, microscale lattice dynamics, embedded within the structural design."²

Meaning that the model represented in this study only captures lattice response for slow changes and ignores local deformation patterns. These optimized structures show how optimization methods can use parametric models to find useful structures.

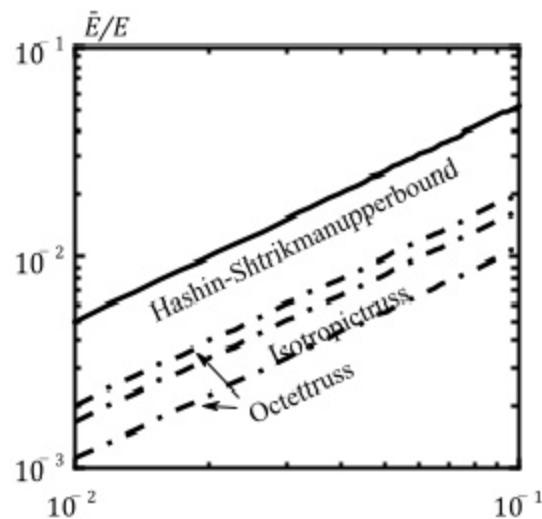


Fig. 1. Stiffness to density scaling

In particular, the optimally stiff isotruss lattice has a superior stiffness-to-density ratio and is elastically uniform, compared to octet trusses. As a result of this structure and many uniform structures, stable lattices can be discussed in terms of how their pattern rotates to conform to some overall design feature. Optimizing designs

with given stiffness and/or strength requirements can also be done using the same method.

Given the specified model, solving a structural optimization problem is logical to determine the optimal lattice structure in each area.

There may be additional constraints required when creating an optimization problem to create buildable lattice materials. Constraints would focus on eliminating structurally sound unit cells with incorrect placements.

It is necessary, for example, to constrain the smoothness of the parameters describing the lattice base unit cell. Otherwise, adjacent cells in the optimized structure could be incompatible - leaving either a gap or an overlap between them.

Once these construction requirements are fulfilled the resulting optimization methods have the potential to control both lattice symmetry and asymmetry in a 3-D environment. As a result, optimal, lightweight, printable lattice structures can be found.

Study 2: Truss-lattice cell structures

There is a research paper written from various research institutions in China which studies various truss-lattice cell structures for various applications in additive manufacturing. The paper is called Architecture design of periodic truss-lattice cells for additive manufacturing. In this paper, the authors look into a novel design strategy of various truss-lattice cell structures which proposes different lattice unit cell configurations, including triangular prism (T), quadrangular prism (Q) and hexagonal prism (H). They do this by considering the tight spatial arrangement that pertains to each shape and manufacturing constraints.

According to their findings, additive manufacturing can be used to fabricate complex components with multiple scale three-dimensional lattice cells, which have superior mechanical and physical properties.

Truss-lattices are composed of rigid joints and uniform or variable cross-section struts. The spatial configuration of truss-lattices can be easily designed and implanted into the

larger-scale and hierarchical components, and several configurations have been proposed according to the crystal structure. Recently, a topological optimization or a study of how spaces are organized and how they are structured in terms of position, method combined with additive manufacturing technology has been adopted to improve the comprehensive performance and macrostructure of the unit cell. The favorable periodic cell configuration should satisfy the requirements of dense arrangement of space and the struts should be entirely continuous. The mechanical properties of 2D and 3D lattice structures with circular nodal fillets can be improved by varying the number of nodes, and the influence of disorder degree on the fracture behavior of disordered lattice materials has also been studied.¹

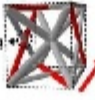
Geometry	1	2	3	4
Triangular prism	 $Z_1=6, Z_2=12$ $\bar{Z}_1^0 = 11.14$	 $Z_1=6, Z_2=14$ $\bar{Z}_2^0 = 12.86$	 $Z_1=6, Z_2=20$ $\bar{Z}_3^0 = 15.00$	 $Z_1=6, Z_2=26, Z_3=4$ $\bar{Z}_4^0 = 17.40$
Quadrangular prism	 $Z_1=8, Z_2=8$ $\bar{Z}_1^0 = 8.00$	 $Z_1=8, Z_2=10$ $\bar{Z}_2^0 = 9.78$	 $Z_1=8, Z_2=14$ $\bar{Z}_3^0 = 13.53$	 $Z_1=8, Z_2=18, Z_3=4$ $\bar{Z}_4^0 = 12.77$
Hexagonal prism	 $Z_1=12, Z_2=6$ $\bar{Z}_1^0 = 6.45$	 $Z_1=12, Z_2=8$ $\bar{Z}_2^0 = 8.31$	 $Z_1=12, Z_2=10$ $\bar{Z}_3^0 = 10.15$	 $Z_1=12, Z_2=14, Z_3=4$ $\bar{Z}_4^0 = 10.74$
Deformation mode	Under stiff, Bending-dominated		Over stiff, Stretch-dominated	

Fig. 2. Cell generation based on density and deformation.

Their findings also show that additive manufacturing technology has shown great potential for manufacturing complex structures, but inherent manufacturing defects need to be addressed. They address these manufacturing defects by using a combination of real-time X-ray micro-computed tomography (CT) and finite element method (FEM). These methods are utilized to numerically analyze the influence and

severity of defects on the mechanical performance of the lattice structure.¹

They also stated that the optimal orientation of struts in the architecture design of the unit cells should be maintained to guarantee the consistency between desired and actual performances. This, from my understanding has to deal with differing tension or compression stresses applied to the microstructures which in turn will differ based on the orientation of the struts.

A summary of their findings and conclusions are as follows;

The proposed design strategy accounts for manufacturing constraints in the lattice unit cell. Based on FEA (Finite Element Analysis), experimental characterization, and theoretical predictions, the influence of nodes' freedom degree, which can be altered by local struts, on the structure's compressive and energy absorption behavior has been systematically studied. Conclusions can be drawn as follows:

Based on the 3D geometric reconstruction of the CT scan, similar diameter distribution characteristics were found between struts printed in different directions. As a result, the proposed design method ensures that struts with different printing directions in the lattice structure will have similar mechanical properties. The method is useful for predicting structural performance.

With increasing the number of struts in the structure, both uniaxial compression test results and FEA results demonstrated an enhanced compressive modulus and ultimate strength. Energy absorption can be negatively impacted by increased joint connectivity, especially for the crash load efficiency. It should be noted that edge-direction struts are added only to joint connectivity, not load bearing. By increasing the overall joint connectivity, the body-diagonal and face-diagonal struts significantly influenced structural performance.

For unit cells with different configurations, the T series (triangular prisms) showed superior strength and energy absorption. The Q series (quadrangular prisms), on the other hand, exhibited higher relative stiffness.

Experimental results as well as FEA results are significantly different from those predicted theoretically. It can be explained by differences in boundary conditions. Under constrained boundary conditions, the FEA results of a unit cell are similar to those predicted theoretically. Under ideal boundary conditions, theoretical predictions remain valid. Therefore, multilayer lattice structures need to be improved further.

Based on these results I can infer that if designed properly there are multiple configurations of the cellular lattice structure which can perform adequately when exposed to various compression, tension and shear stresses.

Fuller's Design Ideology

The design ideology of Buckminster Fuller stems around Ephemeralization and the use of Synergetic design principles.

Ephemeralization is the ability of technological advancement to do more with less until you can do as much as you can with nothing. Buckminster Fuller created the term in 1938 to express the use of less material for greater results. Fuller developed this philosophy partly in reaction to the philosophy of Thomas Malthus.

Thomas Malthus (1766-1834) who was a English economist and demographer published the first edition of *An Essay on the Principle of Population* in 1798. His theory was that a increase in population will naturally happen. According to him this population growth will happen on a geometric progression scale. Thus each increase in population will multiply each previous amount by a fixed number. As opposed to other resources, these will increase only on an arithmetic scale. Therefore, believing that the population will always expand to the limit of substance.

However, Fuller disagreed and felt that technology, improved design, and engineering would help to allow humanity to use the existing resources more efficiently causing greater output with decreased input.

His goal was;

"more and more with less and less until eventually you can do everything with nothing."

He looked at Henry Ford's assembly line as an example of ephemeralization where efficient design was used to increase productivity. Generally, technology increases ephemeralization.

One such example is computing power and efficiency based on Moore's Law, named after Intel founder Gordon E. Moore, which refers to the number of transistors on an integrated circuit doubling every two years.¹¹ As a result, computers that used to take up entire rooms have gotten progressively smaller over the past few decades. Despite speculation that Moore's Law may have reached it's physical limits¹², designers and engineers continue to find ways to increase computing power enforcing the principle of ephemeralization.¹³

The other part of Fullers design ideology is the concept of synergetics.

"Synergetics is the system of holistic thinking which R. Buckminster Fuller introduced and began to formulate. Synergetics is multi-faceted: it involves geometric modeling, exploring inter-relationships in the facts of experience and the process of thinking. Synergetics endeavors to identify and understand the methods that Nature uses in coordinating Universe (both physically and metaphysically). Synergetics provides a method and a philosophy for problem-solving and design and therefore has applications in all areas of human endeavor."

- Synergetics Collaborative¹⁶

1. "101.01 Synergy means behavior of whole systems unpredicted by the behavior of their parts taken separately.
2. 102.00 Synergy means behavior of integral, aggregate, whole systems unpredicted by behaviors of any of their components or subassemblies of their components taken separately from the whole.
3. 962.40 Synergetic geometry embraces all the qualities of experience, all aspects of being."

- R. Buckminster Fuller, Synergetics¹⁵

As with other Fuller concepts, Synergetics emphasizes the entire machine, not individual

parts. In a large part, he explains this by using geometry and geometric structures.

In synergetics, expertise from many fields is utilized, such as thermodynamics, chemistry, psychology, biochemistry, economics, philosophy, and theology. A two-volume book by Fuller outlined his philosophy, *Synergetics*, co-authored by E. J. Applewhite.

Why Lattice?

Why a lattice-based system? In contrast to conventional construction methods, a lattice-based system that is printed instead of built has structural advantages. Anchoring is one of those advantages. In the same way as a suspension bridge that uses point anchors to increase its structural rigidity and conform to different design principles. The same function can be accomplished by a lattice-based system, but in a more efficient and elegant way.

Traditionally, landscapes were manipulated to accommodate design ideas and structural needs in traditional building design and construction. In a lattice-based system, the landscape conforms to the building instead of the other way around. A building's design is flexible enough to adapt to changes in the landscape. A building can not only be constructed on a natural landscape, but its structural members can also be attached to natural landforms, much as a suspension bridge uses tension cables and anchors.

The application of Fullers' ideologies, like ephemeralization and synergistics, in a lattice based, additive manufactured design is more a matter of implementation than actual possibility in terms of lattice geometry.

Conclusion

The following conclusions can be drawn from the study of Fullers' isotropic vector matrices, Candela's study of hyperbolic paraboloids, and the most recent studies, Messner's Optimal lattice structures and the study of the structure of truss-lattice cells.

These studies suggest that, if implemented properly, a lattice-based wall system is likely to

be a feasible option in construction applications. More specifically, if designed correctly the Isotropic Vector Matrices using an Octet Truss design, as originally thought by Fuller, can be a structural achievement which can give additive manufactured printed building an advantage over traditional building.

Although, when additive manufacturing is the method of construction, various other factors need to be considered when assessing the structural stability and strength of a material. These factors include printing quality, material composition, curing efficiency and stability, filament nozzle efficiency, temperature of production and other factors. Additionally, the rapid development of additive manufacturing leads me to conclude that if this medium of construction continues to improve, it will be the ideal construction method for not only adverse environmental conditions but will also be the most efficient in terms of materials used in the construction process.

As such I can say that my design ideology is finding a systematic synergistic design approach which emphasizes dialog, connection with space/function, having it engage with the landscape by utilizing a lattice-based design methodology.

Notes

¹ Relative stiffness-to-relative density scaling relation for: 1) the Hashin-Shtrikman upper bound, 2) the octet truss, in the directions of maximum and minimum stiffness, and 3) the isotruss lattice found in this work. **Messner – Optimal Lattice-Structured Materials.** p 28

² The generation of cell configurations and corresponding relative densities and deformation modes (The red arrow represents printing direction). **Architecture design of periodic truss-lattice cells for additive manufacturing.** Volume 34 ed. P 4

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11. Moore, Gordon E. (1965). "Cramming more components onto integrated circuits". Electronics Magazine. p. 4. Retrieved 2006-11-11.

The future of integrated electronics is the future of electronics itself. The advantages of integration will bring about a proliferation of electronics, pushing this science into many new areas.

12. Kaku, Michio. "Parallel universes, the Matrix, and superintelligence". Kurzweil. Retrieved 2011-08-22.

Physicists are converging on a "theory of everything," probing the 11th dimension, developing computers for the next generation of robots, and speculating about civilizations millions of years ahead of ours, says Dr. Michio Kaku

13. Ray Kurzweil (2001-05-01). "The Law of Accelerating Returns".

Analysis and description of Moore's law. Moore's law is the observation that over the history of computing hardware, the number of transistors on integrated circuits doubles approximately every two years until it reaches a point of max transistor count to processing capacity.

- KurzweilAI.net. Retrieved 2006-06-24.
14. <http://synergeticscollaborative.org/>. Retrieved 2013-11-02.

Description of synergetics and its use.

15. Fuller, Buckminster. Synergetics: Explorations in the Geometry of Thinking (Macmillan Publishing Co. Inc. 1975, 1979). 100.00 Synergy, 900.00 Modelability.

Fuller discusses concepts as diverse as entropy, Einstein's relativity equations, and the meaning of existence become clear, understandable, and immediately involving.

01

HISTORY_

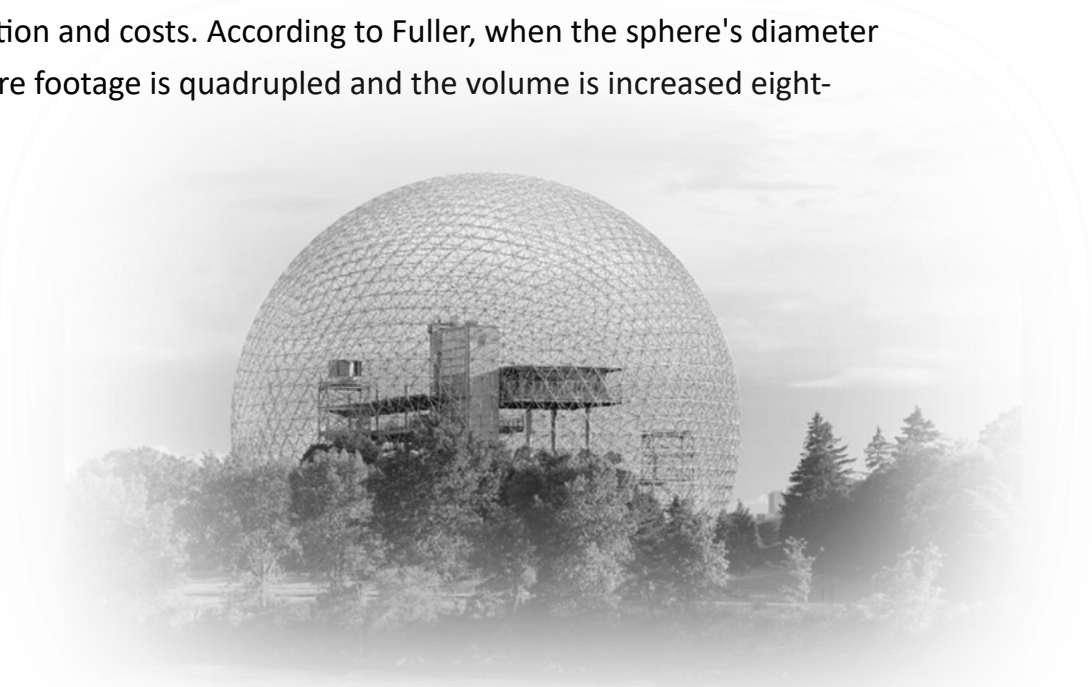
Previous_Structural_Innovations_

Buckminster Fuller

To better understand how different structures can be implemented in the manufacturing process, let's examine previous structural innovations in the field of architecture.

A notable example of this kind of structure is the Geodesic Dome designed by Buckminster Fuller. To demonstrate the difference in strength between a rectangle and a triangle, Buckminster Fuller would apply pressure to both structures. In contrast to the rectangle, which would fold up and become unstable, the triangle can withstand the pressure and is much more rigid - in fact, the triangle is twice as strong as the rectangle. By applying this principle, Fuller was able to create a new architectural design, the geodesic dome, which was based also upon his principle of "doing more with less." Fuller discovered that a spherical structure created from triangles would be extraordinarily strong.

By using the "doing more with less" principle, the sphere encloses the greatest volume of interior space with the least amount of surface area, thus reducing materials consumption and costs. According to Fuller, when the sphere's diameter is doubled, its square footage is quadrupled and the volume is increased eight-fold.



Designinfluences - Buckminster Fuller

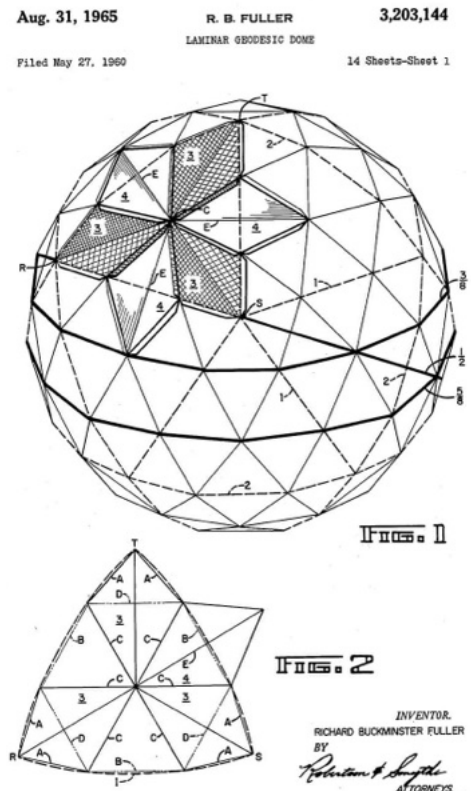
An important project which would push Fuller to patent the term design of the Octet Truss in 1961, is a key component in understanding the structural and functional properties of space filling shapes.

That project, which launched in 1951 and was to be completed a year later, was to produce a geodesic cotton-mill for the North Carolina State College. One of the challenges in designing the cotton-mill was the development of a flooring-structure capable of supporting 200 pounds per square foot. This is important because the development of what Fuller would call the Octet Truss would be developed. This truss was made by the use of grids consisting of combinations of octahedra and tetrahedra.

When grids made up of the Octet Truss units were stacked on top of one another, they produced the space-filling “Isotropic Vector Matrix”.

“Being a geometry of equal vectors and equal 60° angles, it is possible to extend this equilibrium array infinitely outward from the center point of the VE, producing what is called the Isotropic Vector Matrix (IVM). Isotropic means “all the same”, Vector means “line of energy”, and Matrix means “a pattern of lines of energy”.

As a result of this assembly of isotropic vector matrices, its triangular nature was inherently resistant to compression. In 1953, Fuller tested an Octet Truss made from 170 aluminum struts at the University of Michigan. The entire frame only weighed 65 pounds, but it could support a total weight of 6 tons.⁷



Jens.work

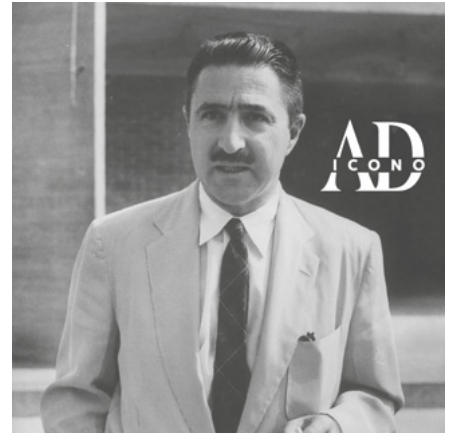
Felix Candela

Another important figure to look at is Felix Candela and his Hyperbolic Paraboloid designs. There are two types of shells according to Candela: the proper shell avoids bending stresses and is doubly curved. This shape can be described as having a saddle curve. This curve can be better described as a set of arches following one directional path with another set of cables or inverted arches in the other, perpendicular, direction. And the improper shell, which carries the load through some bending action upon the material used.

In a shell structure, the thickness is generally much smaller than the width and length. It is important to avoid bending stresses since they can cause ruptures or buckling. To reduce or eliminate bending, it is necessary to give the material a curvature, so that it is shaped like a shell. If properly designed, the structure can span much greater distances and the bending is minimized or eliminated. By using membrane stresses to carry the load, a proper shell ensures that the stress, in tension or compression, is distributed evenly throughout the thickness of the material. Stress equals a force acting on an area.

For shell structures to distribute their own weight adequately, they must be designed with the proper shape, thickness, and material. There is a possibility that in some parts of the shell, high concentrations of forces can be caused by incorrect geometry. The concentration of these elements can cause the material to crack or even collapse completely. In contrast, a properly designed shell is able to distribute forces evenly due to its correct geometry.

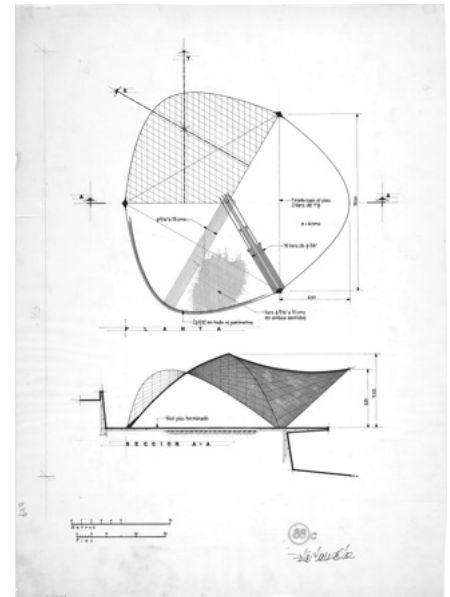
Whenever there are unavoidable high concentrations of forces (such as when a structure is fixed to the foundation), a structure should be thickened to minimize the stress on the structure.



AD.com

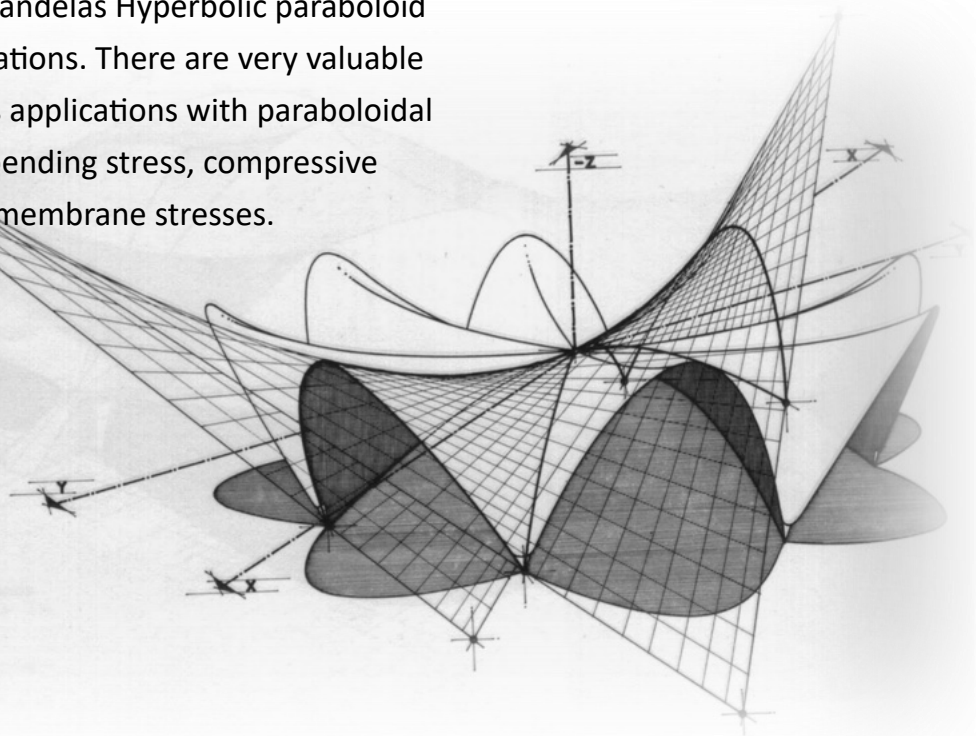
"Of all the shapes we can give to the shell, the easiest and most practical to build is the hyperbolic paraboloid." -Candela, "The Hyperbolic paraboloid," 226

A hyperbolic paraboloid (also called a hyper) has the additional property of being defined by straight lines. The boundaries, or edges, of the hyperbolic paraboloid can be straight or curved. Developing the edges of the hyper involves planes that "cut through" the surface. In order to create his designs, Candela used both straight and curved edges. A straight-edged hyper in the umbrella structure was used to create one quadrant (called a tympanum). The roof of El Altillo Chapel is composed of this single hyper, whose construction reflects the straight lines visible in the final structure. By arranging umbrellas in sequence, he was able to create a large roof covering using multiple hypers.



Architect.com

Space Filling Shapes or an Isotropic Vector matrix such as the Octet Truss was revolutionary and marked the beginning of a new era in lightweight and efficient structural design. Fuller's invention is still used today in a variety of fields, from aircraft to architecture. And despite Candela's Hyperbolic paraboloid not being used in mass applications. There are very valuable lessons to be learned from his applications with paraboloidal shapes as compared to pure bending stress, compressive membrane stress and tensile membrane stresses.



Fuller's_Design_Ideology_

The design ideology of Buckminster Fuller stems around Ephemeralization and the use of Synergistic design principles.

Ephemeralization is the ability of technological advancement to do more with less until you can do as much as you can with nothing. Buckminster Fuller created the term in 1938 to express the use of less material for greater results. Fuller developed this philosophy partly in reaction to the philosophy of Thomas Malthus.

Thomas Malthus (1766-1834) who was a English economist and demographer published the first edition of An Essay on the Principle of Population in 1798. His theory was that a increase in population will naturally happen. According to him this population growth will happen on a geometric progression scale. Thus each increase in population will multiply each previous amount by a fixed number. As opposed to other resources, these will increase only on an arithmetic scale. Therefore, believing that the population will always expand to the limit of substance.

However, Fuller disagreed and felt that technology, improved design, and engineering would help to allow humanity to use the existing resources more efficiently causing greater output with decreased input.

His goal was;

"more and more with less and less until eventually you can do everything with nothing."

He looked at Henry Ford's assembly line as an example of ephemeralization where efficient design was used to increase productivity. Generally, technology increases ephemeralization.

One such example is computing power and efficiency based on Moore's Law, named after Intel founder Gordon E. Moore, which refers to the number of transistors on an integrated circuit doubling every two years. As a result, computers that used to take up entire rooms have gotten progressively smaller over the past few decades. Despite speculation that Moore's Law may have reached it's physical limits, designers and engineers continue to find ways to increase computing power enforcing the principle of ephemeralization.

The other part of Fullers design ideology is the concept of synergetics.

"Synergetics is the system of holistic thinking which R. Buckminster Fuller introduced and began to formulate. Synergetics is multi-faceted: it involves geometric modeling, exploring inter-relationships in the facts of experience and the process of thinking. Synergetics endeavors to identify and understand the methods that Nature uses in coordinating Universe (both physically and metaphysically). Synergetics provides a method and a philosophy for problem-solving and design and therefore has applications in all areas of human endeavor."

- Synergetics Collaborative

"101.01 Synergy means behavior of whole systems unpredicted by the behavior of their parts taken separately.

102.00 Synergy means behavior of integral, aggregate, whole systems unpredicted by behaviors of any of their components or assemblies of their components taken separately from the whole.

962.40 Synergetic geometry embraces all the qualities of experience, all aspects of being."

- R. Buckminster Fuller, Synergetics

As with other Fuller concepts, Synergetics emphasizes the entire machine, not individual parts. In a large part, he explains this by using geometry and geometric structures.

In synergetics, expertise from many fields is utilized, such as thermodynamics, chemistry, psychology, biochemistry, economics, philosophy, and theology. A two-volume book by Fuller outlined his philosophy, Synergetics, co-authored by E. J. Applewhite.

02

LATTICE_

Why_Lattice_?_

In contrast to conventional construction methods, a lattice-based system that is printed instead of built has structural advantages.

Anchoring is one of those advantages. In the same way as a suspension bridge that uses point anchors to increase its structural rigidity and conform to different design principles. The same function can be accomplished by a lattice-based system, but in a more efficient and elegant way.

Traditionally, landscapes were manipulated to accommodate design ideas and structural needs in traditional building design and construction. In a lattice-based system, the landscape conforms to the building instead of the other way around.

A building's design is flexible enough to adapt to changes in the landscape. A building can not only be constructed on a natural landscape, but its structural members can also be attached to natural landforms, much as a suspension bridge uses tension cables and anchors.

The application of Fullers' ideologies, like ephemeralization and synergistics, in a lattice based, additive manufactured design is more a matter of implementation than actual possibility in terms of lattice geometry.

There are other limitations when using more conventional materials like concrete to 3D print with when compared to 3D printing with a lattice-based system. When 3D printing concrete, the building of walls is a layered approach.

Now this is not any different from any other additive manufactured or fabricated piece. Whether that addition of material is concrete, steel, aluminum or plastic composite. The main difference with having a lattice-based system is that you are not only saving material but you are saving weight and time.

The system that is being used now, that is the layering of concrete through an extrusion process adds material and mass layer by layer. The first layer is laid down than subsequent layers are extruded on top of that layer. Those layers however are almost the same, with the same thickness, density of material and geometry as the layer below.

This is where a 3D printed lattice differs. A lattice in itself is a geometric pattern whose points form a repeating pattern. This allows any point to be shifted to any other point through a set of variables. Which in turn would allow the production of a web-like network built on a grid-like arrangement.

All of this is to say that a lattice structure can be manipulated to have higher density in regions that need it, such as higher load areas, and can also have lower density in regions, such as lower load areas.

Voronoi_Diagram_

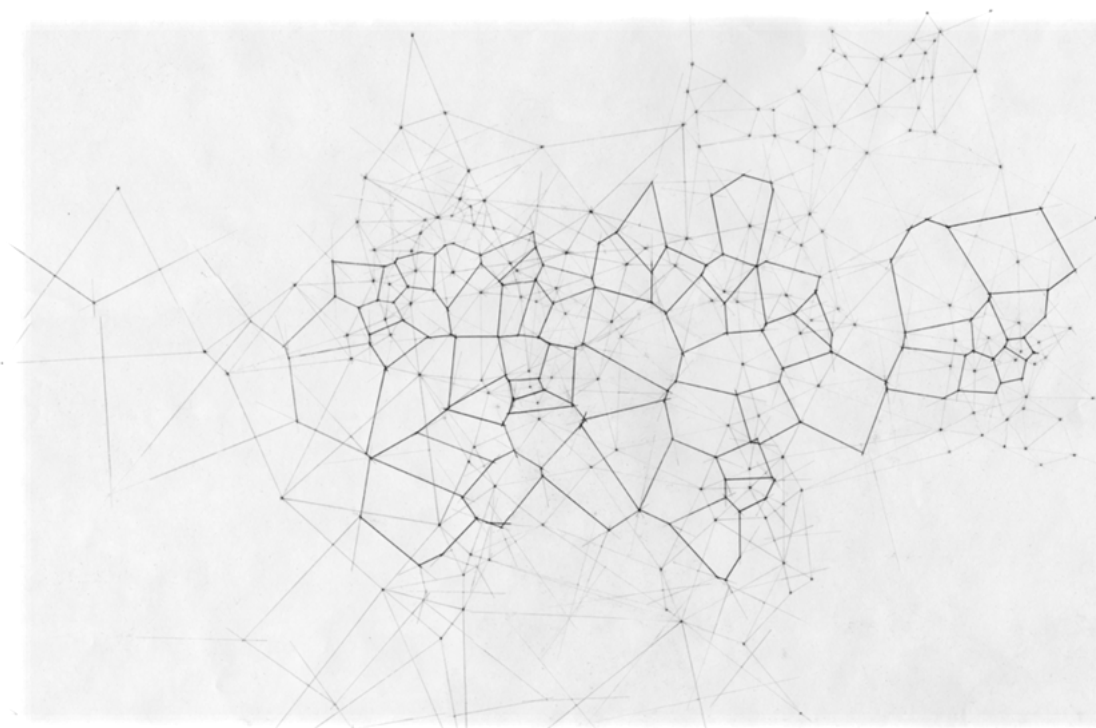
Voronoi diagrams were considered as early as 1644 by philosopher René Descartes and are named after the Russian mathematician Georgy Voronoi, who defined and studied the general n -dimensional case in 1908.

This type of diagram is created by scattering points at random on a Euclidean plane. The plane is then divided up into tessellating polygons, known as cells. One cell around each point. This makes a region bounded by those polygons which is closer to that initial, central point than any other.

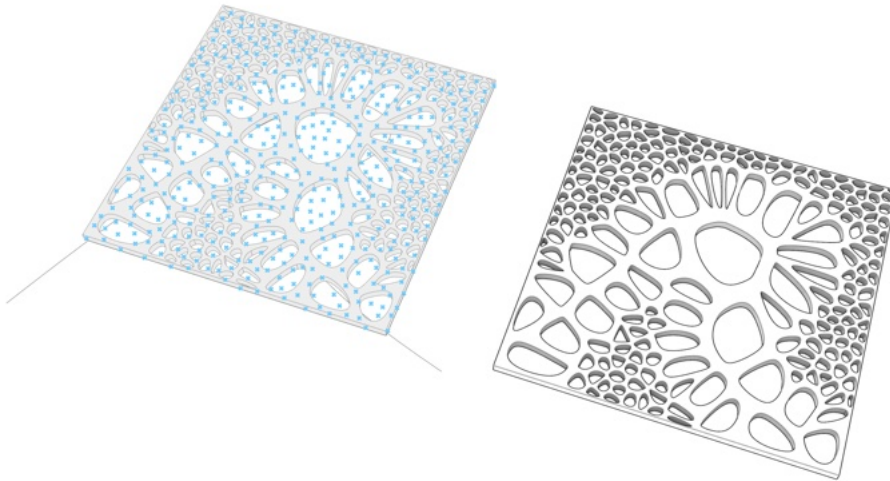
Voronoi tessellations form structured shapes. This type of pattern fills the space as efficiently as possible. This is very convenient if you are trying to squeeze as much as possible into a limited space. Thus the use of this pattern would not only be efficient in forming complex structures, such as those found in architecture, but would also be efficient in material use.



Georgy Voronoi



Point_and_Curve_Attractors_



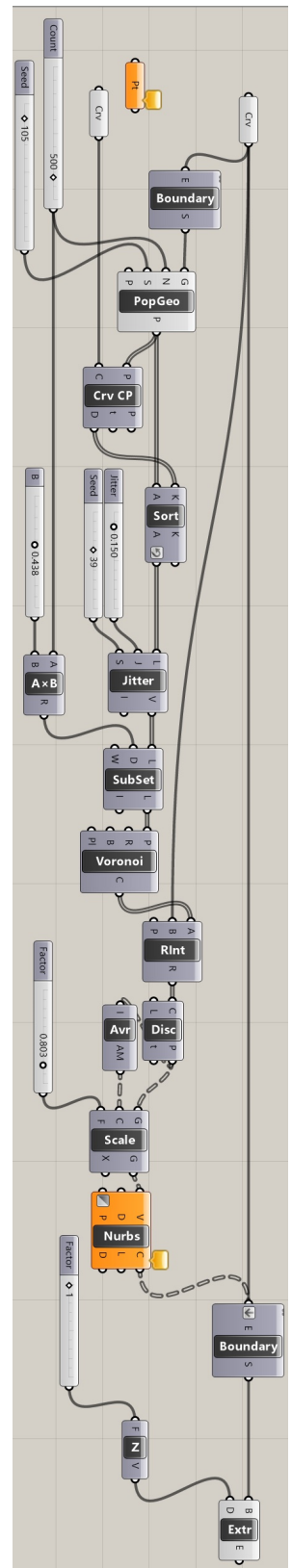
Varying Voronoi tessellation density based on attractor points and curves is shown above.

These attractor points and/or curves, as represented by the line. This will allow the density of points, as represented by the blue points, to vary depending on the distance from the shown line. This in itself would correlate to the number of Voronoi tessellations shown in term of distance from the line.

The grasshopper script shows how setting a point (pt) or curve (crv) within a boundary, can impact the overall attraction or repulsion of points to those set curves or points.

The attraction is set by moving the "factor" box from 1 to 0. 1 is repulsion and 0 is attraction.

The count and seed of the points are determined by the two numeric sliders (count and seed) attached to the popGeo box. The jitter and seed numeric sliders determine the randomness and size of the voronoi cells.



Making_of_3D_Voronoi_Lattice_

The process is as follows;

The boundary is first established. This is the geometric shape that you are working with.

Next, that geometric shape is populated with points. The number of points, factor of randomness and the arrangement can be controlled. After this is done, the lattice geometry is then defined.

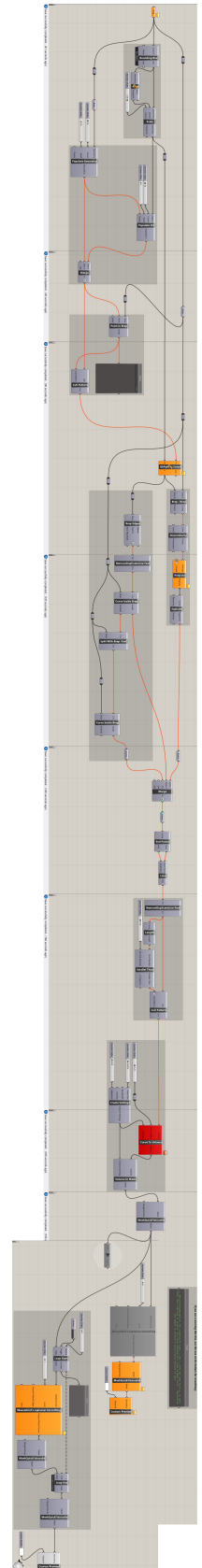
In my case a Voronoi tessellation.

As mentioned before, this tessellation pattern defines certain areas around the points by polygons. Those polygons however have to go through a “cleaning up” process. In which, any redundant polygonal side which intersects another polygon is removed.

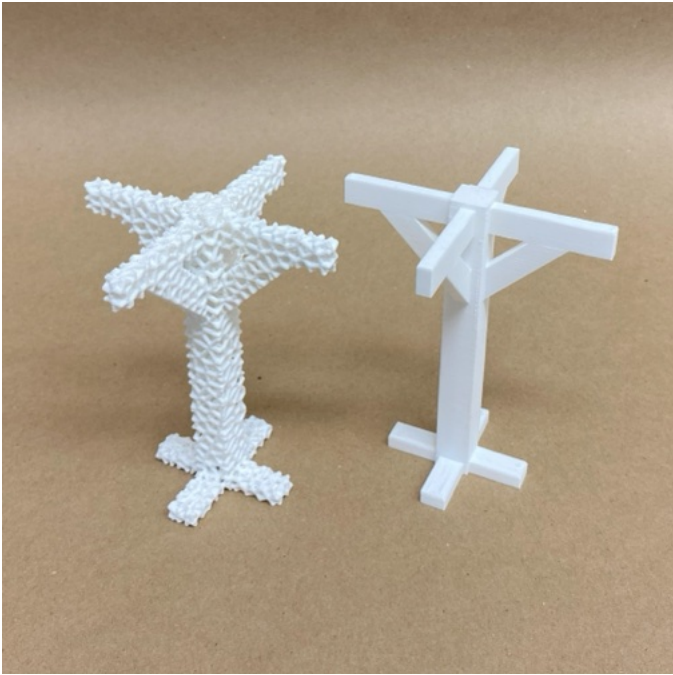
Following this, there are other processes which include:

- The removal of extra, redundant points.
- Optimization of points used within a defined space.
- Optimization of polygonal tessellation calculations.
- Building of the Voronoi tessellation as a 3D geometry.
- Setting the thickness of the Voronoi.
- Making sure that this thickness does not create redundant spaces or underutilized polygonal geometries or that this new geometry does not interfere, intersect or is created on top of other geometry.

In between the process of point creation, definition of lattice geometry and tessellation calculation. This is where the point, line or curve attractors would be inserted. This will produce varying Voronoi tessellation density based on attractor points and curves.



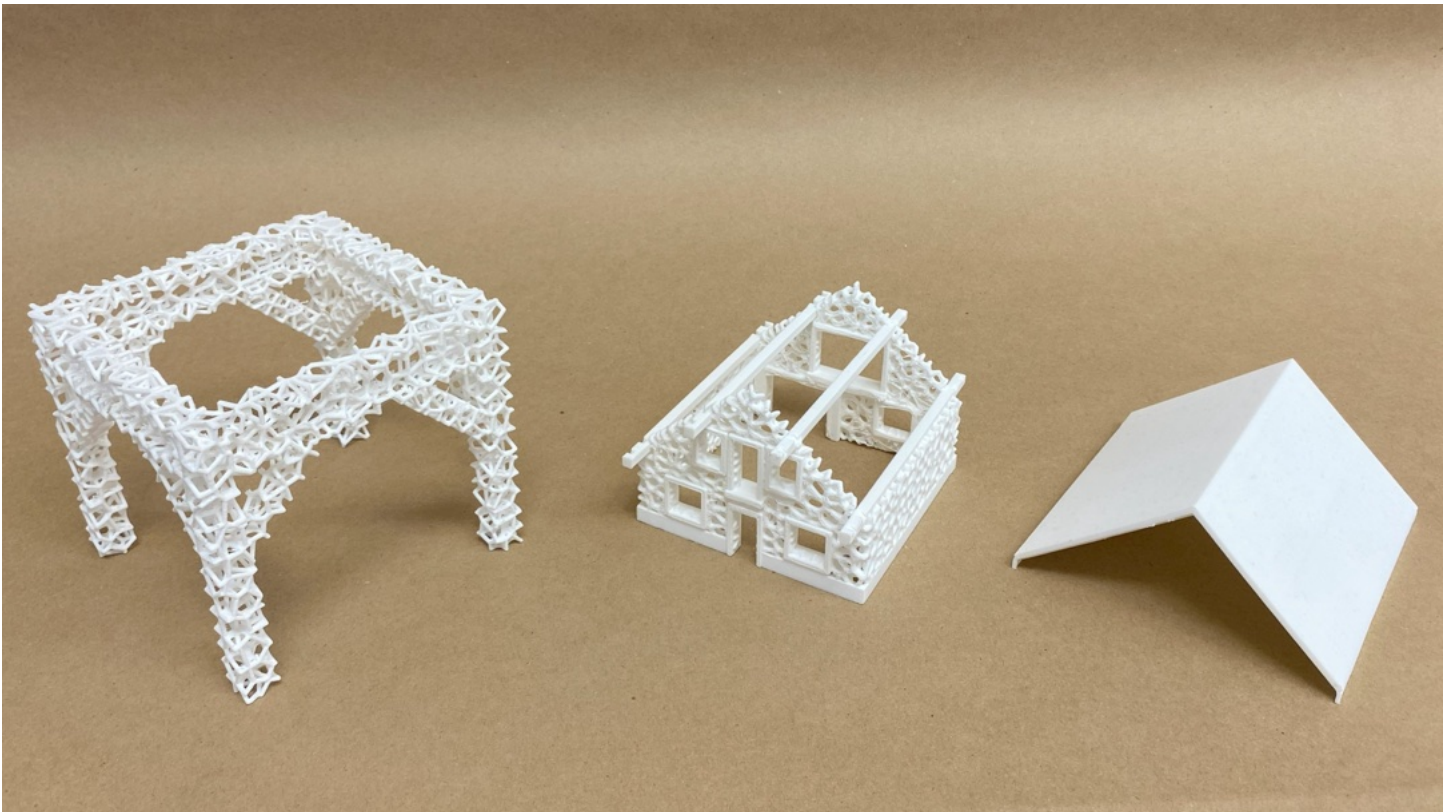
Experimental_Printing_



Experiments Showing Post and Beam Construction



Lattice Frame and House Experiment



Lattice Frame and Structural House Frame



Lattice Frame and Structural Building



Lattice Frame and Structural Building



Lattice Spheres with Varying Density

03

SITE_AND_DESIGN_

Site_

The site that I have chosen is located in one of the snowiest regions in Switzerland, the Furka Pass, connecting the subdivisions of Uri and Valais in the country's south-central region.

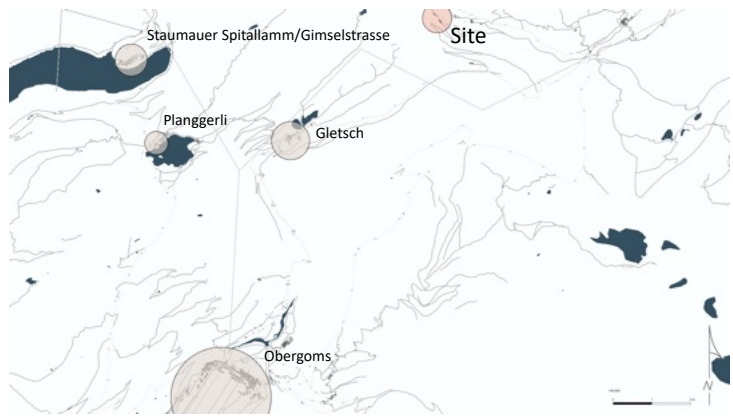
It is also here, in one of the hairpin turns, that in 1882 Josef Seiler built the Hotel Belvedere. This location is considered to be one of the “most iconic, exhilarating and exciting drives” through the Swiss Alps. The scenic road with its tight switchbacks curving up the picturesque mountainside attracts countless tourists. There is also the Rhone Glacier located north of the site. The hotel itself has been closed since 2016 due to financial issues regarding the maintenance, upkeep and transportation of materials/goods to the location. Although the hotel is closed, adjacent is located the Eisgrotte Ronegletcher. This is a tourist destination point, not only for the hotel but for viewing and experiencing the Rhone Glacier.

The site is located adjacent to Hotel Belvedere overlooking the valley and the small town of Gletsch. There are a total of 9 hotels or lodging, 1 Grocery Store, 4 sites for transportation. Those transportation hubs are either a bus or train station and anywhere from 6-8 main sites for hiking. All of these locations are spread between the towns of Gletsch, Obergoms and Planggerli. The nearest location with the majority of hotels and the only grocery store, Obergoms, is about 9 miles or 13.9 Kilometers away.

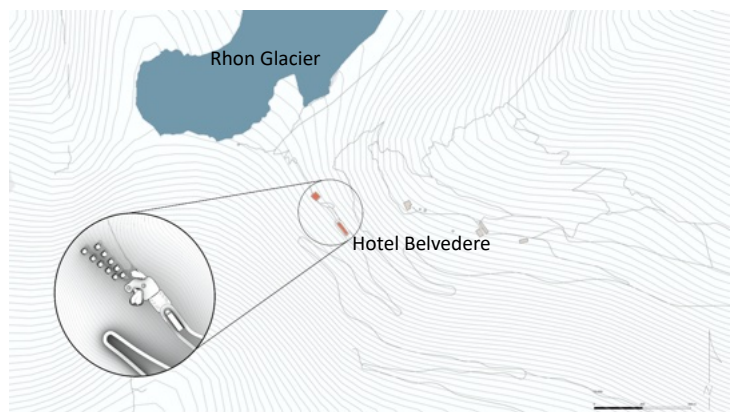
The remote location of the site is one of the many reasons for why I chose it as a starting point. Its ability to give me a very unconventional platform for which I could start designing. One which could show how the idea of a 3D printed building would work best in a location such as this.



Site Location - Country



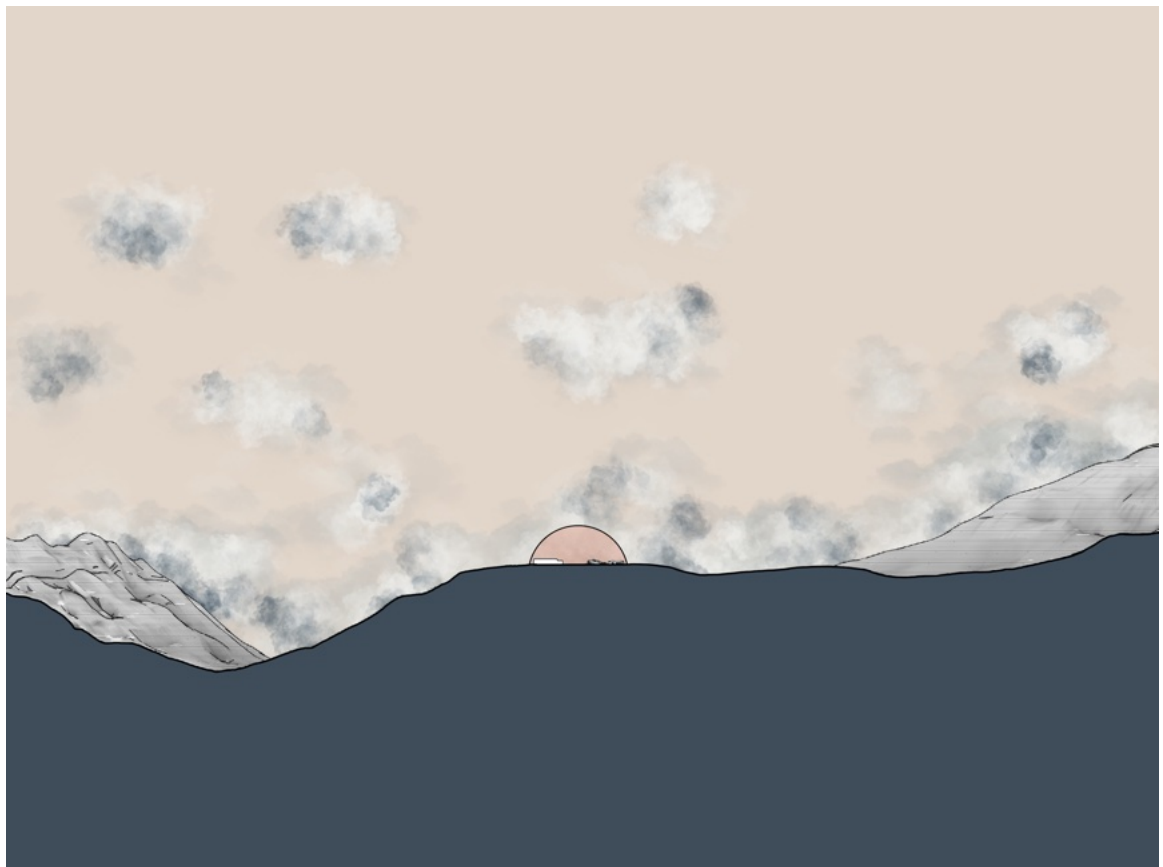
Site Location - Local



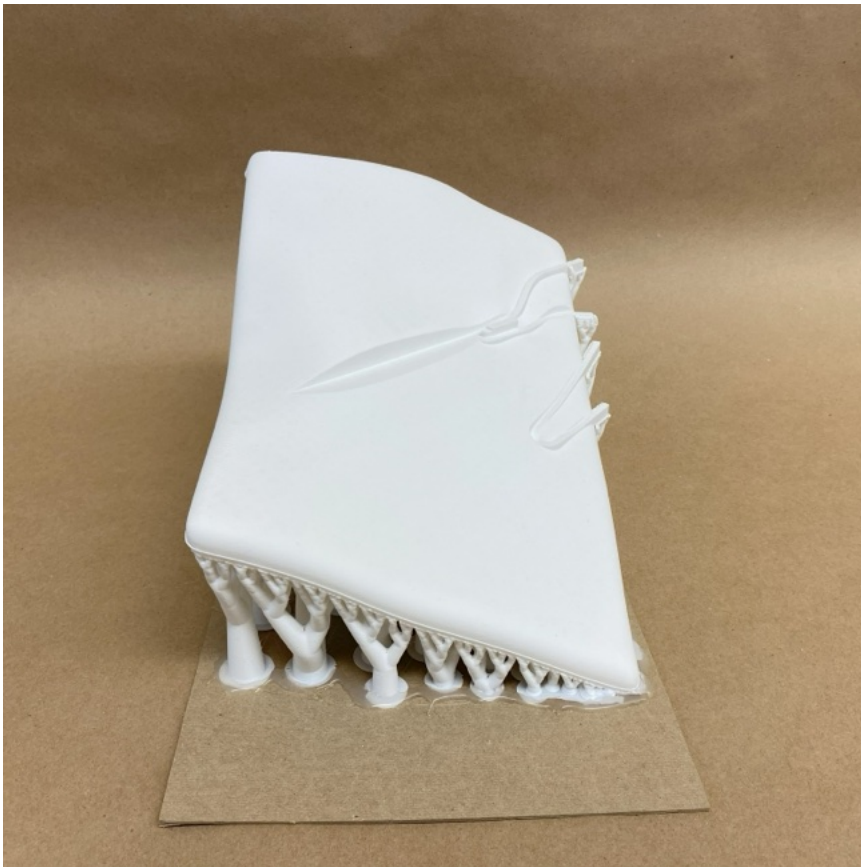
Project Site



East-West Site Section



North-South Site Section



3D Printed Site



3D Printed Site

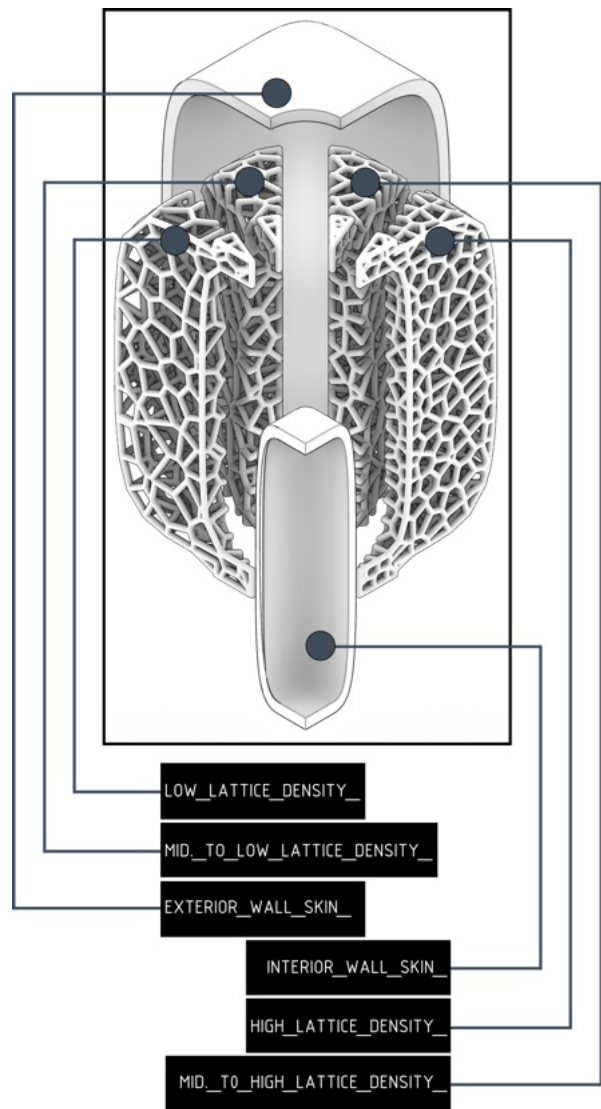
Design_Idea_

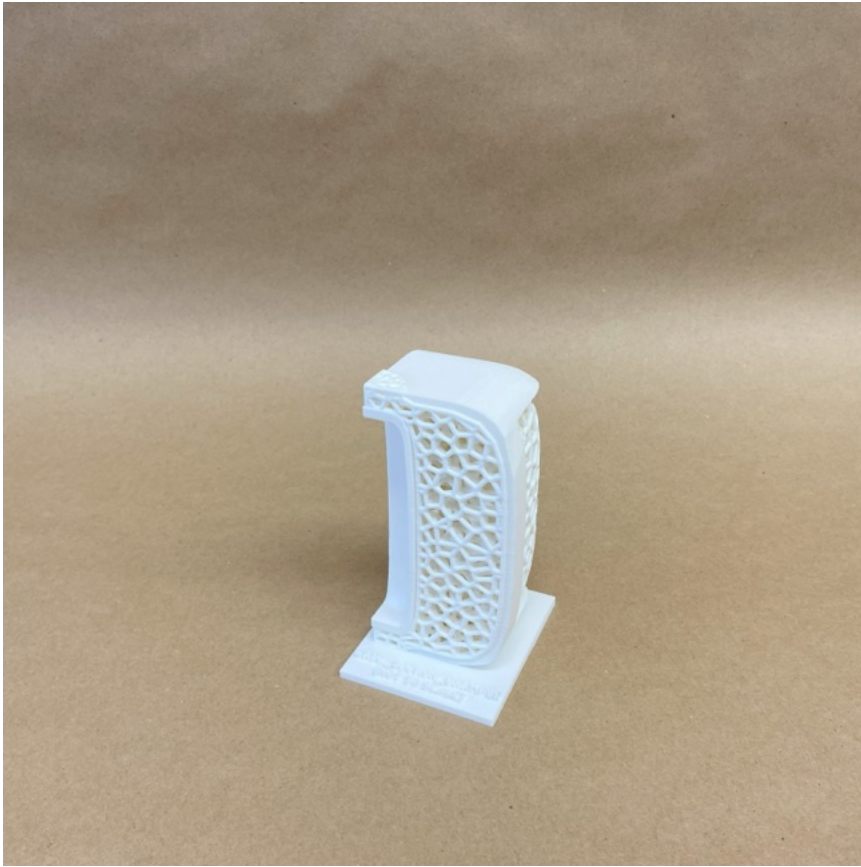
My design process began by considering not just the shape, but also how a lattice structure might be incorporated. The structure of the building would be composed of a lattice, which would then be covered by two separate skins.

A wall would consist of an interior skin, a lattice structure, and insulation materials surrounding it, along with any other utilities. Followed by an exterior skin.

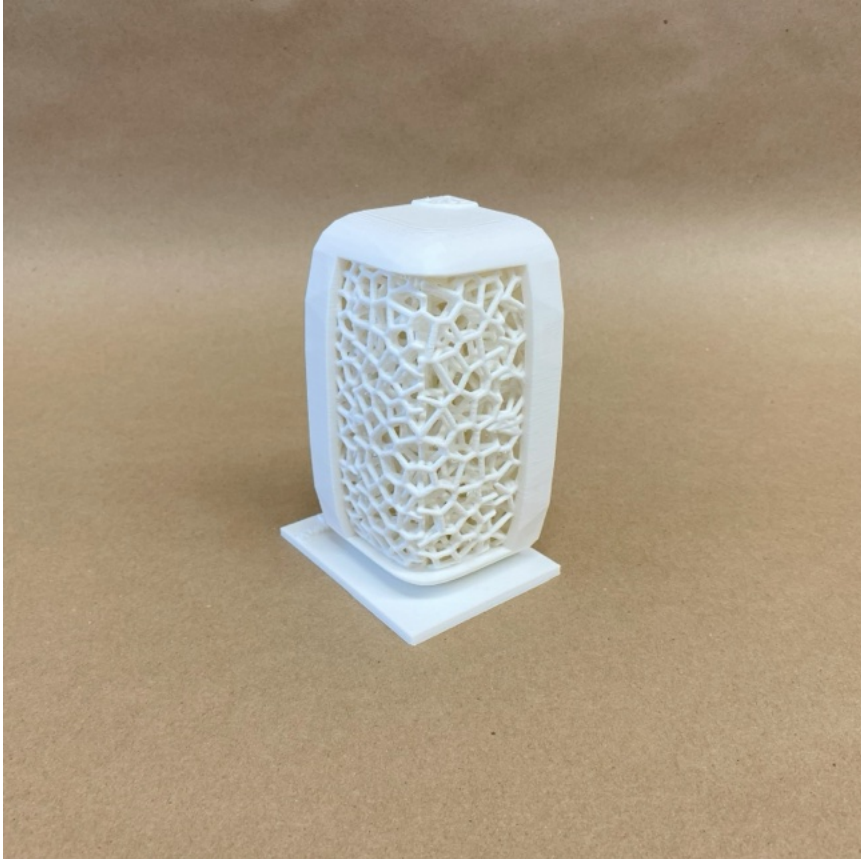
Another benefit that I have found when 3D printing a whole building is that this exterior structure can wrap around the whole building envelope. This means that any type of insulation material can encompass the whole building. Hopefully without any kind of thermal break. Basically, it makes a sandwich. An exterior skin, a lattice structure with insulation, and interior skin.

The next thing that I had to consider was how this 3D printed building would be constructed.

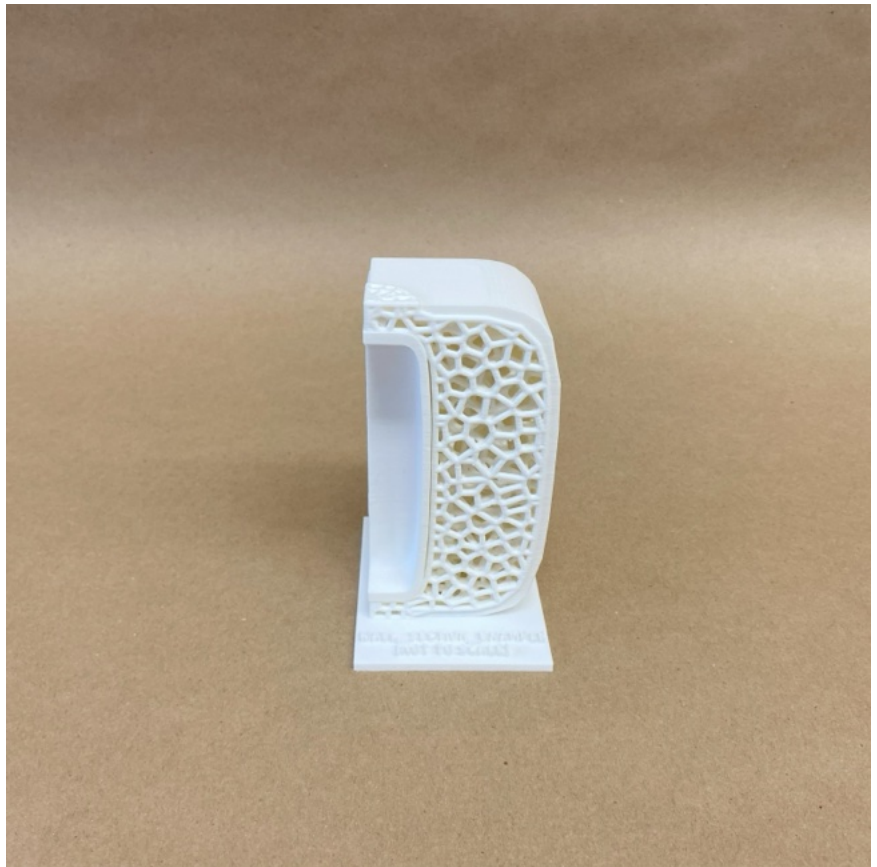




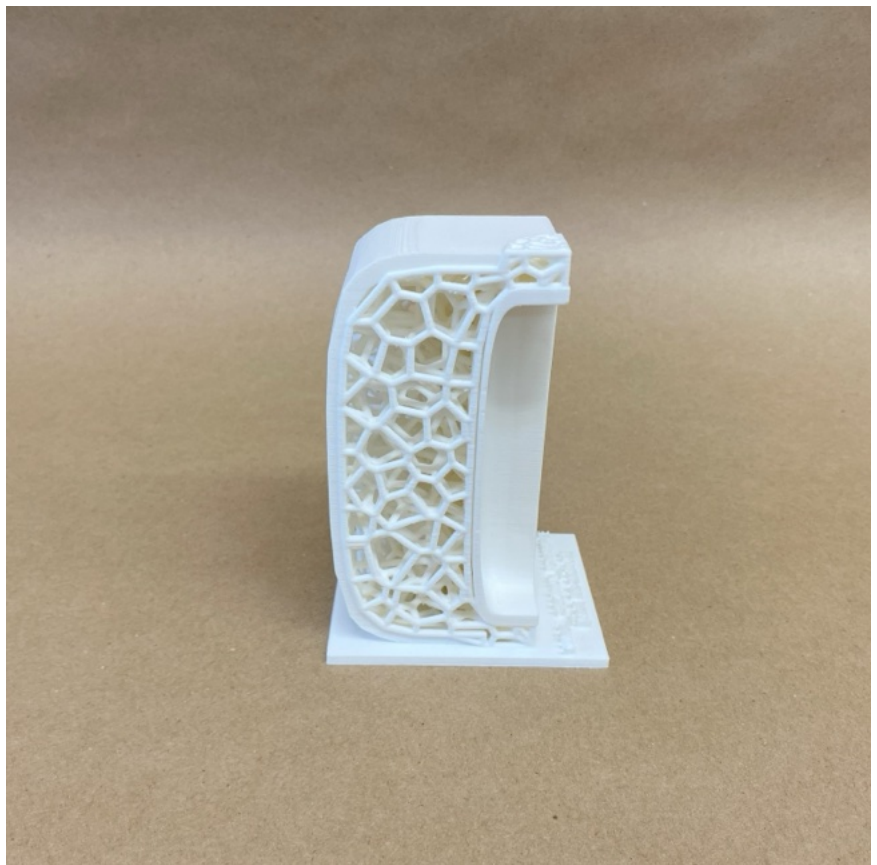
3D Printed Wall Corner



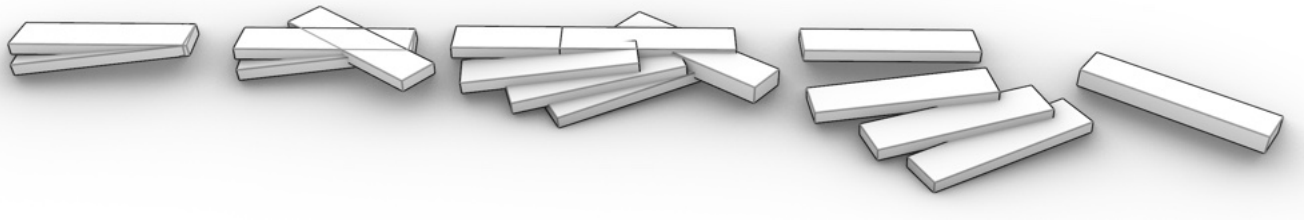
3D Printed Wall Corner



3D Printed Wall Corner



3D Printed Wall Corner



The Basic building design all started out as a basic shape. In this case it was a rectangular cuboid. Out of this shape I would push/pull, add/subtract various geometries to come up with the final form.

This would not only make some very interesting shapes but it would allow for an almost infinite amount of modular designs. All of which could be based on need or use. The overall shape of the building, inside and outside can be tailored around a person's needs or a particular design. Which would allow for a very unique feeling space.

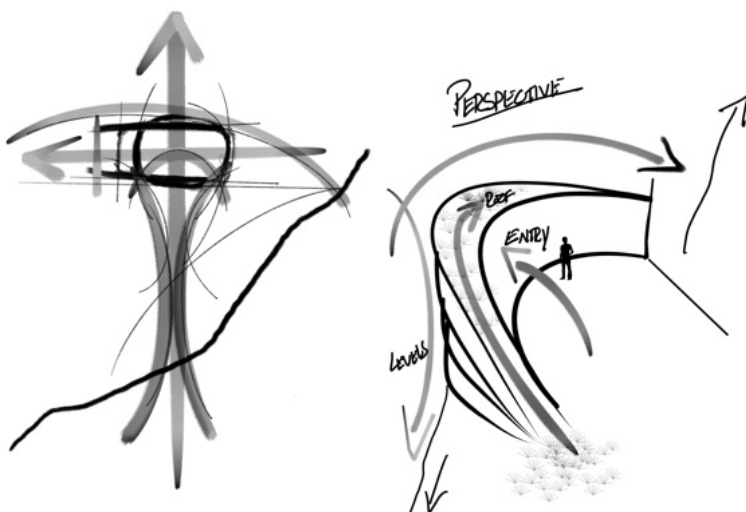
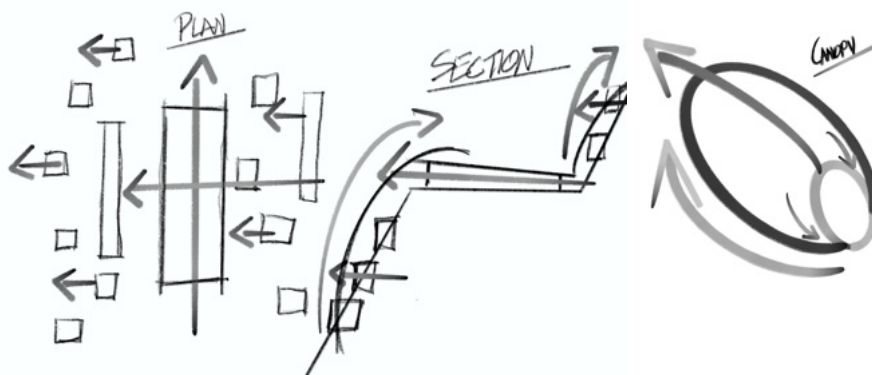
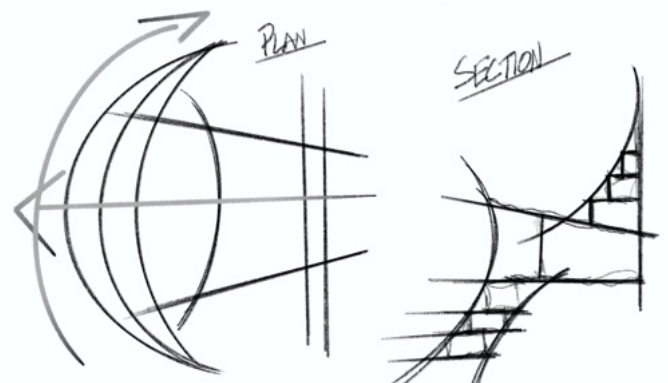
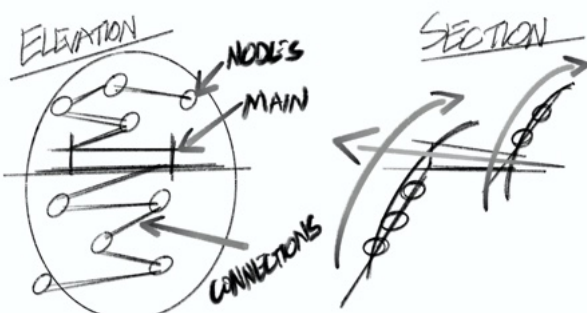
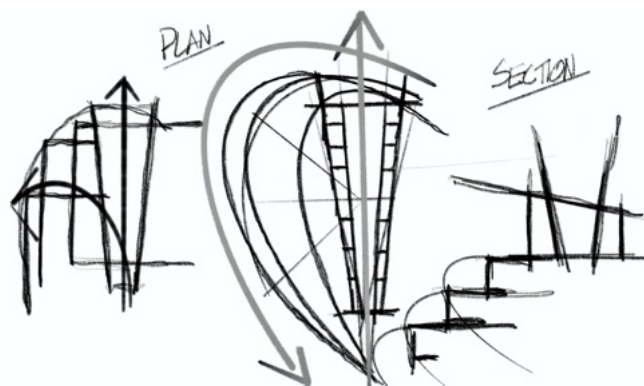
Another thing that I had to take into consideration was whether or not these buildings would be based around a single printed mass or modularly printed, and assembled on site.

Both approaches were used in my design process.

The main structure is designed out of a singular piece which will have various elements attached to it based on need and function. Meaning that from the roof of the building to the window mullions, these pieces can be printed off site with assembly happening on site.

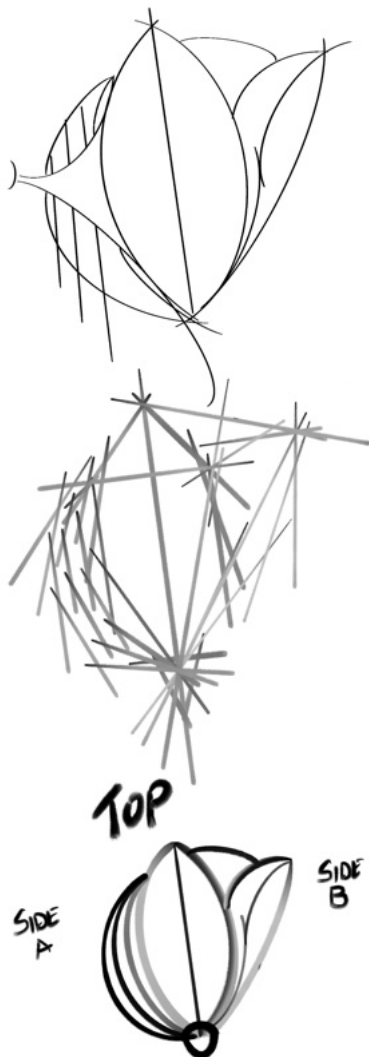
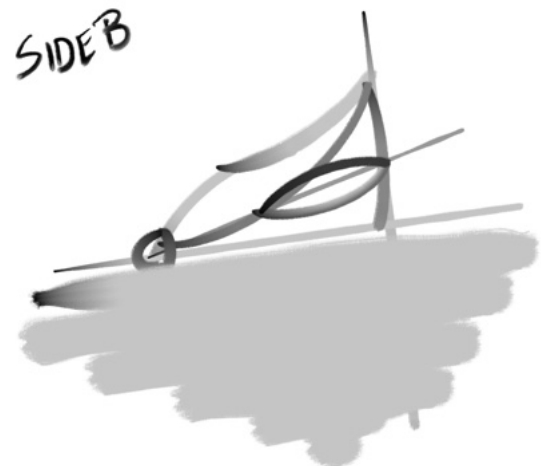
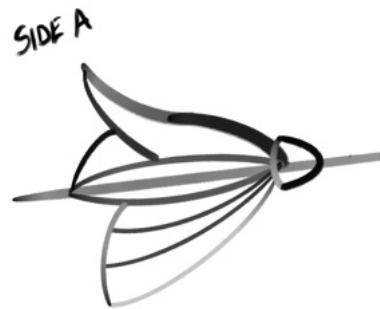
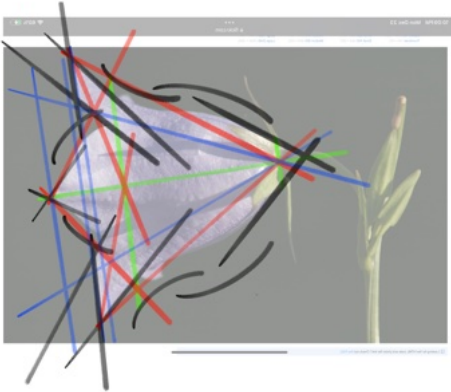
This would not only increase the versatility of the manufacturing process but based on location and need, the cost and production time would vary. If it would be cheaper, more efficient, and less time-consuming to print the whole unit, that can be done. If the opposite is true, where printing each individual component and then having it shipped is the best option, that also can be done.

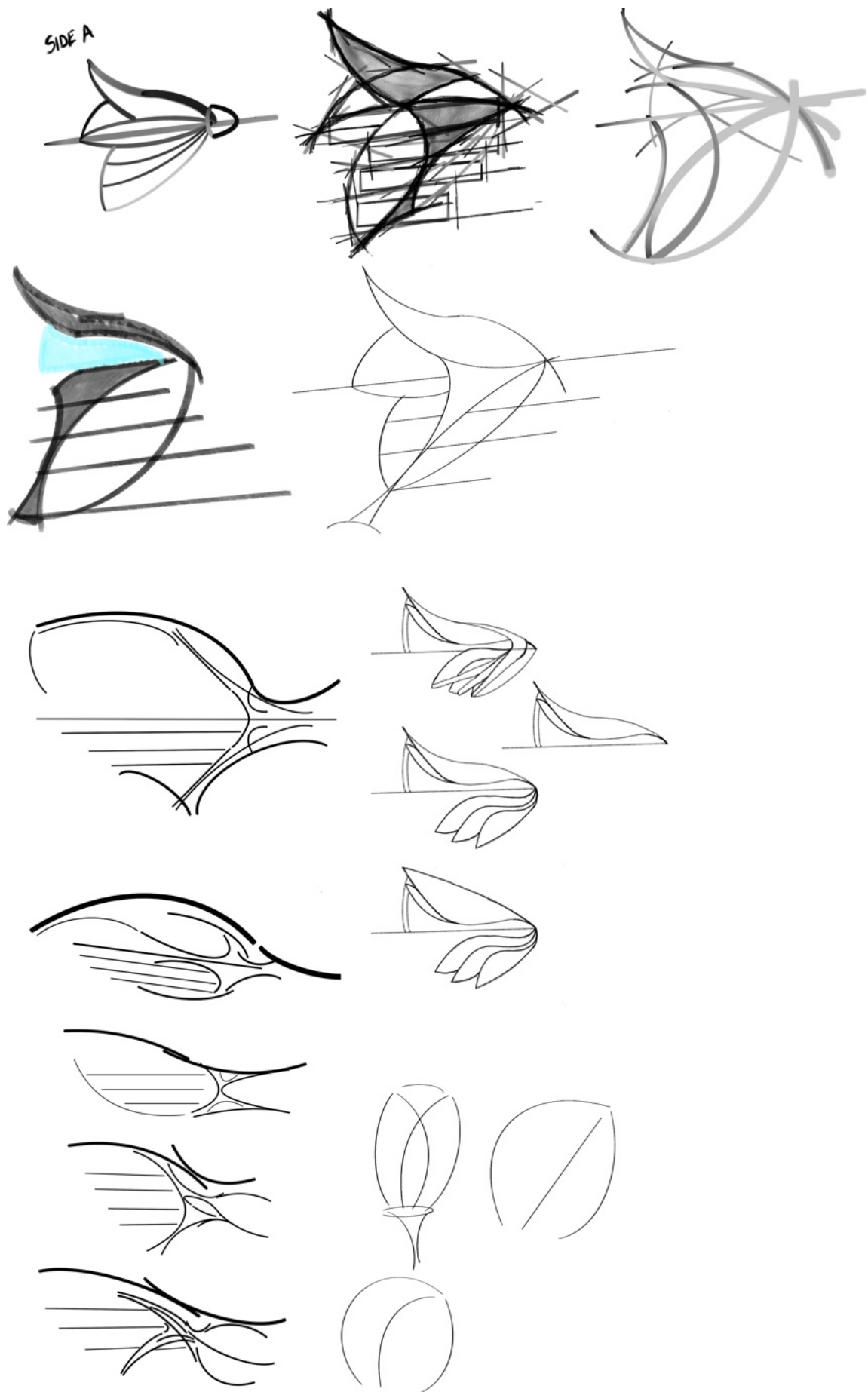
Sketches_





Inspiration - Fairy Thimble Bellflower





Site_Specific_Design_

The site specific design consists of the separation of space through its functional properties. Having three separate building types with varying geometry and attachment styles to the site.

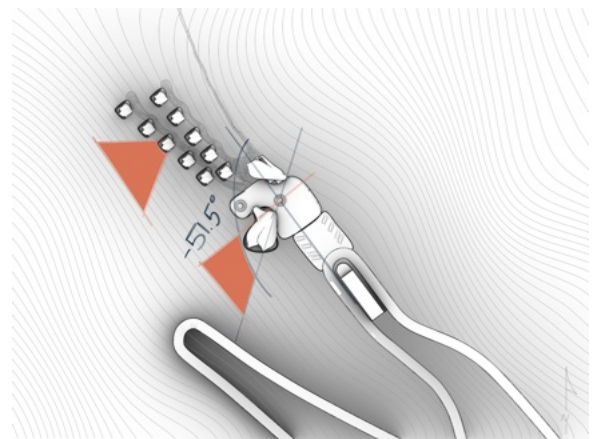
This location would have 3 main building types. A welcome/spa center located at the north-eastern most point, and a restaurant at the south-west. The cabins start from a central axial point on the site and rotate outward towards the west at 5 and 15 degrees respectively, with a downward slope of 5 degrees for the first row and a steeper angle of 10-15 degree decline for the second row.

The welcome/spa building is based on the principle of experience. Experience of the place, site and a location for reflection/contemplation.

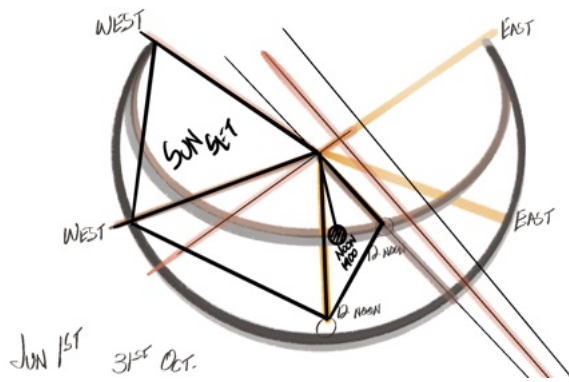
The angle and orientation of the building is situated so that the hallway lines up with the middle of the Belvedere Hotel and the path towards the glacier. The building is separated into rooms based on function and temperature. There are hot rooms, massage rooms, reflection spaces, an exterior hot pool overlooking the valley and a rear terrace overlooking the glacier. This building would be nested into the mountain slope towards the rear, exposing the rocks to the interior of the hot rooms.



Site Massing Diagram



Building Orientation and Angle



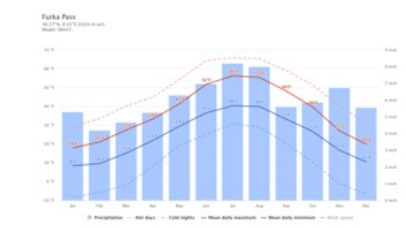
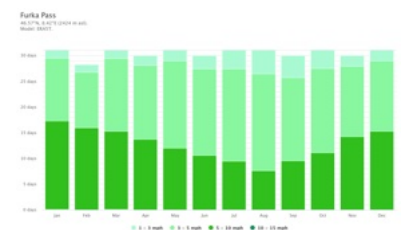
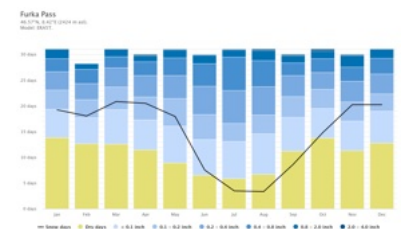
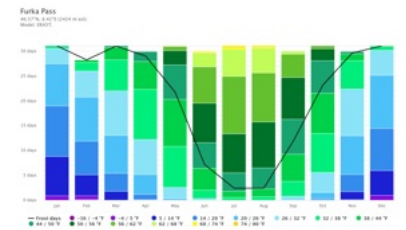
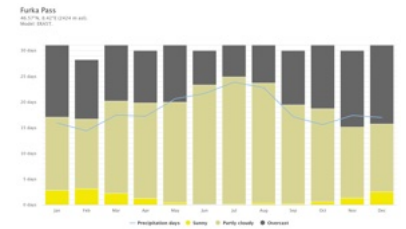
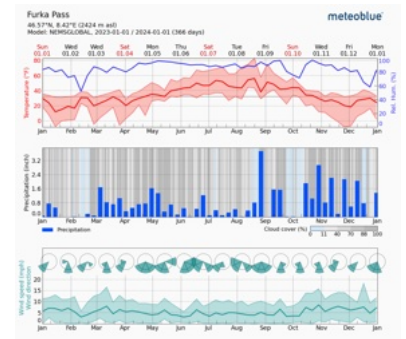
Sun Angle VS Time of Day and Month

In both the restaurant and the cabins, views are the guiding principle.

Both of these buildings face the valley for maximum sun exposure, with the restaurant rotated at a -51.5 degree orientation from parallel. I designed these building locations as such not only for the view of the valley but also due to the climate and temperature. I took the location of the sun and the orientation of the building into consideration, due to the fact that the Furka Pass is mainly open during the summer months which is from May to October in this location. The average temperature is in the mid 60's with lows in the 40's and highs in the 70's.

There are several appendages of the restaurant and cabins that focus on a single point. This minimizes the impact on the landscape while supporting the structure's weight. A flower stem was the main inspiration behind this design.

There is also a roof feature on all of the buildings that resembles a flower's petals. This flower is the Fairy Thimble Bellflower, native to the Alps and Switzerland. There are 5 petals on this particular flower, each rotating at 137.5 degrees around its stem. The petals on each building follow this principle of having one, two, or three petals.

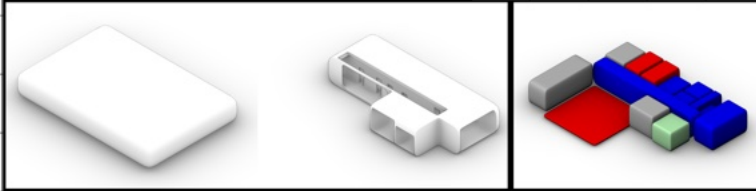


04

BUILDING_DESIGN_

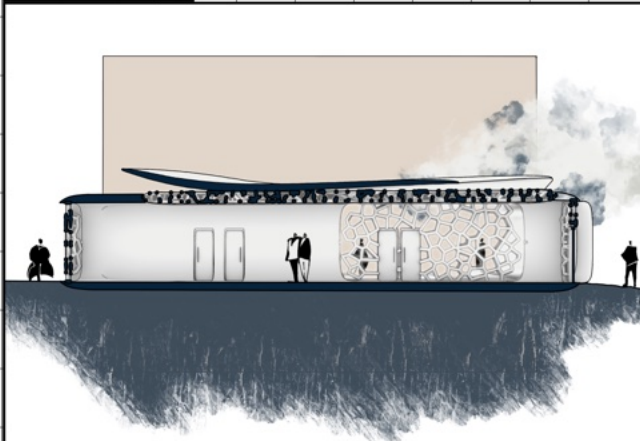
WELCOME_01_RELAXATION_

MASS_MODEL_SCULPTING

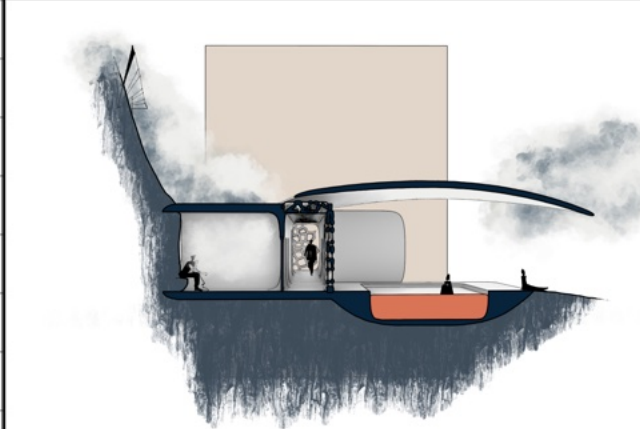


LEGEND:
RED-HOT_ROOM, GREEN-MASSAGE_ROOM, GRAY-REFLECTION_ROOM/TERRACE, BLUE-OTHER

SECTIONS

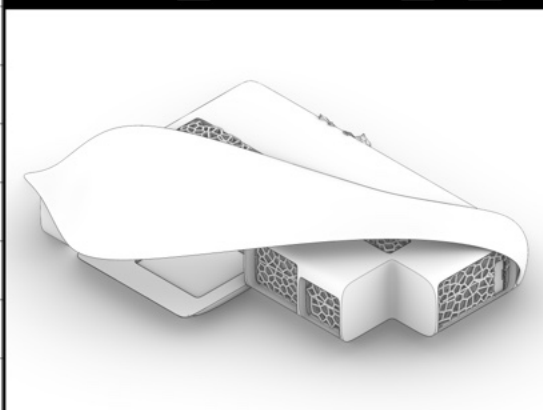


EAST_WEST_SECTION

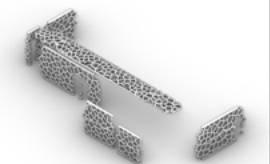
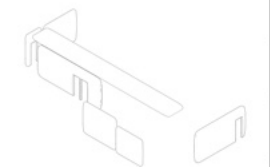
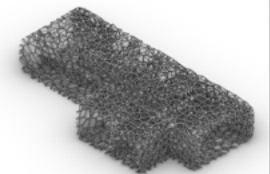
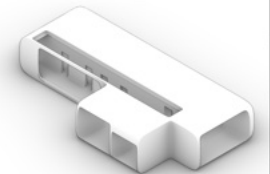
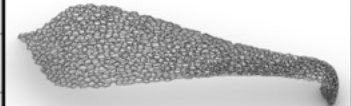


NORTH_SOUTH_SECTION

ISOMETRIC_PROJECTION_OF_MODEL



MODEL_PARTS





3D Printed Building 1



3D Printed Building 1



3D Printed Building 1



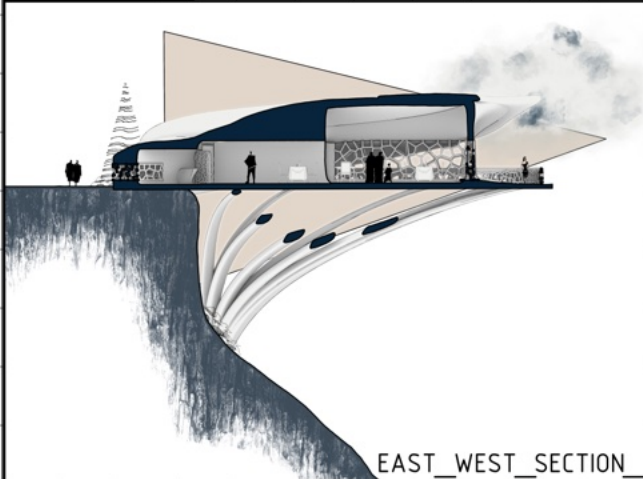
3D Printed Building 1

RESTAURANT_02_SUSTENANCE_

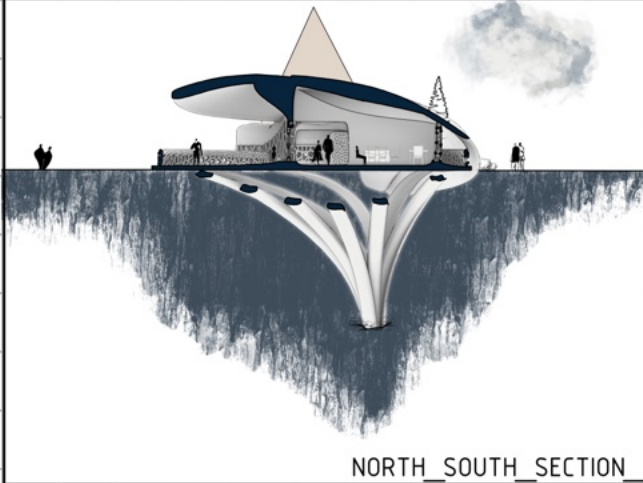
MASS_MODEL_SCULPTING_



SECTIONS_

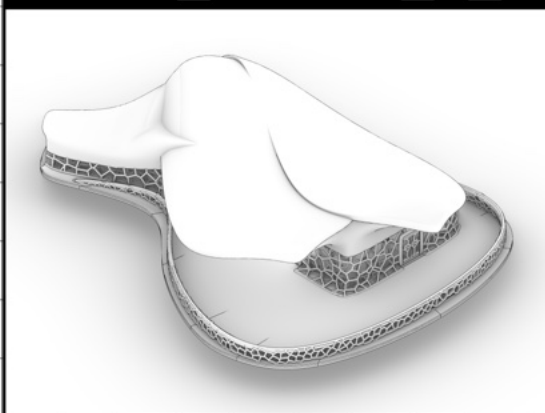


EAST_WEST_SECTION_



NORTH_SOUTH_SECTION_

ISOMETRIC_PROJECTION_OF_MODEL_



MODEL_PARTS_





3D Printed Building 2



3D Printed Building 2



3D Printed Building 2



3D Printed Building 2

CABIN_03_HABITATION_

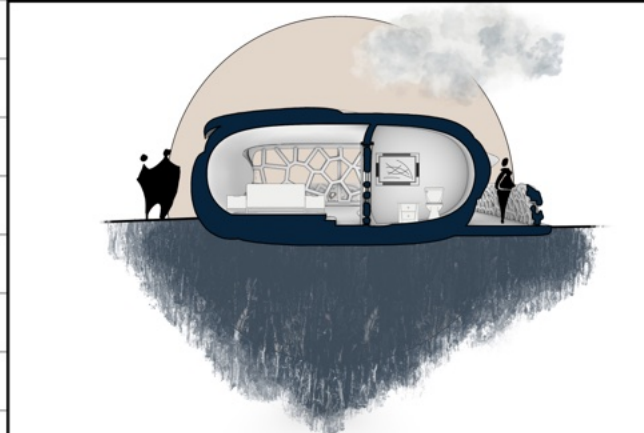
MASS_MODEL_SCULPTING_



SECTIONS

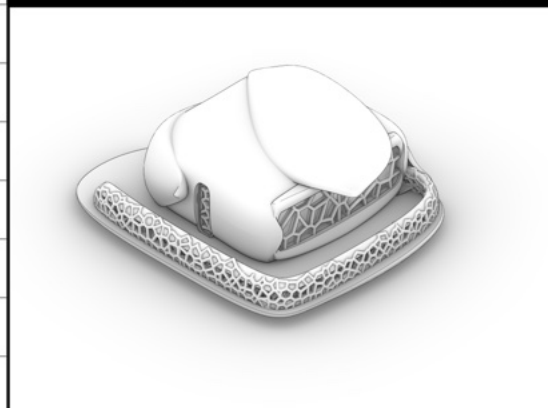


EAST_WEST_SECTION

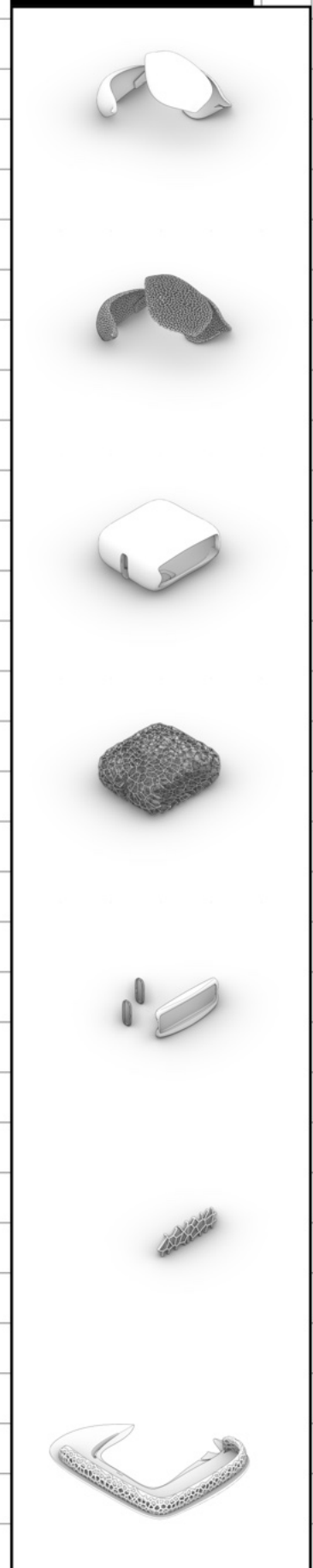


NORTH SOUTH SECTION

ISOMETRIC_PROJECTION_OF_MODEL_



MODEL_PARTS_





3D Printed Building 3



3D Printed Building 3



3D Printed Building 3



3D Printed Building 3



Site Drawing

