Contemplative Space:
Design for Generative Parametric Tessellations Applied to a Shell Structure

by

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I hereby declare that I am the sole author of this thesis. This is a true copy of the thesis, including my required final revisions, as accepted by my examiners.

I understand that my thesis may be electronically available to the public.

ABSTRACT

This thesis focuses on surface articulation of a shell structure constructed through a generative, parametric, modular design process. The shell form uses vault topology that adapts to varying site conditions such as topography and shape and that serves as contemplative space. Contemplative and aesthetic qualities have been achieved by analyzing aspects of spatial vernacular *muqarnas* and emulating aspects of their geometry within new surface ornament. By abstracting *muqarnas*, and exploring aniconic character informed by both vernacular precedent and contemporary parametric design methods, the design offers a specialized new interpretation of this historical type of ornament.

The design proposes an expandable master system. Two strategies based on this system are illustrated, both organized with similar components: columns (load-bearing modules) and bridges (modules for covering spans). Different behaviours are exhibited: first, symmetrical and homogeneous form and, second, non-symmetrical and heterogeneous form. The second layer of this complex system uses the topology of a vault system. A decoration system proposed for articulating interior-oriented surfaces is based on algorithmic geometry. This system offers two different characters, first inspired by *muqarnas* as a specific vernacular ornament, primarily from traditional Persian architecture, and second as a non-cultural, neutral ornament originating from computational design and achieved by deformation of mesh division. Software tool use is illustrated, demonstrating how scripted Grasshopper software components hosting custom C# code passages are used within a multi-layer design process.

Research informing this design focuses on historical and contemporary architecture. Contemporary precedents, "Arabesque Wall," by Benjamin Dillenburger and Michael Hansmeyer, and "La Voûte de LeFevre" by Brandon Clifford and Wes McGee are described. An analysis of these precedents explores how emerging digital technologies informed by history, can create a new design ecology and culture. Additional discussion considers cultural and phenomenological observations and aesthetics of the design in its physical and psychological

aspects, considered in contexts that range from topology of the form to visual perception of the internal “contemplative space.” This investigation indicates points of contact between arabesque art as vernacular ornament and contemporary, computer-based art. Computational and parametric design is considered with regards to its effect on contemporary design culture.

Parametric strategies, software, and C# coding used in the thesis are illustrated. The spatial ornament known as *muqarnas* is analyzed as one example of algorithmic ornament, illustrated through a contemporary “art of the knot” designed using parametric tools. In the last part of the research, features of the vault system are demonstrated historically and through individual examples of each kind. In parallel, contemporary shell structure and form optimization by means of computational simulation and morphogenesis are investigated.

The parametric system developed in the thesis design provides an opportunity to design a complex geometrical system that can be applied to shell-like envelopes. Design studies included within the thesis feature free-standing shelters capable of hosting a variety of public or private activities. Emphasizing visual and decorative qualities, visualizations of the applied design system are developed and positioned within sites in different locations.

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1.0 INTRODUCTION

This thesis focuses on a parametric, componential shell structure constructed through a generative modular system at global and local scales. The shell form uses vault topology as a historical precedent, is adaptive to various site topography, and serves as contemplative space. The contemplation of inner surface achieves through analysis of particular spatial ornament, *muqarnas* as a case study. The operation of its multiple layers of character and its contemporary interpretation developed further in the introduction. Beginning with the first question of this thesis—how is it possible to apply lessons from history, regarding aesthetic and topological notions, to design a contemporary architecture?— the work proposes two strategies in a multi-layer system that aim to show a fusion between historical and contemporary architectures.

This is achieved through parallel investigations in several areas, namely two precedents: "Arabesque Wall" by Benjamin Dillenburger and Michael Hansmeyer, and "La Voûte de LeFevre" by Brandon Clifford and Wes McGee; the contemplative sense in design through Laura U. Marks' argument in *Enfoldment and Infinity: An Islamic Genealogy of New Media Art*; the arabesque spatial ornament, *muqarnas*; and parametric methodologies and techniques to create a computational environment suitable for two proposed design strategies.

The relevance of the two precedents to the thesis design is, firstly, the use of historical precedents to inform contemporary architecture. In the first precedent, the design is generated through cultural geometrical ornament and aspects of arabesque art such as symmetrical and rhythmic form and an algorithmic system of two-dimensional, aniconic pattern. This system leads the thesis to an analysis of a spatial ornament originating in Persian architecture known as *muqarnas*, which is used in the first design strategy. In the second precedent, "La Voûte de LeFevre," the use of vault topology as a historical precedent and the modular system using distorted mesh division for the shell structure informs the second strategy of the thesis design. The similarity between precedents and design appears also in the projects' subjective





Figure 1-1 One example of the first proposed design strategy, Modular

Figure 1-2 One example of the second proposed design strategy, Vault

character as contemplative space, which can be seen especially in “Arabesque Wall” through its use of the algorithmic system of Islamic art generated with parametric techniques. The second point of relevance of the precedents to the thesis research and design is their use of computational methodology and techniques. Informed by these aspects, the thesis design uses a series of written C# codes incorporated with Grasshopper plug-ins in Rhinoceros (a three-dimensional modeler software), as well as a historic vernacular topology.

First, in both designs, the standard generative system called the “master system” is proposed at the global scale. At this level, the design can be changed based on various site’s regional character. The next sub-layer of the design in both strategies presents the form topology and geometrical decoration of the shell, which on the one hand are similar and on the other different—the topology of the system is similar but the character of the structure and geometrical componential ornament is different. Figure 1-1 demonstrates one example of the first strategy, code name, modular, proposed as a large-scale public space located in a contemporary city, Dubai. In the first strategy, the symmetrical forms of two modules, column and flat (bridge), are repeated along the master system based on the area of the site and the outcome is a homogeneous, modular system. Figure 1-2 demonstrates one example of the second strategy, code name, Vault, proposed as an open public space located in a historic setting, Palace Square in St. Petersburg, Russia. The second strategy, which also contains column and flat modules, proposes a heterogeneous, modular system showing a relaxed form of the vault topology using Kangaroo plug-ins as a form-finding tool.

Both strategies propose a stand-alone envelope. In the first strategy, the designed envelope acts as a decorative skin that can be applied to the conical surface attached to the truss and beam structure. For static purposes, structural elements such as beam and truss are manipulated to allow the design to perform as a stand-alone shell structure. the design offers speculation on how the structural elements can be oriented in terms of form topology. In the second strategy, the designed components are self-supported, meaning that changing the size of the mesh division and the thickness of the components determines the construction of the stand-alone shell structure. The inner geometrical ornament proposed in the two strategies are based on, first, cultural aniconism, Arabesque art, and lessons from history; here *muqarnas* is analysed as one case study, and second, the deformation of mesh division offered by computational design.

The aesthetic sense of the design, both in the whole topology of the form and the interior ornamentation, is considered beyond the purely visual. In *Enfoldment and Infinity: An Islamic Genealogy of New Media Art*, Laura U. Marks argues that using codes and algorithms not only in the primary system of aniconic arabesque art but, also, in the computational design behind the creation of all lines and surfaces, especially for the decoration and aesthetic sense, addresses both the subjective and objective characters of the design. This character creates a contemplative space that plays with the human senses, eyes and memory and is perceived differently depending on the beholder's wisdom. It invites us into itself by offering infinite contemplative information in one deep space. The great polymath Al-Haytham's point of view is that "perception is time-based, deductive, and subjective: it is perception itself that unfolds the world." He also argues that perception is based on the beholder's choice and happens in a ''glancing'' or ''contemplative way''.[1]

It is worthwhile to mention that in this thesis, not only does using the primary system of art of knot as an algorithmic system in the Modular strategy represent the contemplative character of the design, but the parametric design empowers this character as another algorithmic system. Both contain the infinite universe of data and code, unfold a part of this universe, and display haptic space as an image. Two seemingly infinite universes combined to create one infinite layer, dictating the complexity of the proposed design system.

This parametric, complex design provides an opportunity to design a complex geometrical system to be applied to the shell envelope as an object through the notion of subjectivity—an object that is familiar but still foreign, classic but contemporary. Invoking this system for creating a public space could be one possible realization—a shelter for protecting people from weather conditions, capable of hosting any suitable public or private activity.

The digital computation system proposed in this thesis provides the possibility of dealing interactively with all parameters, from form finding to small-scale interior components. It allows thinking about the "adaptive system," meaning that the system can be applied everywhere based on the geographical region of the design, activities, and desired scale. Emerging advanced technologies in design culture need an essential evaluation of parameters. These parameters are internal and process-coordinated by external limitation. Moreover, Ferda Kolatan and Jenny E. Sabin argue in *Meander* that parametric and computational

design create a different design culture and ecology in architecture, giving us an open-ended, infinite result. This book expresses how technology helps architects to define a new category of principles in terms of "techniques," "performance," and "aesthetic quality" in design culture and architectural practice in contemporary time.[2] Kolatan and Sabin continue:

> These advantages afford the ability to address design research in terms of rational construct. Systemic evolutionary models fully invested in multiple concepts of time, qualitative difference, and ecological context.[3]

From this research, the second question of the thesis appears: how can designers deal with this unbounded method of design given the limitation of reality based on optimum fabrication, responsive structure and aesthetic values? In the thesis design, the outcome is developed based on these boundaries and constraints.

1.1 AREAS OF RESEARCH

According to the digital-vernacular character of the thesis, the overall research area is divided into two categories, historical and contemporary. The representative of the historical area is architectural topology, while the contemporary approach is using computational principles and digital technologies.

In the first area of research, two precedents are described. In different ways, each of them shows a fusion between history and the contemporary—one by using vernacular ornament in the same way as the thesis proposes (arabesque art) and the other by choosing vault topology, creating the componential surface using mesh division, and considering the historical vault topology as a form. It also considers the structural behavior of the vault system and its analysis through computational techniques, but this type of analysis is not part of the thesis design scope. They each show the different aspects of computation and parametric design in this research area. The first example, called "Arabesque Wall," by Benjamin Dillenburger and Michael Hansmeyer, demonstrates advanced usage of a 3D printer for big structural forms with high detail complexity. In this project, in the system of the design, the architect, Dillenburger, uses the aniconic character of Islamic pattern by the means of a computational generative tool. [4]





Figure 1-3 **Top** First Precedent, "the arabesque wall", by Benjamin Dillenburger and Michael Hansmeyer

Figure 1-4 **Bottom** Second Precedent, "La Voûte de Le-Fevre", by Brandon Clifford and Wes McGee

The specific two-dimensional organic patterns from the history of Islamic architecture are used in this example. The rhythm and symmetry of this kind of architecture clearly show themselves in the form topology and the pattern emerges in the depth of the design, creating the complex form of the art. The rhythmic features and interwoven form of the pattern of this art play with the perceptions of viewers. The pattern gives various visual and mental perspectives to different people, exactly in the same way as the subjective character of the thesis design. The similarity of this strategy to that used in the thesis is that the identified pattern decoded with the aid of computational digital techniques creates a contemplative art craft, which frames the first design strategy. In the second precedent, "La Voûte de LeFevre" by Brandon Clifford and Wes McGee, the fusion between past and contemporary architecture is clearly perceived. The aim of this design is to use the "stereotomic vault" structure and create the contemporary topology with the aid of advanced computation and technological fabrication.[5]

The analysis of this precedent indicates the result as a contemporary vault componential surface created from mesh division. After simulation and calculation of the structural aspects and the aesthetic notions of the design, the integration of the performance of the components and their weights is considered. Structural behavior, as considered in this precedent, is not used as a key aspect to inform the thesis. Rather, the relevant aspects of this precedent that help to frame the second design strategy are its use of historical vault topology in a contemporary way and the computational techniques used to generate the design system, such as mesh relaxation for creation of form and distortion of mesh division for creation of components.

In the next level of research, the idea of "contemplative space," referring to the subjective character of the design, is explored. As Marks argues, this idea can be observed in aniconic art created based on algorithm and codes. She shows that these features are the points of contact between arabesque art and new digital art.

Marks proposes a system called the "enfoldment-unfoldment aesthetic." Briefly speaking, she demonstrates that both, arabesque art and new digital art contain the three layers of "infinite," "information" and "image," making visible the invisible information from an infinite universe as a readable image (art). A single observer, based on their subjective position,

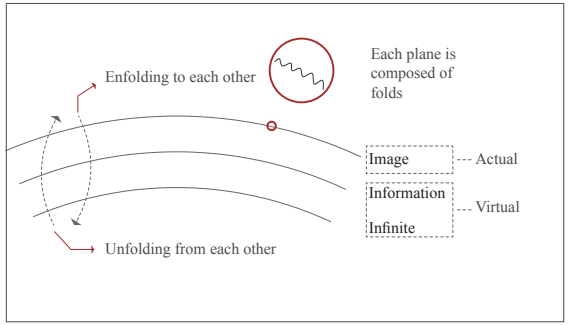


Figure 1-5 **Top**

Diagram from Enfoldment-Unfoldment Aesthetic system, proposed by Laura U. Marks, demonstrating the similarity between Islamic thought and new digital media.

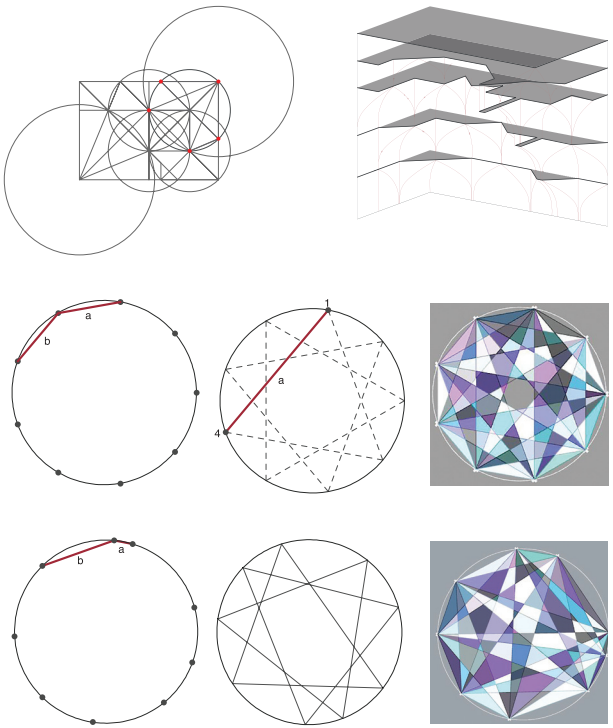


Figure 1-6 **Group** **Left**, Position of each tier; height and transmission lines according to the method of fabrication
Right, Extracting the main parameters: circle, divider points, and connection lines, based on two-dimensional analyses of the system of patterning

Figure 1-7 **Middle** system of Proposed Parametric Design, Persian Art, ‘’Art of knot’’, Even Mode

Figure 1-8 **Bottom** system of Proposed Parametric Design, Persian Art, ‘’Art of knot’’, Random Mode

perceives it differently from another observer. [6] In this chapter, after studying the subjective character of arabesque art as a vernacular art, the point of contact with new digital media as a contemporary practice is explained.

In the fourth chapter, the value of computational design and emerging technology in the field of architecture is studied, followed by an explanation of the integrated computational system used in the thesis. For achieving the desired goal in the parametric design, this specific part of the design is initially developed with standard Grasshopper native components. In response to the complexity of the parametric solution, this decision is later altered to scripting using the C# programming language. This part of the thesis is developed through an external association with Peter Fotiadis, who wrote the primary C# code related to the design. The provided code was combined with the native Grasshopper components hosted by Rhinoceros to generate the thesis design. The coding details, according to the program and software used in this design system, will be elaborated later in the chapter.

In Chapter Five, an analysis of the vernacular spatial ornament called *muqarnas*, originating in Persian architecture, is illustrated. One historical case study, located in Isfahan, Iran, is selected and an analysis of all the functional components involved in the creation of *muqarnas* is demonstrated. This part of the thesis decodes the two-dimensional and three-dimensional geometrical system of this ornament, which is converted into the contemporary parametric design proposed in the following part. The key parameters in the two-dimensional pattern are revealed through step-by-step analysis; figure 1-6 left, indicates the last step and one highlighted circle, their divider points, and their linkage as main parameters. Moreover, the initial parameters involved in the projection mode are figured out through analysis of the construction method; figure 1-6 right, demonstrates the applied tiers on different levels and the connection lines between them in the pattern.

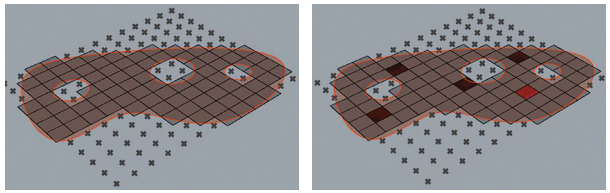
First, the proposed parametric design; figure 1-7 (even mode) and figure 1-8 (random mode), shows the main parameters in the creation of the two-dimensional arabesque pattern, namely the circle, points as divider, and the connections between the points. Then, the designed pattern is projected onto the dome topology as inflated modules to give a similar sense as *muqarnas*. ‘‘Even’’ mode refers to the square system of arabesque art, but the ‘‘random’’ mode has the same system which by changing only one parameter it can enrich the complexity and contemplation sense of the design, and also increase the aesthetic sense. The proposed pat-

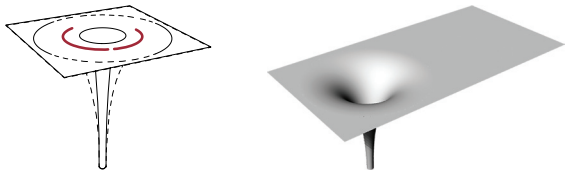
tern system is used in the first design strategy. Called the “modular” strategy, it is inspired by cultural ornament and can apply only in specific locations identified with this art language.

In the last research chapter (Chapter Six), studies of selected historical vault topologies are carried out. Research about the history of the vault as the only way to cover long spans, its structure and behaviour, and illustrations of the main kinds of vault structure are presented. The contemporary research looks at the shell structure, its behaviour, and optimization to achieve an efficient form. Also, multi-objective optimization, so-called “computational morphogenesis,” and the role of innovative simulation in achieving optimum form and structural behaviour is briefly described. [7]

The two proposed design strategies, Modular and Vault, and the design process from development of the form topology to the interior generation are described using diagrams, illustrations and a theoretical explanation of the applied system with various examples. The following chapter offers several site potentials for each design strategy. The series of selected sites is based on parameters such as scale and region to show the implication and application of the design for public space activities. Because the first strategy uses vernacular ornament of arabesque art, the sites proposed are based on their identity: Isfahan, Iran and Dubai, UAE. No specific genealogy is provided for the decoration of the second strategy because of the use of a neutral aesthetic resulting from deformation of the mesh division. It has global features and is not designed for any specific location.

The different sites proposed to show the potential of this design include St. Petersburg, Russia and Las Vegas, USA. In the first strategy, a bus station in Isfahan and, in the second strategy, Palace Square in St. Petersburg, are chosen as places to show the design at a small scale and, more importantly, how contemporary architecture meets history. To demonstrate the design at a large scale, Al Mamzar Island, Dubai is the site for the first design strategy and a mixed-use public space in Las Vegas serves as the site for the second strategy.





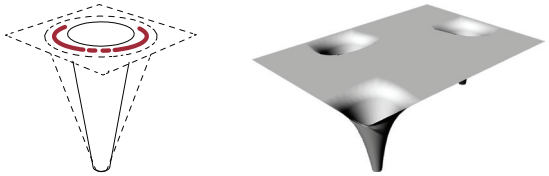


Figure 1-9 **Top** Master System, standard level of Design

Figure 1-10 **Middle** Form Topology in Modular strategy

Figure 1-11 **Bottom** Form Topology in Vault strategy

1.2 DESIGN SCOPE

The design includes three main parts: the master system; the first design strategy, code-named “Modular”; and the second design strategy, code-named the “Vault” strategy. The two strategies, Modular and Vault, contain three layers of making. The first step is standard for both, capable of expanding based on the region where the design is implemented. In both strategies, all levels of the design are part of one generative, modular system, which is a global grid system for form topology and patterning that has one root.

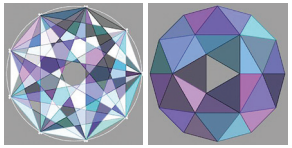
As the standard level, the master system entails a rectangular grid pattern in X and Y axes, generated based on the boundary of the geographical region. This system provides actions such as “taking” and “storing” modules. The desired, selected modules act as columns, and the remaining modules acts as bridges between the columns. In parallel, the “deleting” action can eliminate modules sequentially or all together.. The main parameters considered in this step; figure 1-9, are region, size of the modules and the numbers of the modules in both directions.

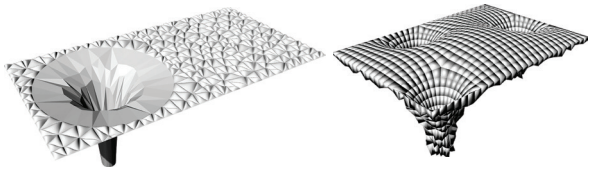
After achieving the modular base system with regards to its main purpose, two strategies are proposed for the shell structure. Both are based on the same system, and contain two modules: the column, for load bearing, and the bridge, to connect the columns. The only differentiations are in the congruence/regular features of the whole system and the surfaces used. In the first strategy, all conical units are similar and the surface used is NURBS (non-uniform rational B-spline). In the second strategy, by contrast, each unit is different—the system is heterogeneous—and the surface used is Mesh. The topology shape is formed in the primary step of both strategies, and each parameter of the modules such as height, radius factor and scale is considered. Because of the method of using the physics engine for finding the form in the Vault strategy, other parameters such as spring force, mesh division and gravity values are considered as a way to change the shape and height of the modules of the shell structure. The division size of the mesh surface can also be varied based on the scale and complexity of the form.

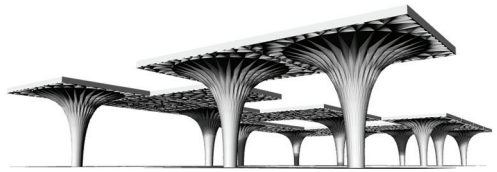
After achieving the topology of the form, the method entails the creation of a pattern to project onto the form using tessellation. In the “Modular” design, the pattern inspired by *muqar-*

nas is first introduced. Two options are proposed—star and aggregate patterns—in different modes of random and even. The origin of the system contains the circle and divider points, as well as a way of linking between points. All parameters are the same as the system ingredients. Based on point population along the region, the second option is offered with three sub-options. In the first and second sub-options, the parameters are the offset circle and the point division in the inner circle. In the third, the parameters are the measurement between inner and outer circle and a count of the division points. In the second "Vault" strategy, the mesh division distorts, and its parameters are the density of division points and the vertices of division, creating three and four faces.

The third step for both strategies is creating the solid component based on the pattern. In the first design, the pattern is projected onto the cone and flat modules. Then, the solid components, for which the thickness and projection factor are the critical parameters, are created. Finally, in the Vault strategy, the distortion mesh creates a solid component for which thickness size is considered. Also, another option called elimination, representative of a contemporary way of thinking is provided, which randomly eliminates the solid to create a porous design. In the end, the two proposed strategies combined with the master layer represent the full system of the design. Figure 1-15 in the following page demonstrates tree diagram of all steps integrated within the design scope.







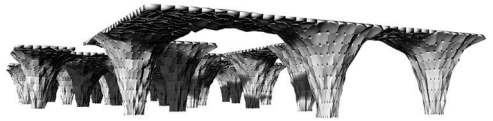


Figure 1-12 **Top** Patterning step in Modular strategy

Figure 1-13 **Middle** Solid making
Left: Modular strategy
Right: Vault Strategy

Figure 1-14 **Bottom** System combination with Master step,
Top: Modular strategy
Bottom: Vault Strategy

THE DESIGN SCOPE DIAGRAM

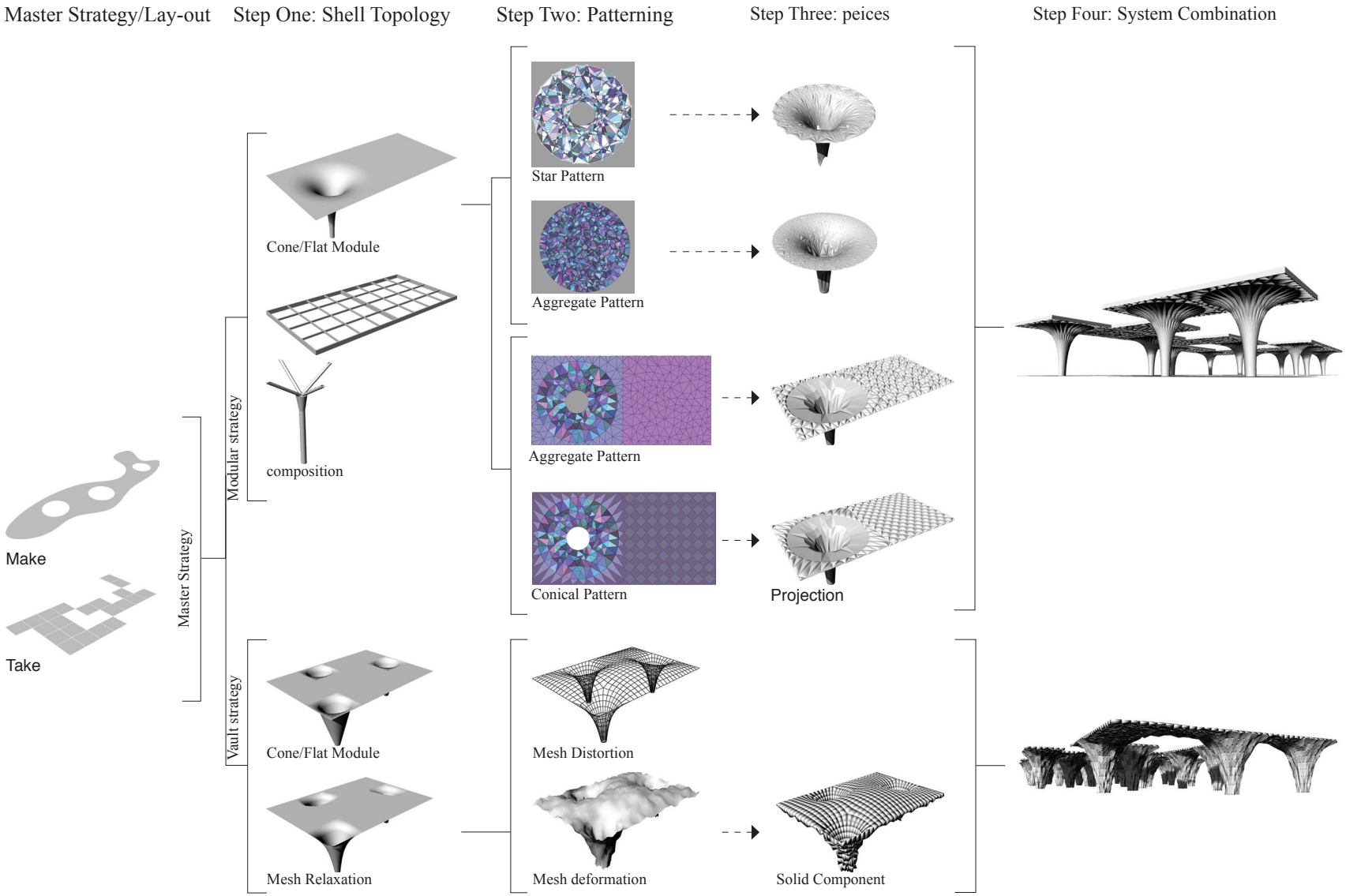


Figure 1-15 Tree diagram of all steps integrated within the design scope.





Figure 1-16 **Top** Grasshopper components, plus C# code for Kangaroo engine, in the Grasshopper Environment, used in the design system

Figure 1-17 **Bottom** The portion of the written C# Code

The general design is represented by a modular strategy of conception in both the topologies of the structure and of the ornament, defining a historic and contemporary architecture. This approach also shows an aesthetic sense based on psychological and physical perception, attempting to reach the senses at the level of the sublime and "mysticism."[8]

In this method of design, reductionism is not perceived in the visual result. It invites us into itself and offers infinite information in one "contemplative space." Although the profound sense of information is only readable by those who can perceive the line and the universe of the code behind it, the first sense taken from this space is intended to be pleasant and wonderful.

Parametric design is integrated into the whole system presented in this thesis, from its origins and visualization of the abstract lines to enhancing the creation of a deep haptic space. During the design process, this field was enriched through the wonderful contribution with Peter Fotiadis, the author of the C# codes, who kindly shares his experience in terms of parametric and computational design based on codes and programming. The following section of the introduction explains the specific software used for scripting and modeling to achieve the desired goals of the thesis.

1.3 PARAMETRIC DESIGN

The thesis, alternatively, used a C# scripting approach integrated with parametric/graphical editors as a parametric method, achieving the desired goal in a shorter time.

First, the selected environment of the design is Rhino used as the surface NURBS modeler, then, in the Grasshopper graphical layout, the native component is dragged and dropped and connected based on data organization, which visualizes the information contained in the C# code and creates a contemporary parametric environment. Two figures show part of the computational design environment used in the second strategy. The first figure (1-16) illustrates the Grasshopper components in the form-finding step of second strategy combined with the C# codes; the second figure (1-17) shows the hidden C# code used in a specific part of the design. It is worthwhile to mention that "no native component (other than the ones used for controlling primitive geometry attributes: colour/visibility) can be found in the definitions used. Many methods exploited are not available at all in Grasshopper as it ships."[9]

ENDNOTES

1. Laura U. Marks, *Enfoldment and Infinity: An Islamic Geneology of New Media Art* (Cambridge, MA: MIT Press, 2010), 62.
2. Ferda Kolatan and Jenny E. Sabin, *Meander: Variegating Architecture* (Exton, PA: Bentley Institute Press, 2010), 8.
3. Ibid., 16.
4. Morgana Moriero, "Further analysis into 3D printing: Looking at the 3D printed computational architecture, the 'arabesque wall,' made by Benjamin Dillenburger and Michael Hansmeyer," *Materials Innovation*, accessed August 2016, http://mgcarla.tumblr.com/post/136604685030/further-analysis-into-3d-printinglooking-at-the
5. Brandon Clifford and Wes McGee, "La Voûte de LeFevre: A Variable-Volume Compression-Only Vault" in *Fabricate: Negotiating Design & Making*, ed. Fabio Gramazio et al. (Zurich: gta-Verlag, 2014), 146-53.
6. Marks, *Enfoldment and Infinity*, 6.
7. Sigrid Adriaenssens et al., *introduction to Shell Structures for Architecture: Form Finding and Optimization* (London: Routledge/ Taylor & Francis Group, 2014).
8. Gülru Necipoğlu, *The Topkapi Scroll: Geometry and Ornament in Islamic Architecture* (Santa Monica, CA: Getty Center for the History of Art and the Humanities, 1995), 191.
9. Peter Fotiadis.

2.0 PRECEDENTS

In this chapter, two relevant precedents are analyzed: *Arabesque Wall* by Benjamin Dillenburger and Michael Hansmeyer and *La Voûte de LeFevre* by Brandon Clifford and Wes McGee. In both precedents, as in the thesis design, vernacular architecture is used in a contemporary fashion by means of computational and digital technologies in design and fabrication. Again relating to the thesis design, the method used in each precedent is algorithmic generative geometry, with lessons from history and computational design, in the first and second precedent, respectively.

Besides the similarity of the primary idea, each precedent has an approach similar to the thesis. The first precedent, *Arabesque Wall,* was selected because of its similarity to the first strategy presented in this thesis, with its two-dimensional pattern of arabesque art used as a vernacular, aniconic art with a symmetrical and rhythmic character. Even more so, they share similarities in terms of their subjective characters and personality.

In the first design strategy proposed in this thesis, the shell structure is a homogeneous, symmetrical, conical form, similar to the first precedent, whose form uses symmetry and rhythm. Then, the spatial geometry and ornament of *muqarnas*, a system of two-dimensional patterned arabesque art, is used as an inspiration in the patterning step of the design. This step is also informed by the "Arabesque Wall" precedent, which uses an aniconic, two-dimensional arabesque pattern to create a complex algorithmic design at different scales. The resulting aesthetic creates a subjective character, meaning that the line, system and code of both the vernacular pattern and computational design used to generate the project's final outcome create a haptic space perceived differently based on the beholder's senses and wisdom.

The second precedent, *La Voûte de LeFevre,* uses the vault topology and aims to model the volumetric, compression-only behavior by means of computational simulation, calculation and fabrication technology. The design topology of this precedent is a "stereotomic" shell structure created by crystallizing the mesh division, which bears a resemblance to the second strategy proposed in this thesis.

In the second design strategy proposed in this thesis, the shell structure has a heterogeneous form inspired by vault topology as a historical precedent, similar to this second precedent. The structural behaviour of the vault topology is also considered in this precedent, an aspect that is not within the scope of the thesis. Another similarity is the use of mesh surface division to create solid components, an approach which in this thesis is chosen to generate the volumetric components. Other options, such as the size and thickness of components, are considered in this thesis, which could further be considered as options to control structural behaviour.

In what follows, both precedents are investigated in terms of their conceptual idea, the purpose and method of the design, material use, fabrication, and structural behavior, if applicable.

2.1 ARABESQUE WALL

Benjamin Dillenburger and Michael Hansmeyer

Purpose

In this project, Dillenburger, the architect, uses the aniconic character of Islamic pattern and the "intricate constellation" to create an ornamental topology at the scale of the particle called "algorithmically generated geometry." The piece achieves the desired geometry by using "a computer program with a graphical user interface that allows you to draw geometric objects and to adjust them dynamically."[1] *Arabesque Wall* demonstrates advanced usage of 3D printing for both the large-scale form and the highly complex, micro-scale detail.



Figure 2-1 3D-Printed *Arabesque Wall*, by Benjamin Dillenburger and Michael Hansmeyer





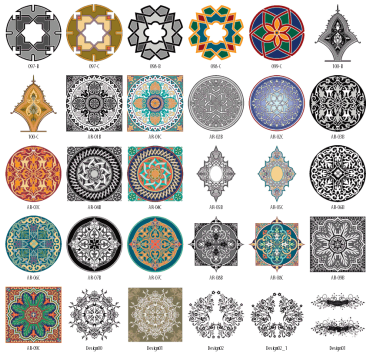


Figure 2-2 **Top** 3D-Printed *Arabesque Wall*, showing the Symmetrical Design

Figure 2-3 **Bottom-left** The basic structure and motif pattern.

Figure 2-4 **Bottom-right** The patterns used in *Arabesque Wall*

Design

The form is inspired by traditional symmetry shown in the figure 2-2; it is rhythmic, the interwoven curvature and the arabesque pattern provide a subjective character to this art, playing with the perceptions of viewers and giving various visual and mental perspectives to different people. The principles of the design for both factors, form and pattern, follow the geometries and mathematics based on "iterative tiling and division of surfaces."[2]

Structure

The structural system is driven by two basic forms laid on a two-dimensional arabesque pattern, the spiral and the kapali. The figure 2-3 shows these two aspects; the turquoise are the spiral points and the white one is kapali. They are created in parallel layers; then, the motif curves are generated inside these lines to create an interwoven effect.

One is the bones of the pattern and second is the motif shape inside the primary structure, like two layers on top of one another.

The motif's patterns, shown in the figure 2-4, are the kinds used in the design, and provide a deep look inside the project.[3]

Material

The material used in this project is a silica sand made from crystal. This material is mainly used for industrial moulding and casting. The advantage of using this material in a 3D printing machine is that it is ready for casting and there is no need for baking.

After printing the project, a coating application is required, which preserves the whole structure. The coating helps to protect the structure's fragile detail from erosion.[4]





Figure 2-5 **Top** The coating process preserves the structure.

Figure 2-6 **Bottom** *Arabesque Wall*

2.2 LA VOÛTE DE LEFEVRE

Brandon Clifford and Wes McGee



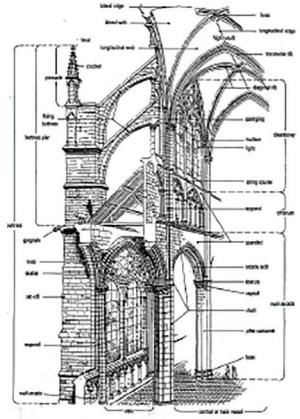


Figure 2-7 **Top** *La Voûte de LeFevre*, first prototype

Figure 2-8 **Bottom** Section, Amiens Cathedral, showing compression-only structure in vault topology used in the past.

Purpose

The design seeks to demonstrate the possibilities of contemporary fabrication technologies given historical experience and knowledge, and considering the volume's role in the vault system. The research proposes a thin-shell, compression-only structure. The thin shell is a new approach to providing material efficiency, and the compression-only system is identified as an ancient method. The architect of this design proposed a system to determine the potential of the compression-only structure with a "variable-volume unit." The purpose is not returning to the past but, rather, it is a method to improve on forgotten historical knowledge using the latest methods of fabrication.

The project starts with the question: "What would it mean to produce a project dedicated to volume, permanence, and weight?"[5]

The structural behaviour of forms designed by architects in an imaginative and conceptual way are often difficult to deal with. And in most cases, the form will change during the process of design. But in this project's strategy, not only is the aesthetic notion of the form topology considered, but the decoration also responds to the structural problem.

Method of simulation and calculation:

Two techniques are used to achieve the desired goal:
1. Particle-spring system
2. Volumetric physics calculation

In the particle-spring system, the form is composed of particles that connect to the “linear elastic spring.” In this system, each particle has its place, vector, and mass: each one is different from its neighbour. This system is required for both form-finding and calculating the different load points. Moreover, the “thrust vector” is calculated and its force is solved by redirecting it to the thickness of the material. [6]

Design

First, structurally, the virtual, non-ideal geometry is created with the compression-only system. After fixing the desired form, a volumetric calculation is performed to estimate the weight of each unit. This means that if unit number one is twice as heavy as unit number two, the hollow method does not work and the material takes this into account.

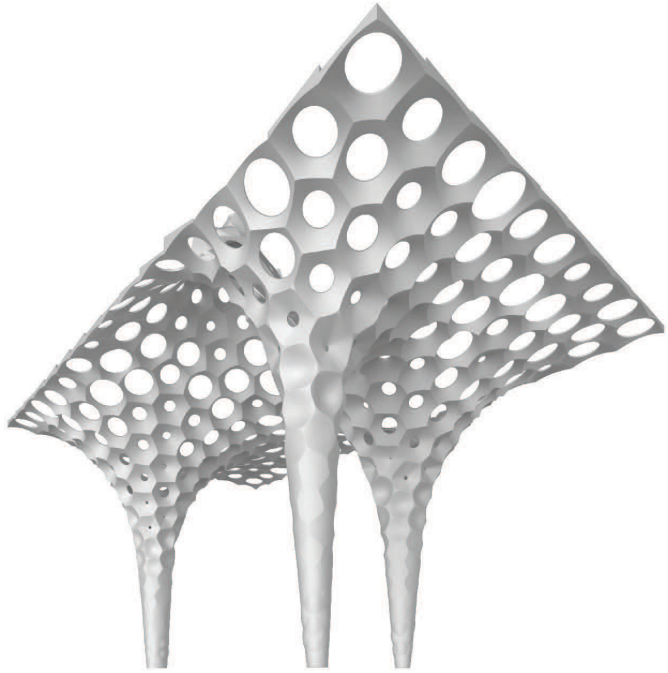


Figure 2-9 **Top** 3D model, *La Voûte de LeFevre*, using the Particle-spring computational simulation method.



Figure 2-10 **Top-Left** Diagram of the calculation of the variable volumes, showing the equalization of volume of the enclosed surfaces with the vertical thrust on the particle.

Figure 2-11 **Top-Right** The particle-spring system, showing nodes beyond the geometry.

Figure 2-12 **Bottom** Bulge outward in column

Then, the particle-spring system is applied: the particles cover the whole surface, including the upper and lower boundary. On this level, the system needs another particle-spring system to relocate the particle's nodes into a suitable position over the surface and increase their distances when they reach the upper side.

For developing the units and preparing them for fabrication, the calculation needs three factors: top and below the edge of the surface; the position of each particle on each unit; and the depth of each unit, which is considered during form-finding. Each particle finds a "virtual thrust network" during the calculation, when they move to find equilibrium.

Each particle in its place creates a three-dimensional "Voronoi" and joins with the lower parts of the geometry. The centroid point finds the closest point with the top parts and shapes a circle. The curve and circle generate a surface by loft action and are trimmed from the whole. The back side of each unit is flat so it can lay on the CNC machine bed.[7]

Bulge Outward in Column

This design attempts to show the transition from the column to the vault. In this design, this is not real but an illusion. Clifford argues that, in reality, the column and vault are different. A column is a single solid unit, and the vault is fragmented. The reason for this "false reality" is the use of wood, illustrated by the texture. Each column has the thrust vectors inside, which are vertical. Clearly, the column cannot stand horizontal thrust. In other words, it is impossible to continue the component to the ground. To solve this, the architects of this design use "rhetoric," a new strategy, which is "Conical-Boolean." It symbolizes a gradual shift from components to a smooth solid. The creation of the "bulge outward" illustrates the force in the column because of the load of the vault overhead.[8]

Fabrication

In this design, the machine used for fabrication is CNC (Computer Numerical Control), with a 5-axis Onsrud router. Through tool-paths called swarfs, this machine eliminates the material to reach the effort weight. The edges of the tools are used to eliminate the material instead of a point bit, because this method can trace the geometry with lines against the points.[9]

The relevance of the two precedents analyzed in this chapter, *Arabesque Wall* and *La Voûte de Lefevre*, to the proposed design (Modular and Vault strategies) can be summarized in two main points. The first is the key idea behind the designs, which is the integration of historical design methods with contemporary architecture. This idea can be seen to manifest in each example in a way close to the spirit of the thesis, by using vault topology and arabesque art, with each of these represented in the Vault and Modular design strategies, respectively. The second series of congruence is the significant role of the algorithmic and mathematical system of arabesque art and the use of generative computational design and tools, as well as their effects on design and fabrication development and their impact on thinking through factors such as structure, form and aesthetics. The thesis combines these two points to build on the knowledge generated through the precedent projects to propose a complex design strategy, presented in the last chapter.



Figure 2-13 Fabrication by CNC (Computer Numerical Control) machine.

ENDNOTES

1. Morgana Moriero, “Further analysis into 3D printing: Looking at the 3D printed computational architecture, the ‘arabesque wall,’ made by Benjamin Dillenburger and Michael Hansmeyer,” *Materials Innovation*, accessed August 2016, http://mgcarla.tumblr.com/post/136604685030/further-analysis-into-3d-printinglooking-at-the
2. Benjamin Dillenburger, “Arabesque Wall,” accessed September 2016, http://benjamin-dillenburger.com/arabesque-wall/.
3. Adam Williamson, “Biomorphic Art: The Art of Arabesque,” accessed August 2016, http://artofislamicpattern.com/resources/introduction-to-islimi/.
4. Moriero, “Further analysis into 3D printing.”
5. Matter Design, “La Voûte De LeFevre,” accessed August 2016, http://www.matterdesignstudio.com/la-voute-de-lefevre.
6. Brandon Clifford and Wes McGee, “La Voûte de LeFevre: A Variable-Volume Compression-Only Vault” in *Fabricate: Negotiating Design & Making,* ed. Fabio Gramazio et al. (Zurich: gta-Verlag, 2014), 146-53.
7. Ibid.
8. Ibid.
9. Matter Design, “La Voûte De LeFevre.”

3.0 CONTEMPLATIVE SPACE

This chapter aims to explain an important aspect given consideration in the proposed design, called contemplative character. This concept is analogous to the subjectivity of the design, besides its objective feature. This section of the thesis argues how the aesthetic values of the design, generated by the algorithmic tessellation ornament—based on arabesque art as vernacular strategy and deformed mesh division as a computer-based method—can enrich this character of the design. The first move is understanding exactly what contemplative space is, followed by an explanation of the subjective features and points of similarity between the two strategies.

3.1 WHAT IS CONTEMPLATIVE SPACE?

The word "contemplative," used in this thesis to denote a specific character given to a space, arises from the notion of infinity. Another word for introducing this concept is subjectivity, meaning that the subjective features create an impersonal, "contemplative" space that is perceived differently based on the beholder's wisdom. The abstract line, moving along the surface, creates a haptic space and plays directly with the eyes and human senses. The abstract line is the best way of introducing the art, because it is the only way to make visible the invisible.

The deep invisible information is laid down, layer by layer, in a complex system, which becomes visible based on the perception and faculty of judgment. This enlarged, complex system is a "zone of indetermination," meaning that this is a time-based art, a large zone in which the "inner capacity" for perception is infinite. An infinity is created in the space, waiting to be discovered.[1]

This so-called contemplative space acts as a mediator, similarly to an ornament within new digital media. This space gives a different experience to different people, not saying exactly what it means and what is behind it, but capable of being perceived differently.

In *Enfoldment and Infinity*, Laura U. Marks proposes the system of the "Enfolding-Unfolding aesthetic." This system, which will be demonstrated in this chapter, shows the three main layers of the artwork, "Infinite, Information and Image." The "image" is the perception, which, as mentioned above, is read based on the intellect and sense of the beholder. Marks argues that the similarity of new digital media to Islamic art is inevitable, and both have the three main features of "invisibility, legibility and aniconism."[2]

Marks shows how the abstract lines of arabesque art create this so-called contemplative space, then compares it with digital art to argue that it has the same character—in her view, new digital media has the same objective-subjective features; in other words, it too represents the actual-virtual world. The virtual world or subjective feature related to the universe of code and algorithm appears in parallel with the actual world or objective feature related to the perceptible image and outcome. This concept enriches the idea of the thesis, because both of the proposed strategies try to reveal a contemplative space by considering its subjective character, one by



Figure 3-1 Si-o-seh pol, Isfahan, Iran, 1602

using the aniconic, algorithmic geometry of the arabesque art using computation design and, the second by using a deformation method offered by computer-based art. They are both based on algorithmic geometry deployed within a rational system. This means that they show a specific way that "the image unfolds from the imperceptible: that relationships can be known rationally.[3]

The first strategy, inspired by *muqarnas* as a geometric ornament using a mathematical system, referring to "fractal patterns, patterns that are recursive, scalable or self-similar and contain an infinite length within a finite boundary."[4] The second strategy uses the basic surface division system, which the computer inherently offers as a mesh. What this means is that the result of both is creating a contemplative, subjective value for the space by considering the aesthetic sense.

3.2 OBJECTIVE-SUBJECTIVE CHARACTER OF ARABESQUE ART

Aesthetic of Proportion in Architecture: Objective Character

The concept of having taste, or *dhawq* in Arabic, is defined as the power to understand the aesthetic sense, which creates an emotional quality. The same system applies to the science of music, and it has two sides, the theoretical and the practical. It also concerns grammar, logic, and rhetoric, and can have an effect on the soul. The arts of music, poetry and calligraphy are based on craftsmanship or *fan* (Arabic), meaning that all fields of art are related to science.

In relating various art forms, Jerome W. Clinton wrote of Persian manual versification that "from the point of view of the literary critic, at least, poetic aesthetics and the aesthetics of art were co-extensive."[5] Additionally, "[t]he epistle in love and ideal beauty argues

that one loves only beauty (al-husn), a natural emotion that makes the ear and the eye long for harmonious sounds and compositions."[6] Proportion and harmony are very often involved in aesthetics. For example, in music and poetry, two things are involved in creating beauty: the science of proportion and the modality of harmony. All arts applying the principles of ratio and proportion become pleasant and beautiful. Proclus has an argument about the beauty and order of mathematical discussion; he said that the beauty of mathematical discourse brings us to the intelligible world, creating a memory of things that are always stabilized, and brilliant with divine aesthesis.[7] He noted that geometry "arouses our innate knowledge, awakens our intellect, purges our understanding, brings to light the concepts that belong essentially to us."[8]

Psychology of Visual Perception: Subjective Character

The spiritual attraction of art is due to its objective-subjective features. This art has a sense of imagination, or *mutakhayylia* in Arabic, inspired by surrounding organic life, such as a web made by a spider or a honeycomb made by bees. The Persian polymath Ibn Sina argued that the collaboration of inner senses such as imagination, cognition, and aesthetic perception with the rational and intellectual senses that distinguish us from animals, creates this objective-subjective art. The structure of the spirit and its activities, senses and the relationship between them and their hierarchy are all the important things that an artist should consider for creating a piece of pleasant art, transferring a message or giving a specific feeling to human viewers. This beauty is only perceived by the eye of the heart, not the eye.[9]

Ibn Sina linked two important factors that an artist possesses: the internal sense of imagination and estimation, meaning the creation of abstractions of imagination and going upward to the next level, beyond materiality. Besides the five senses, he also added two more: the "common sense" coordinating the internal sense and "recollection," restoring forgotten things in memory. According to this philosophy, perceptions happen at three levels:

Inferential perception: a pure sensation such as light and colour
Glancing perception: embodied in visual memory
Contemplative perception: when it takes a long time to perceive because of unfamiliarity and complexity.[10]

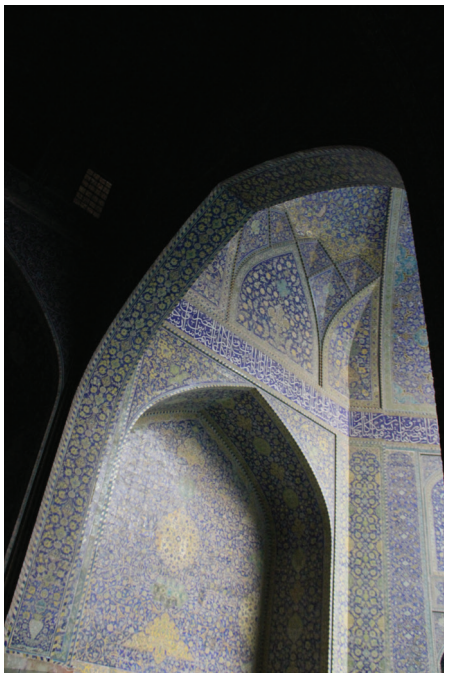


Figure 3-2 This image aims to show how an algorithmic, decorative interior; light; colour; and calligraphy play an important role in creating a contemplative space.

3.3 DIGITAL MEDIA ART AND THE ENFOLDING-UNFOLDING SYSTEM

This section aims to describe the analogy between the fundamental principles of Islamic art and new media art. Laura U. Marks conducted extensive research about the fact that contemporary media art has profound origins in Islamic art and philosophy. In her book, *Enfoldment and Infinity,* Islamic art refers to arts for religious and ritual intents, or even not strictly religious but for Muslims of specific cultures. New media art refers to computer-based art, which is basically created through code and algorithm.[11]

Enfolding-Unfolding System

Marks proposed a new theory of similarity called Enfolding and Unfolding and illustrates the relationships of the visible, legible and invisible that define both Islamic art and new media art. Generally speaking, in both, "a point can unfold to reveal an entire universe. ...The idea of Enfolding-Unfolding is the complete form of Deleuze's viewpoint about the Labyrinth.... The smallest unit of matter is the fold, not the point. Each fold being connected to the entire plane, has a point of view on the whole."[12] This vast plane, called the "Plane of Immanence," contains an infinite number of folds, and "sometimes one of these enfolded units unfolds and becomes actual."[13]

"Image," "Information" and the "Infinite" are three layers of the Enfolding-Unfolding concept proposed by Marks. Deleuze has the same idea about the cinema, or time-image, as the best contemporary media. It has two planes of infinity (virtual state) and the plane

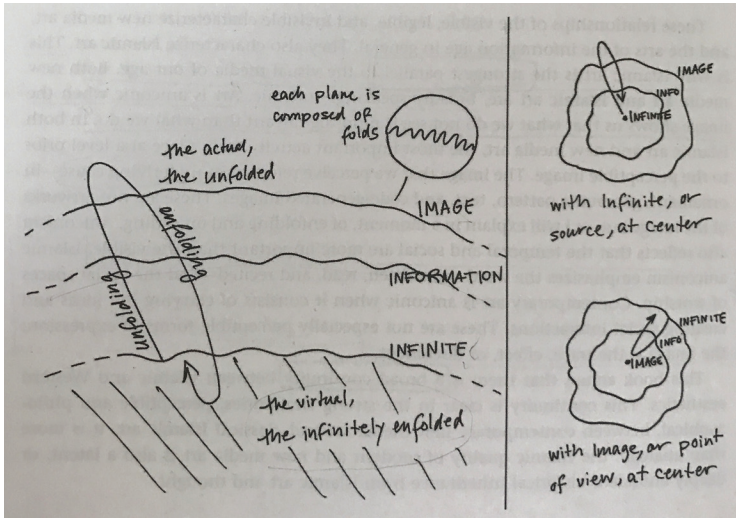


Figure 3-3 «Image," "Information" and the «Infinite» are three layers of Enfoldment-Unfomdment System, proposed by Laura U Marks showing the similarity between New digital Media and Islamic Thoughts.

of the image. Time is considered infinite and images unfold from this infinity.

Marks proposes the third plane exactly between them: the plane of Information, "[a] plane through which the semiotic process passes before images can arise."[14] These three layers "enfold each other and unfold from each other."[15]

The infinite field or the plane of immanence is an interface for information and the information is an interface for the image. As is clear from the diagram in Figure 3-3, the infinite layer is not perceived, but is contemplative and "can be known by perceptible effect." Then, Image and Information are the result of the unfolded, specific aspects of this infinitely enfolded realm and become actual.

These three levels are real, and categorized into two groups of virtual and actual. The virtual is the prerequisite for the actual and comes from the infinite level. The actual is all existences, within which information and image are a subgroup.

Enfolding-Unfolding in Computer-Based Artwork

All computer-based media art comes into the visual, perceptible world through layers of codes and algorithm. The infinite area of codes and programs acts as the interface for another infinite layer: from the act of the programmer to all material and energy consumption. Some of these codes and algorithms are readable, close to the human language, mediating between user and hardware. This mediation can happen in different layers to perceive the final result: World (Infinite), Code (Information), Perceptible (Image). [16]

Enfolding-Unfolding in Islamic Art

In Islamic Art, comprehensible artifacts such as calligraphy make observers conscious of other underlying codes, which perhaps have a complex series of interfaces and emanate the idea of the word Qur'an toward GOD. But the interesting point is that the perception is different for individuals depending on their beliefs and faith. Mohammad Arkoun, invoking ninth-century Iraqi thinkers, said that "there is no access to the absolute outside the phenomenal world of our terrestrial, historical existence"[17]: God (Infinite), Word (Information), Perceptible (Image). [18]



Figure 3-4 Calligraphy Art, Sheikh Lotfollah Mosque, Isfahan, Iran

There are thus seven points of contact between Islamic thought and the concept of digital art. Each point is described for, first, Islamic art, and second, digital art, and then the way it is considered in the design part of the thesis. It is worthwhile to mention that because of the use of an actual algorithmic system (aniconic arabesque art) combined with virtual algorithmic tools (parametric design and programing) in this thesis, these points are enriched two or three times and can define deeper layers of the system.

1. Unity

Islamic Art: *Tawhid* (Arabic) for all believers of Islamic thought comes from *wahid* (Arabic), meaning "one." This word is repeated many times in the Qur'an and relates to God.

Digital Art: Algorithms provide a sense of unity in this field, because information is created from them and decomposes to them.[19]

Thesis Design: selecting the square as the only geometry (unit) in all steps of design.

2. From Unity Arises Infinity

Beside unity, how could God be infinite?
Islamic Art: there are two ways of thinking:

• Absolute unity: God has no attributes and character like humans and animals and instead of quantity, has qualities such as power, goodness, and knowledge.
• Emanation, meaning that God is one and the universe is infinite, and the universe emanates from the unity of God. In another word, God is the first principle of everything, like one, which is the first principle of other numbers. [20]

Digital Art: All computer-based art creates an infinite virtual world that derives from the algorithm or smaller entity.[21]

Thesis Design: in the design strategies, the square is the only geometry used and developed at different scales; in other words, self-similarity is used at different scales of design from the Master system to the interior surface pattern. The square is considered as the only geometry (unit), from which infinite algorithms and data arise at different scales, showing infinite lengths in a finite boundary.

3. Unfolding is Directional: A Concept of Vector

Islamic Art: instead of representing God with symbols or icons, Islamic thought brought orientation towards God, indicated on a vector or trajectory. This is a sign toward Mecca.[22]

Digital Art: It is also directional and it returns to the networking of "remote users," who are "a large group of people, remote from each other in time and space, all focused their efforts towards a center of attention, cheered in the awareness that others have done so and would do so in the future." [23]

Thesis Design: All steps of the design can focus individually on the general scheme and affect the outcome. They all have one purpose, but can work independently and activate individually to create changes; the direction of all the data are toward one same purpose.

4. Unfolding is Performative

Islamic Art: the art of knots and calligraphy are two examples in Islamic art that show the word of God and the sense of unity and infinity. These arts also invite observers to contemplate and read. [24]

Digital Art: one task of computer-based concepts is to unfold algorithmic instructions and Visualize complex interdependence and new information. [25]

Thesis Design: Parametric design tools such as Grasshopper, as a graphical editor, open an opportunity to visualise the otherwise invisible codes and algorithms within the design system.

5. Aniconism

Islamic Art: it is aniconic because God is represented with the senses and words, which are mediations between God and observers. It cannot indicate with symbols and iconic figures because infinity cannot be unfolded.

Digital Art: there is no way to make visible the infinite field of codes and algorithms behind digital art: “The infinite cannot be presented.” It illustrates them in a way in which we can read and listen to them.[26]

Thesis Design: The thesis design itself defines aniconism because of its use of codes and algorithm; it is impossible to visualize the infinite information behind the system.

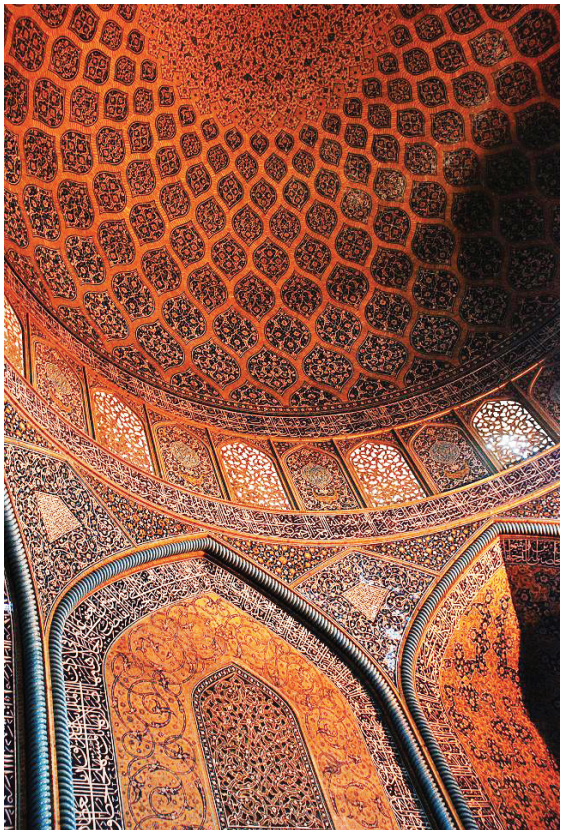


Figure 3-5

Aniconic arabesque art, inside of Sheikh Lotfollah Mosque, Isfahan, Iran.
These images aim to show how algorithmic geometry, surface division, light, color, and calligraphy play an important role in creating a contemplative space.

6. Abstract Line and Haptic Space

A mode of abstraction is created because of the aniconic features of these arts. More importantly, this is the only way to make visible the invisible and to present the infinite. The abstract line and haptic-space are two forms of presenting without using figurative icons, as considered by Deleuze and Guttari. This abstract form of art, when line and shape move freely, brings different senses and implications to different observers. [27]

The proposed design strategies act as abstractions because of their aniconic features. This means that part of the information of the infinite universe of data unfolds the proposed design and creates a contemplative space which is perceived differently by each beholder.

7. Embodied Perception

In both Islamic and computer-based arts, "the work of art plays out in time, unfolding image from information and information from the infinite"[28]—from forming the algorithms to the recognition of the observers, which is not yet the final result. In Islamic art, the body is not important to present as an icon, but it is important as a "medium of reception."[29]

Islamic philosophies based on rational thought consider the "internal faculties" as an important mediation between perception and intellect. In other words, "[p]erception is time-based, deductive, and subjective, it is perception itself that unfolds the world."[30]

There are two modes of perception: the immediate (senses) and the contemplative (faculty of judgment). As Ibn Sina said, the observer, by the aid of senses and mind, converts the perceptions into the abstract visual art of the depiction created in the brain.[31]

In thesis design, the perceiver requires memory and a comparative ability for judging the work; those with imaginative power have this ability to perceive the subjective or virtual character of work. The thesis design acts as a mediator, it does not transmit the actual meaning but an effect on beholders, who may imagine it in different ways.

ENDNOTES

1. Laura U. Marks, *Enfoldment and Infinity: An Islamic Geneology of New Media Art* (Cambridge, MA: MIT Press, 2010), 18.
2. Ibid., 2.
3. Ibid., 151.
4. Ibid., 156.
5. Gülru Necipoğlu, *The Topkapi Scroll: Geometry and Ornament in Islamic Architecture* (Santa Monica, CA: Getty Center for the History of Art and the Humanities, 1995), 185.
6. Ibid., 187.
7. Ibid., 191.
8. Ibid.
9. Ibid., 198.
10. Ibid., 191.
11. Ibid., 32.
12. Ibid., 5.
13. Ibid., 37.
14. Marks, *Enfoldment and Infinity*, 4.
15. Ibid., 5.
16. Ibid., 10.
17. Ibid.
18. Ibid.
19. Ibid., 37.
20. Ibid., 38.
21. Ibid., 39.
22. Ibid., 43.
23. Ibid., 47.
24. Ibid.
25. Ibid., 49.
26. Ibid., 52.
27. Ibid., 57.
28. Ibid., 61.
29. Ibid.
30 Ibid., 62.
31 Ibid., 63.

4.0 PARAMETRIC DESIGN

As the main method of thinking through the design process and the use of its tools as the performative techniques for realization of the thesis design, parametric design plays a central role in this thesis. Parametric design has created a new design culture in architectural practice, generating a range of possibilities and solutions.The algorithm and code realms of the system are used as ways of dealing with computational morphogenesis and multi-objective optimization in the design of the shell structure. Also, using parametric design as one aspect of a computer-based methodology because of its relationship with mathematical design using code and algorithm, enriches the contemplative character of the thesis in the aesthetic sense. This character of parametric design relates to Marks' argument about infinite information and image layers integrated in digital media art systems, which was discussed thoroughly in a previous section (Chapter Three). Because of the complexity of the thesis design, the computational method became a combination of C# code hosted with Grasshopper components and environment through the external contribution of Peter Fotiadis.

In the first part of this chapter, the comprehensive meaning of parametric design and its theoretical features are elaborated. Then, the specific parametric techniques and tools used in the thesis design are explained.

4.1 WHAT IS PARAMETRIC DESIGN?

As a new paradigm in architecture, parametric design involves specific factors to achieve a shift between static and active solutions. Algorithms and advanced computational techniques are not for generating the drawing but, rather, engendering rational possibilities; in other words, it is not about a solution but the group of possible consequences.

The main factors in parametric design are generating geometry and form defined by a group of crucial parameters and creating a rational relationship working in a loop. This system has a hierarchy between mathematics and geometry, which generates infinite possible solutions for the design.[1]

In "Digital Morphogenesis and Computational Architectures," Branko Kolarevic defines parametric design as a new paradigm in architectural design, in the sub-category of computational architectures related to computer-based developments of form and transformations, or "digital morphogenesis." He also explains Mark Burry's definition of parametric design:

> In parametric design, it is the parameters of a particular design that are declared, not its shape. By assigning different values to the parameters, different objects or configurations can be easily created. Equations can be used to describe the relationships between objects, thus defining an associative geometry, i.e., the constituent geometry that is mutually linked. [2]

4.2 THE NEW DESIGN CULTURE

In their book, *Meander: Variegating Architecture,* Ferda Kolatan and Jenny E. Sabin discuss computational design as a new design culture. They argue that this advanced technology has begun to fundamentally alter design thinking and understanding in research and architecture, both in theory and in practice. The resulting possibilities present a big shift in design culture and principle. In the first part of their discussion on the origins of generative design technique and parametric tools, Kolatan and Sabin say that "[g]enerative design techniques emerge with references to natural systems, not to mimic them but to work trans-disciplinary by translating the benefits of flexibility, adaptation, growth and complexity into the realm of architectural expertise."[3] They claim that parametric design tools are not only for running the workflow, but form part of an "intelligent design ecology" in which various important factors and dynamics connect and respond to each other and the entire design system like a loop.[4]

The Subjective Feature of Parametric Design

As discussed in the previous chapter, computational design and digital art have the same character as aniconic art, which is based on algorithm and code, using data from the infinite universe and unfolding the image. The result can be read based on the human sense and perception of the beholder. Parametric design, in a subcategory of this field of design because of its aniconic character and use of infinite code and algorithm to process information, therefore has a similar subjective personality. Moreover, the parametric tools used to generate the system and ideas have a performative character and can be used to enact performance.

In-Completion and Time-Based Design

In "Deference to Difference," William MacDonald argues that computational design through generative techniques is an evolutionary system understood in multiple concepts of time. This system can be evaluated by "qualitative" criteria related to "quantitative" utilization. Moreover, he brings up Stewart Brand's point of view in *How Buildings Learn,* which underlines these features as "in-completion and time" in architecture and follows Brian Eno's idea on "a teleconference on design"[5]:

> we are convinced by things that show internal complexity, that show the traces of an interesting evolution. Those signs tell us that we might be rewarded if we accord it our trust. An important aspect of design is the degree to which the object involves you in its own completion. Some work invites you into itself by not offering a finished, glossy, one-reading-only surface. This is what makes old buildings interesting to me. I think that humans have a taste for things that not only show that they have been through a process of evolution, but which also show they are still part of one.[6]

Ambiguity can be the result of a parametric design system and can have a positive sense for design, in that there is hope for continued change. This feature is realized because of the open-ended design, applications and infinite solutions offered by the system. This

open-ended, complex system, with a series of solutions based on combined actions, generates two methods: bottom-up and top-down. The top-down, “master plan” method is time-based, “a sequential time-phased mechanism.” It acts like the system of “part to whole,” meaning that one system incorporates multiple times and dynamic relations to create change through different possible scales.[7]

In the area of computational design, the hierarchical approach is still considered, but a new concept of hierarchy emerges. This hierarchy is laid out not only according to the order of design development, but also contains logical principles in which even details can affect the general organization and vice versa. In *Atlas of Novel Tectonics*, Reiser provided two diagrams demonstrating the classical, simple hierarchy and the complex hierarchy pursued in the thesis design. [8]

In this thesis, the design methodology is formed by both logics: a simple, top-down, hierarchy, consisting of several steps to develop the final parametric shell structure, and a complex, bottom-up hierarchy based on each particular step and details which have an inner hierarchy, which does not enable to exploit to their parts. This emergent approach in architectural design is defined as a whole-to-whole relationship. [9]

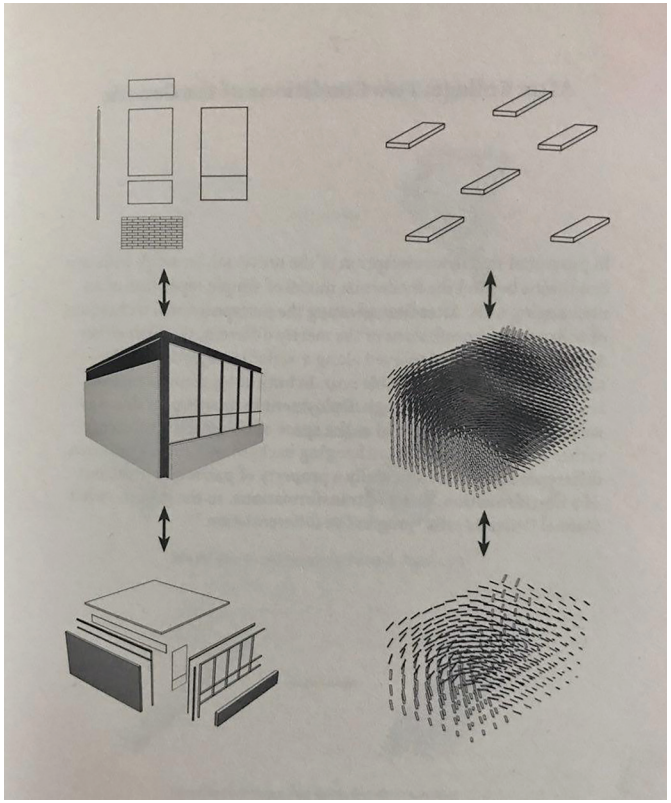


Figure 4-1

Left : ‘’Simple Nested Hierarchy: Whole Reducible to its Parts’’
Right: ‘’Complex Hierarchy: Whole More than the Sum of its Parts’’. From Reiser, *Atlas of Novel Tectonics*.

4.3 COMPUTATIONAL METHODOLOGY

In this thesis, a fully parametric approach is used to achieve the desired outcome. First, the conceptual idea from the patterning step is composed by the author using native components driven by Grasshopper plug-ins in Rhinoceros.

Because of the complexity of the thesis and proposed strategies at several dependent scales, the author of the thesis used an alternative contribution in the area of computational scripting. Integrating computer programming into the digital design procedure opens unique opportunities, enabling the designer to create and customize a suitable computational environment around their own design system and approach. It simplifies the complex system of modeling and also shortens the modeling time and extends time for design thinking. These aspects of emerging computational technology in architectural design lead this design, at this level of the work, to use an alternative route of C# code as a specific definition interface with a graphical editor to achieve the parametric design, shifting its potential.

For the design, the written C# code combined with Grasshopper as a “graphical algorithmic editor” and the custom definitions integrated with parametric components create a suitable computational environment. Furthermore, the code and Grasshopper elements are integrated with the larger algorithmic custom definitions such as Kangaroo, as a live physics engine.

Each specific series of C# code relates to each step of the design illustrated with Grasshopper components, and each series of code uses those components to mechanize the input and output data. In other words, the Grasshopper component mechanizes and launches the C# codes.

Firmware Constraints

Besides the clear advantages of computational tools and firmware, they have some constraints and limitations. The constraints are rarely taken into account at the academic level. A thesis usually proposes a way to exploit a new idea, not considering an optimum compromise between ideas vs. methods/procedures to achieve them in real life.

Here, the aim is to consider both new ideas and their real-life implementation in the best possible way, attempting to reach an optimum comprise between new ideas and reality. This can be considered at three levels:

1. The hardware’s abilities and limitations.
2. The minimum possible response time concerning the holistic parametric approach.
3. The capabilities of the parametric software used and the limita -tions of the hosting CAD application.

ENDNOTES

1. ParametricCamp, “What is Paramedic Design?” accessed November 2016, http://www.parametric-camp.com/en/what-is-parametric-design/.
2. Branko Kolarevic, “Digital Morphogenesis and Computational Architectures” (paper presented at SIGraDi, Rio de Janeiro, Brazil, November 25-28, 2000), 4. http://cumincades.scix.net/data/works/att/fbc9.content.pdf.
3. Ferda Kolatan and Jenny E. Sabin, *Meander: Variegating Architecture* (Exton, PA: Bentley Institute Press, 2010), 8.
4. Ibid.
5. William MacDonald, “Deference to Difference,” in *Meander*, 16.
6. Ibid.
7. Ibid., 17.
8. Jesse Reiser, *Atlas of Novel Tectonics* (New York: Princeton Architectural Press, 2006), 50.
9. Ibid.

5.0 MUQARNAS

In this chapter, one of the vernacular spatial ornaments and geometries of arabesque art, known as *muqarnas* and originating in Persian Art, is illustrated as a case study. The chapter aims to give a comprehensive understanding of this art, beginning briefly with its definition, materials, structural behaviour in buildings and methods of construction. Then, a specific example located in Isfahan, Iran, is analyzed from the two-dimensional system of the drawing to its system of tessellation. Next, the study is extended into computational design with inspiration from the "art of knot" (a two-dimensional system of arabesque art). The proposed design in this part, called Parametric Art of Knot, is developed and applied as the decoration for the first, "modular" design strategy.

5.1 WHAT IS *MUQARNAS*?

> The muqarnas is a vaulting system based on the replication of units arranged in tiers, each of which supports another one corbeled on top of it. The final result is a stairlike arrangement that is sometimes referred to honeycomb or stalactite.[1]

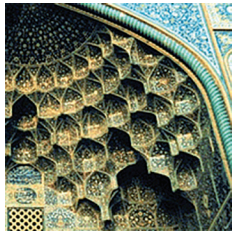


Figure 5-1 **Top** Mihrab, Sheikh Lotfollah Mosque, Isfahan, Iran

Figure 5-2 **Bottom-Left** Honeycomb, referring to the shape of *muqarnas*.

Figure 5-3 **Bottom-Right** Stalactite, refferring to the shape of *Muqarnas*





From Left to Right

Figure 5-4 **Top-Left**	Ceramic Tile
Figure 5-5 **Top-Middle**	Stone
Figure 5-6 **Top-Right**	Plaster Panel
Figure 5-7 **Bottom-Left**	Iwan
Figure 5-8 **Bottom-Middle**	Chapiteau
Figure 5-9 **Bottom-Right**	Corner

Material

The materials used in *muqarnas* compositions are wood, brick, plaster and stone. More recently, contemporary materials such as glass, metal and fabric have been used too.[2]

Building Location

Muqarnas units can be applied in various locations, namely inside an entrance vaulting, niche, minarets, column, etc.[3]





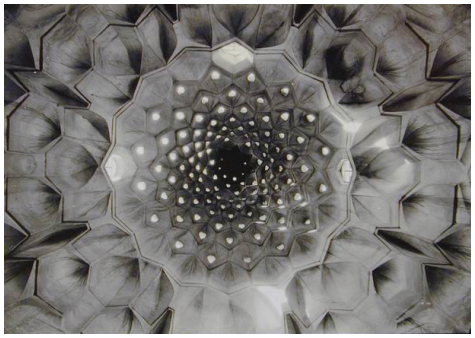


Figure 5-10 **Top** Exterior View, Nur al-Din Dome in Damascus, 1172

Figure 5-11 **Bottom-Left** Exterior view, Tomb of Zumurrud Khatun in Baghdad,1193

Figure 5-12 **Bottom-Right** Interior view, Tomb of Zumurrud Khatun in Baghdad

Behaviour

Muqarnas can generally be seen from inside a vault and in some cases, it is also visible from outside. Two images show the spatial shape of *muqarnas*.[4] Besides the self-supported structural performance of *muqarnas* in some cases, it has decorative features, in which all units are suspended or connected to the structural component.

Chronological and geographic origin

There are many arguments about the chronological and geographic provenance of *muqarnas*. Whether it originates in the northeast of Iran in the tenth century or North Africa and Baghdad in the eleventh century, the important fact is that "by the twelfth century, the *muqarnas* has become a common unifying feature connecting the diverse architectural productions in several countries from North Africa to Iran."[5]

Etymology of the word muqarnas

The etymology of *muqarnas* is obscure. It has Greek origins in *Koronis*, and is related to an English root, "cornice." The words listed under the root qrns show other meanings such as falconry (*qirnas*), a sword in the stair shape (*muqarnas*), and an overhanging cliff (*qirnas or qurnas)*: "The etymology connection between the topographic *qirnas* and architectural *muqarnas* is alluded to in Persian lexicons such as Ali Akbar Dihkhuda's (1879-1955) Lughat-nama."[6]

Methods of Construction

The Qajar method of construction is the most common strategy. This method is described by a master builder doing *muqarnas* in Isfahan. At first, the full size of a two-dimensional rectangle is drawn on the floor set with the size of the semi-dome and the outline of each level, or tier, is sketched. The design is started "by visualizing its three-dimensional projection on the basis of his traditional empirical knowledge."[7]

After finalizing the design without the aid of paper, black charcoal is used to draw the division into each tier. The top line of the lowest tier is a starting point at which slabs of *ghach* (plaster) are cast on the floor. Before becoming rigid, the slab is reversed and the pattern left by the black dust for next tiers. The same action is required for each tier.

Two-Dimensional drawing of Muqarnas, Art of Knot

> The mode of geometry design codified in these fragmentary scrolls was identified as the girih (Persian, "knot") by traditional central Asian master builders who still use such scrolls. This term refers to the nodal points or vertices of the weblike geometric grid systems or construction lines used in generating variegated patterns for architectural plans and decorative revetments in two and three dimensions (each "knot" center where a number of construction lines intersects has an n-fold rotational symmetry).[8]

The drawing's entire mathematical system is based on this creation.

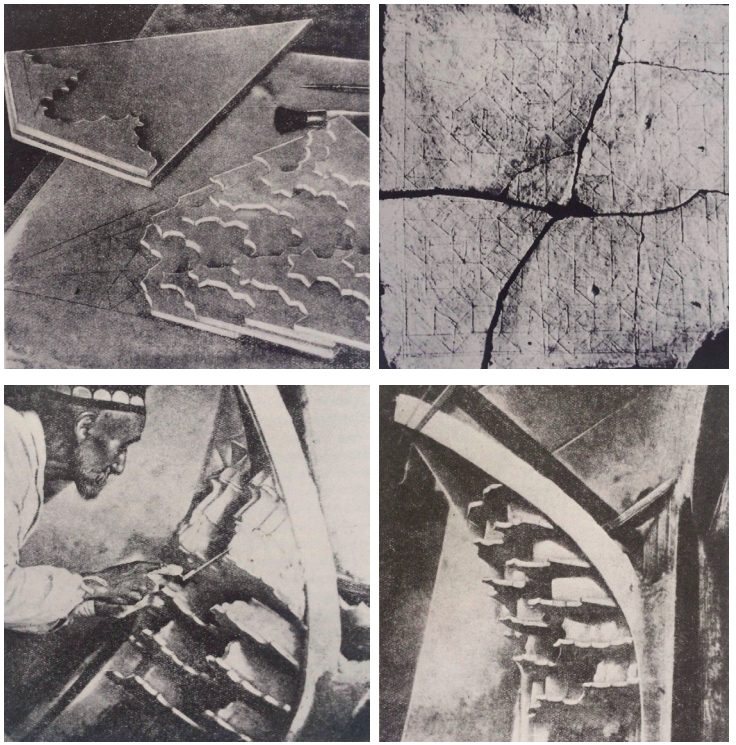


Figure 5-13 **Top-right** The first discovered drawing in Takht-i-Sulayman (1270) indicates on a 50-centimeter plaster slab the projection of the muqarnas vault.

Figure 5-14 **Top-left** Creating the tiers based on two-dimensional Pattern

Figure 5-15 **Bottom-right** Arranging in a suitable place and pour with Plaster, (Gach)

Figure 5-16 **Bottom-left** excavating the desired shape

5.2 ANALYSIS OF THE SPATIAL GEOMETRY OF *MUQARNAS*: CASE STUDY, JAMEH MOSQUE IN ISFAHAN

Because of the complexity of the system, the following analysis of the spatial geometry of *muqarnas* will focus on an existing example of one kind, located in Isfahan. The two-dimensional system of drawing and the three-dimensional, modular mode is shown in one of the semi-domed entrances in the Friday mosque in Isfahan. Through all steps of analysis of *muqarnas* by the author, the important characters of the pattern are defined.



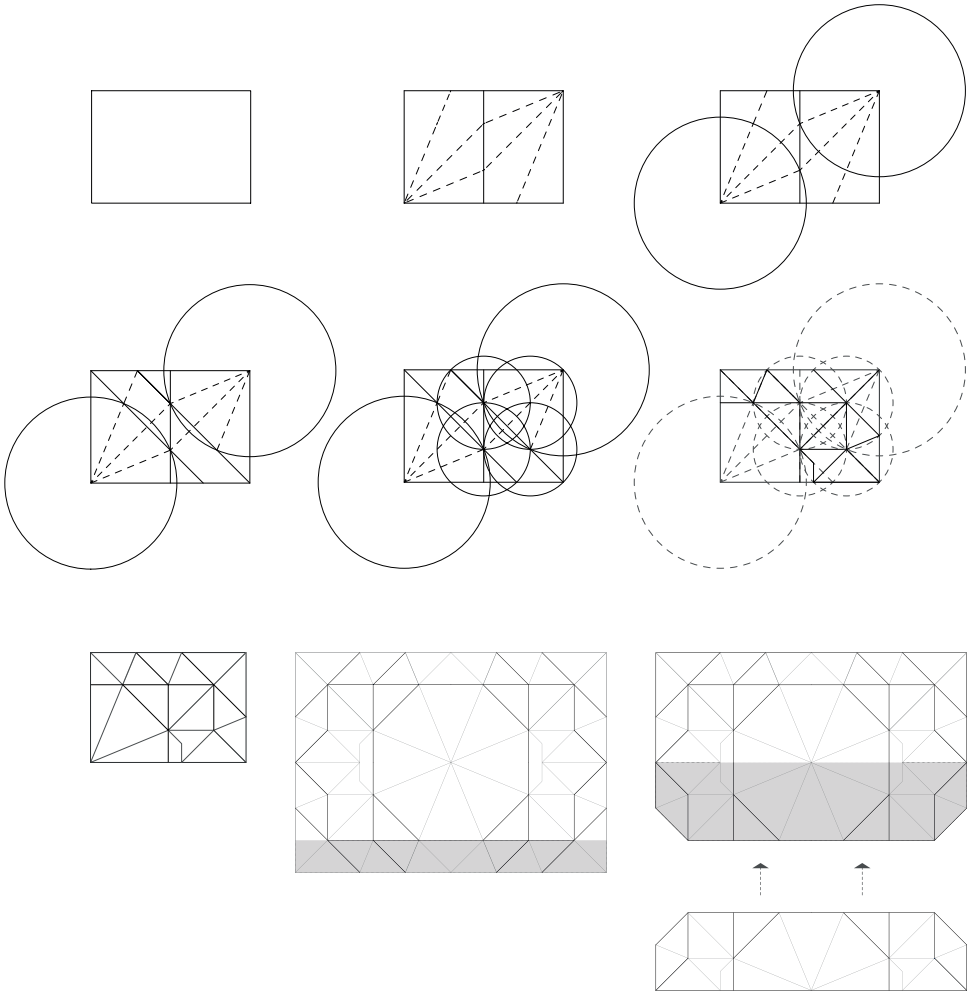
Figure 5-17 Courtyard of Jameh Mosque, Isfahan, Iran, showing three kinds of muqarnas in the entrances.

The steps of two-dimensional drawing



Figure 5-18 The square style of muqarnas, known as a “strong Primitive,” located on the south side of the Jameh Mosque.

Figure 5-19 The step-by-step method for the two-dimensional drawing of the case study:



From Top, Left to Right

1. Drawing the repeating part with actual proportions
2. Dividing the rectangular base plan in half, and at four equal angles from the top right and bottom left corners
3. Drawing circles with the length of one of the division lines as the radius
4. Connecting the two points that intersect with the circles with lines
5. Drawing four smaller circles with the size of the small middle line as radii and centers at the intersections of lines and circles
6. Connecting the intersection points as shown
7. Highlighting the main lines, construct pattern and keeping the final result
8. Repeating the base plan with two symmetrical reflections and removing the last row of lines, as shown
9. Selecting the colored part of completed pattern, which is half, and doing additional reflections, then attaching it to the whole

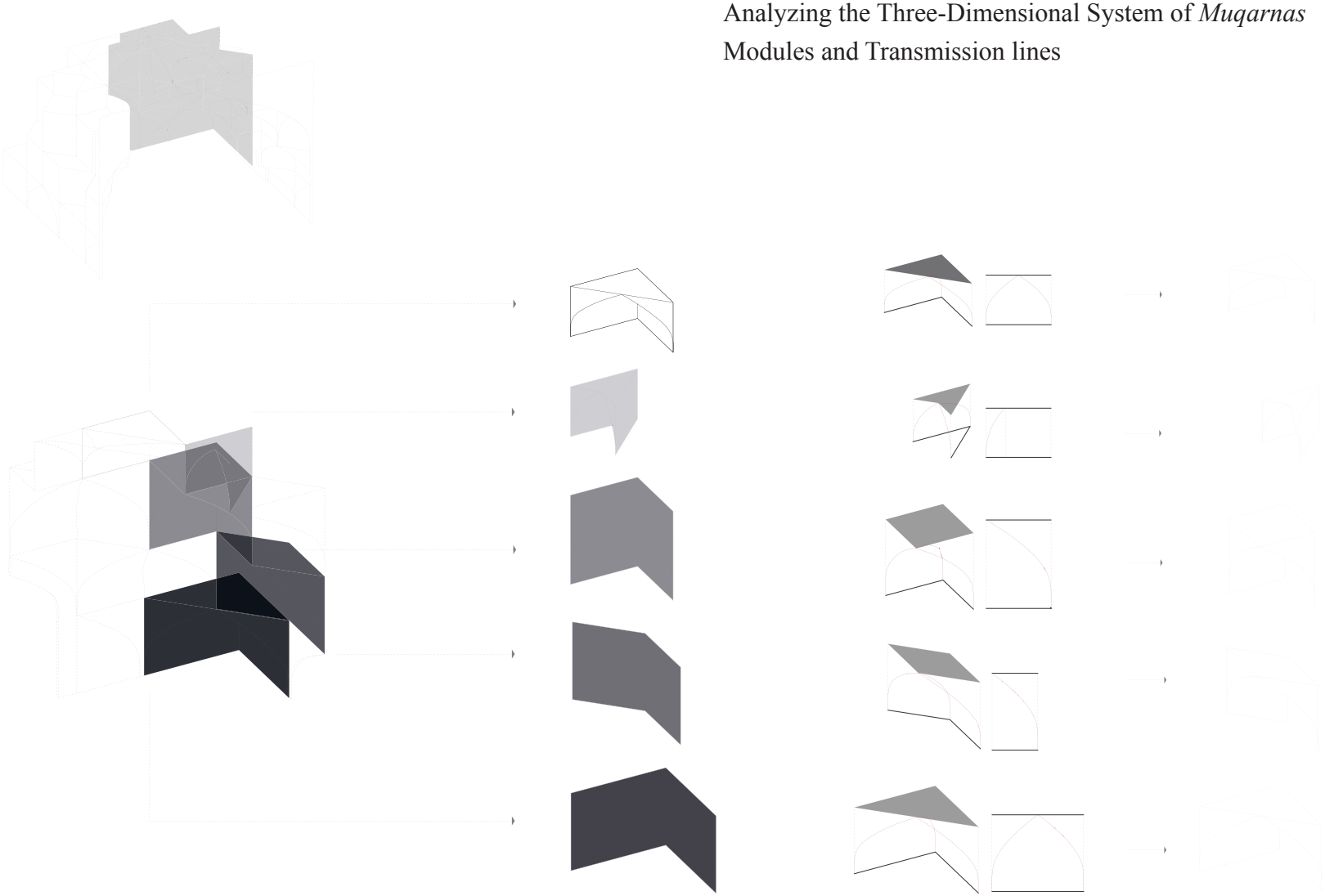


Figure 5-20 **Left** Different repeated modules of one quarter of the dome. Modules from top to bottom: Half Square, Biped, Square, Rhombus, Two Half Square

Figure 5-21 **Right** Position of each component, height and transmission lines

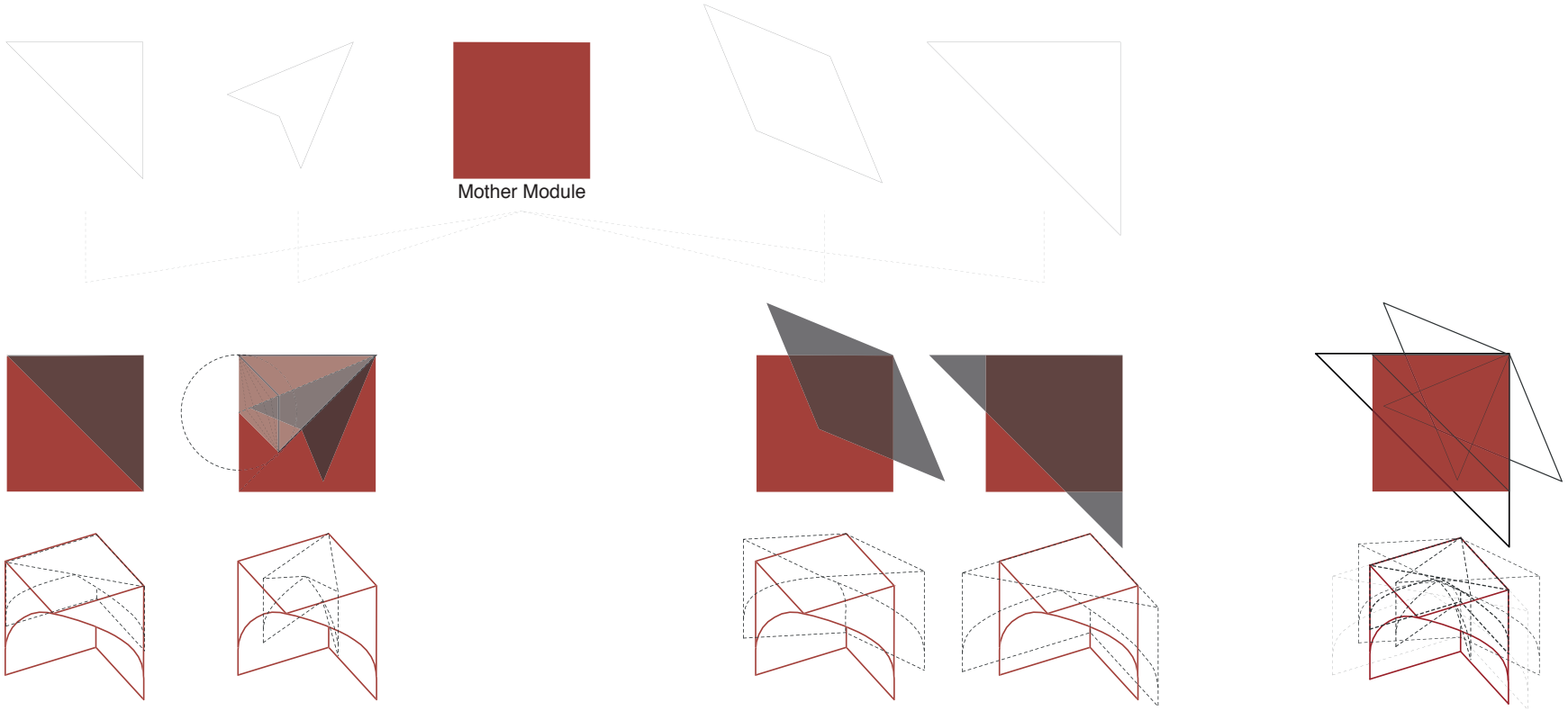


Figure 5-22 Comparing each module with the main, so-called “mother” component, and the mode of variegation.

Exploiting Key Parameters for Design

After analyzing *muqarnas* as a case study, the key parameters of the proposed design are generated, primarily for the Modular strategy. The method of construction and the relationship between the tiers of the two-dimensional pattern and their projection onto the form lead the design to a specific hierarchy. First thinking about the two-dimensional pattern and then applying the lines of tiers in subjected pattern on form topology to create a transformation from base plan to above boundary.

Also, through analysis of the two-dimensional pattern of *muqarnas* by the author, two important characters of the pattern are defined:

1. Four-fold symmetry, meaning that one quarter of the pattern is drawn as the origin and its other parts are created by twice mirroring the original part.

2. All lines are connected by divider points on the circles. This means that the interior pattern of the rectangular plan is generated by, first, the circles; second, divider points on the circles; and, lastly, the linkage of these points creates the desired pattern.

These factors form the main parameters of pattern creation and also a way of projecting the designed pattern on the form.

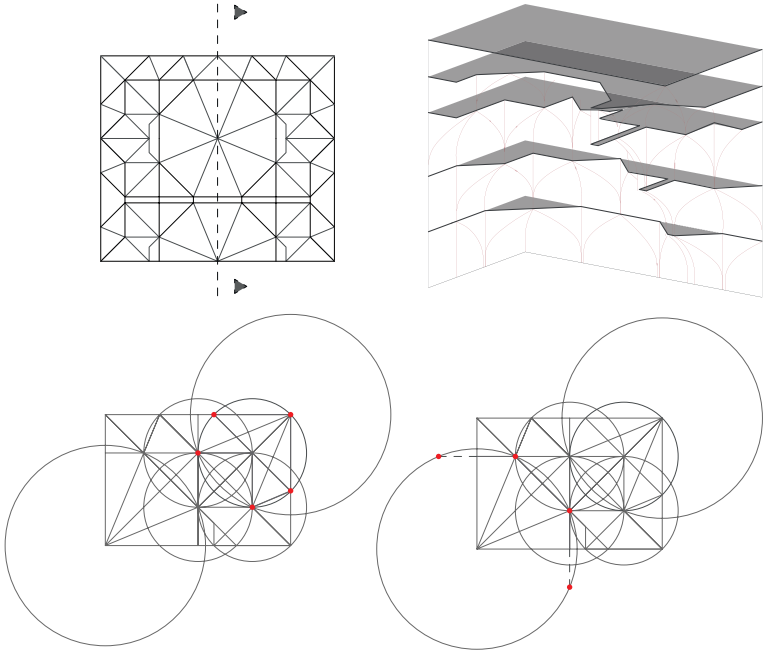


Figure 5-23 **Top** The system of tiers refers to the fabrication method, demonstrating projection of the outlines of the pattern, tiers at different levels, and their connection by Transmission lines.

Figure 5-24 **Bottom** The basic system of two-dimensional pattern used in *muqarnas*, demonstrating the main parameters to generate the pattern: the circle, the divider points on the circle, and the linkage between the points. Here, two random, large and small circles are highlighted.

5.3 THE PARAMETRIC DESIGN, ART OF KNOT, INSPIRED BY *MUQARNAS*

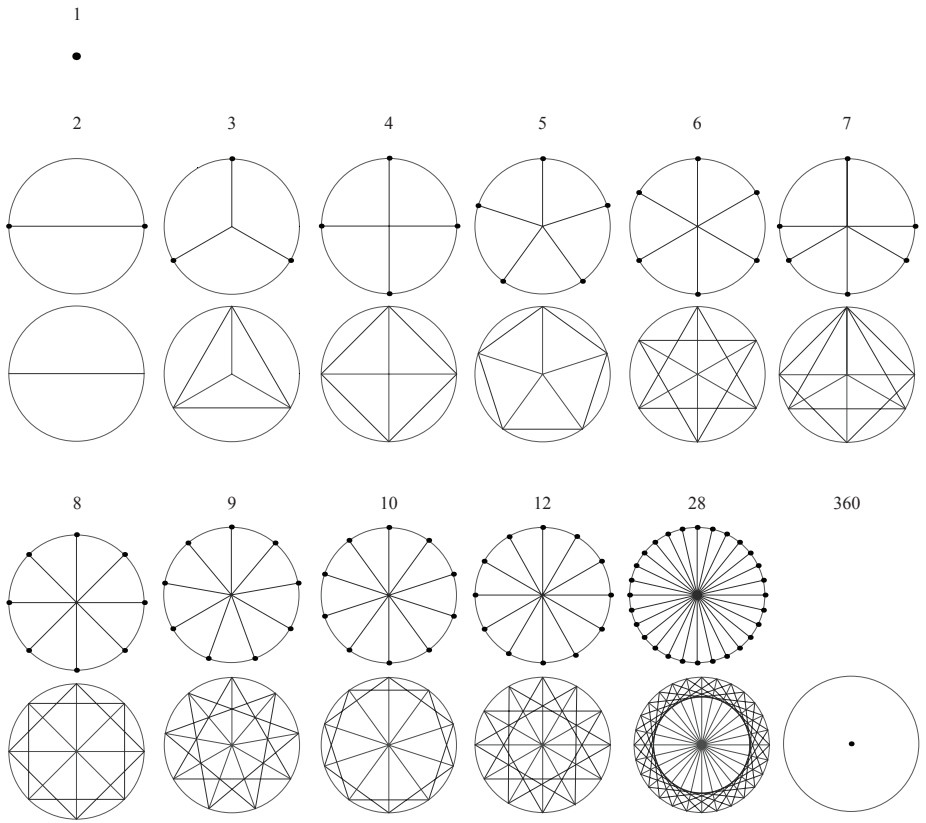


Figure 5-23 The primary system of Arabesque pattern is decoded from an analysis.

After analyzing *muqarnas* and extracting key parameters from the two-dimensional system and projection method based on tiers, the primary pattern system to be applied in the first design strategy is proposed. This system has the same drawing principles as the art of knot, or Girih (Persian), generated by Nader Ardalan and Laleh Bakhtiar in their book *The Sense of Unity: The Sufi Tradition in Persian Architecture.* The points as dividers start from 1 and increase to 360.

The system of two-dimensional pattern is defined by three parameters: a circle; the points, which evenly divide the perimeter; and the linked lines between points, which connect according to a specific system, which shows in figure 5-23.

Two-dimension pattern, ‘‘Even Mode’’

In the first step, the basic system of the star pattern is developed parametrically. It has the potential to change the main parameters of the knot pattern, namely, the size of the circle, the numbers of the points (giving variable length), and the system of connection. One mode of this pattern (division of circle with 9 points) is illustrated in different possible versions to demonstrate the complete system.

In this example, figure 5-24, the first row of circles shows the “shift” mode, providing a system for connecting the points with different steps. The line connects from the first point to the next point by one step, called “shift one.” Different versions can be created; instead of one shift, the line can jump to the second point, a procedure called “shift two,” and so on. shift number can increase based on the numbers of dividing points. The “branch” shows another mode, which creates a more complex pattern. The branch (n) shows how many lines (n-1) start to link. As can be seen in Figure 5-24, in the “shift two” and “branch three” mode, the first step starts from the second neighbor and creates the first branch, but for creating a second branch as demanded, the point jumps to the third point rather than the second. The first step starts from the shift mode and could be increased, but not more than four steps. If it requires more branches, past the fourth step it starts from the last shift that was not used.

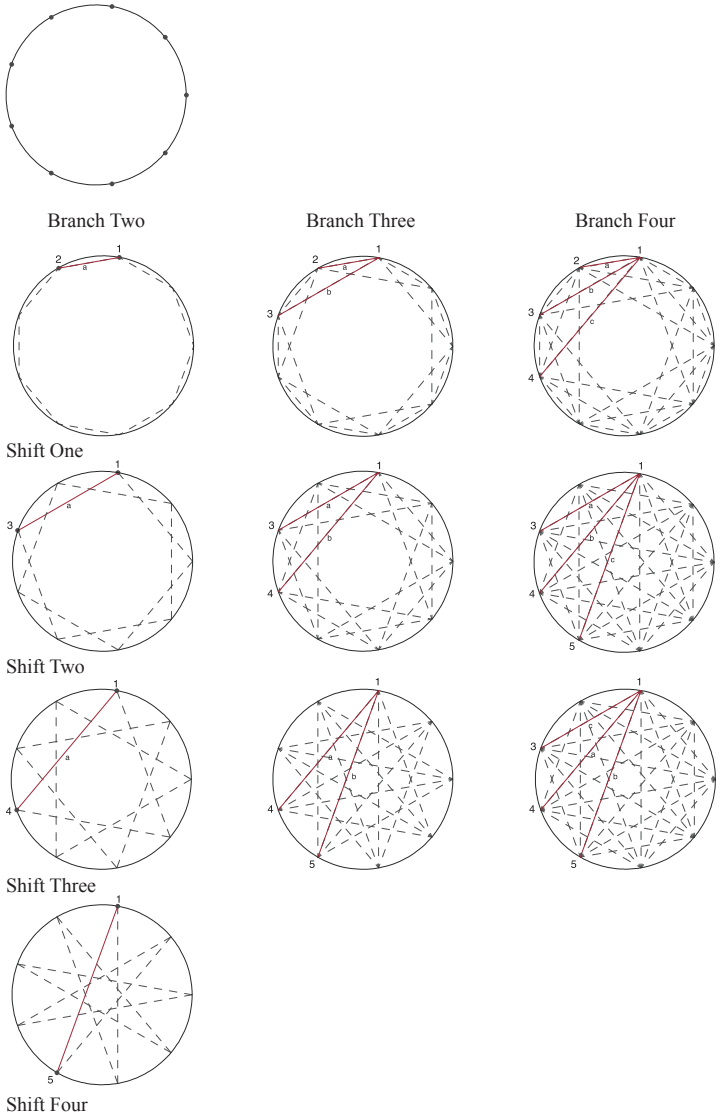
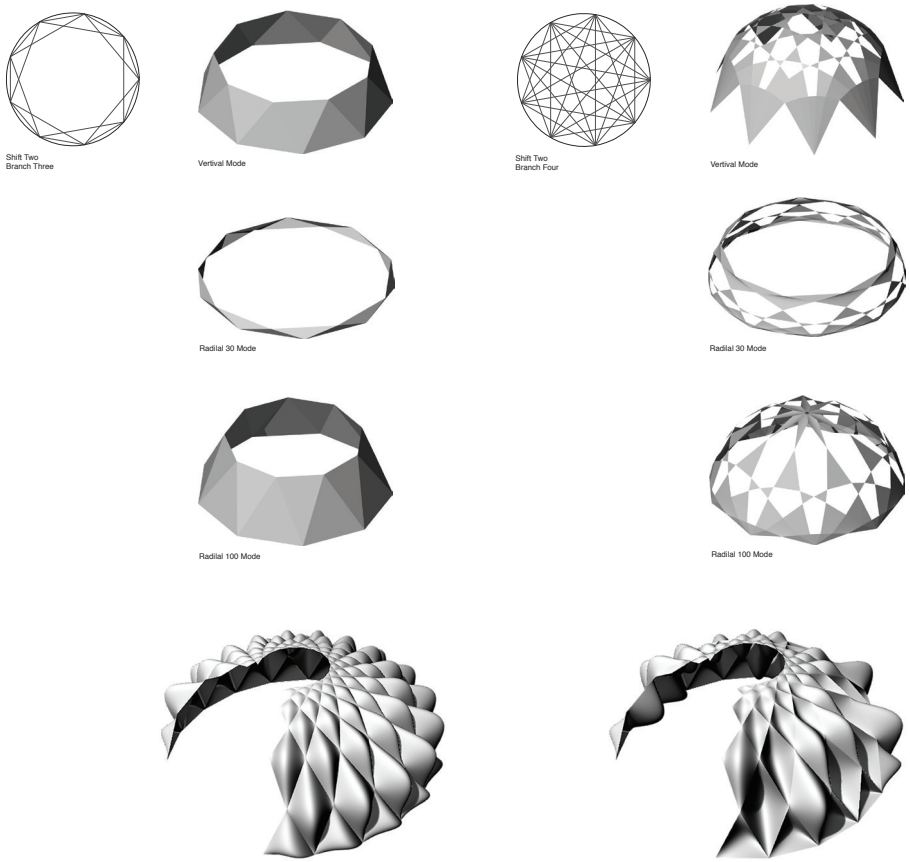


Figure 5-24 The main parameters in creating the Star pattern, Even mode



From Two-Dimensional Pattern to Three-Dimensional Module

Before indicating more potentials of this pattern (more in Modular strategy), the traditional form of a dome or semi-dome is created as a surface to show how the two-dimensional pattern can tessellate and relay onto the surface. The form can be changed along different parameters over the whole dome (radius and height) and the system of tessellation works in two modes, radial and vertical. The radial mode can create infinite versions of the dome shape.

Inflation Mode

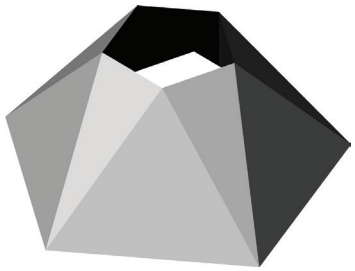
The two examples below show the “inflation” mode in the dome shape as a demonstration, applied on each component. This system can be used either completely on one side or randomly on both sides of the dome.

Figure 5-25 The projection system of the Star pattern; the dome is considered as a topology to involve a sense of the past

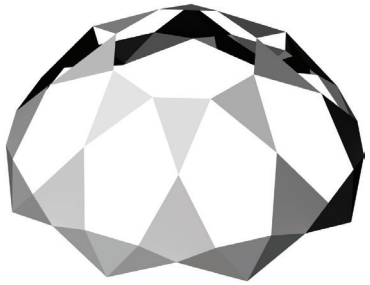
Figure 5-26 **Left** Applying Even Inflation mode to each component

Figure 5-27 **Right** Applying Random Inflation mode on each component

The Various Examples with Different Modes



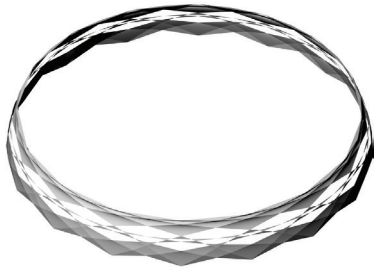
Division: 5
Shift: 3
Branch: 3
Mode: Vertical



Division: 8
Shift: 2
Branch: 3
Mode: Radial 90



Division: 13
Shift: 3
Branch: 4
Mode: Radial 70



Division: 16
Shift: 6
Branch: 3
Mode: Radial 20



Division: 28
Shift: 8
Branch: 4
Mode: Vertical



Division: 50
Shift: 16
Branch: 3
Mode: Radial 110

Figure 5-28 Different examples of the Star pattern with various parameters such as division, shift and branch

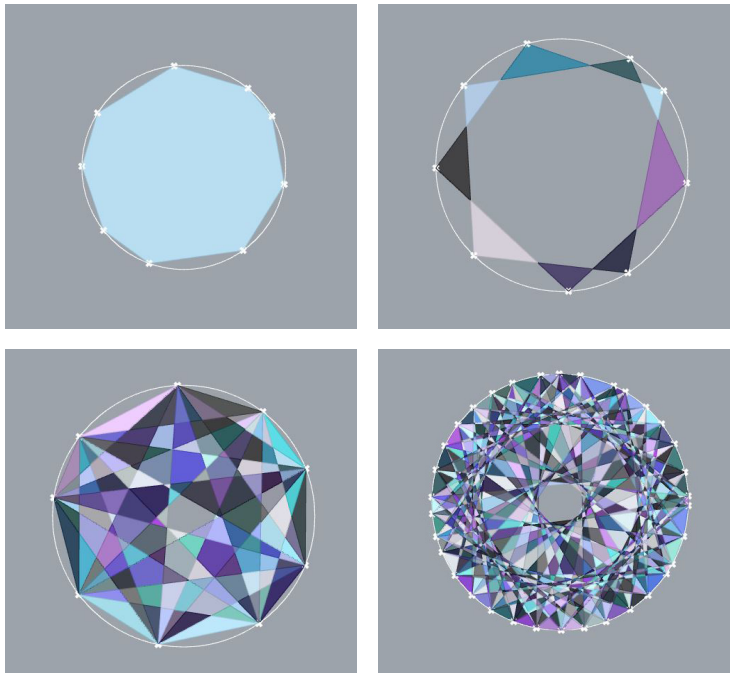


Figure 5-29

From Left to Right, Top to Down

Some examples of the Star pattern, Random mode, with different parameters

Detail: Division: 9
Random length

Detail: Division: 9
Shift Two
Branch two

Detail: Division: 9
Shift three
Branch four

Detail: Division: 34
Shift nine
Branch four

Two-Dimensional Pattern, “Random Mode”

After finalizing the basic system of the star pattern, recognizing the characters and solidifying the main parameters, more possibilities generated from changing parameters in the star pattern are run. One of the main parameters in this system is the length between the points dividing the circle, which is the same in the first option. In the second approach, the mode of various lengths on the circle is applied. More detail and possibilities are illustrated in the Modular Strategy section. Here, in figure 5-29, for more clarity, several examples are demonstrated.

“Even” mode refers to the square system of arabesque art, but the “random” mode has the same system which by changing only one parameter it can enrich the complexity and contemplation sense of the design, and also increase the aesthetic sense. This option shows the power of parametric design and tools. It indicates that in a practical way applying the random parameters, needs time, skill and expertise. Even It can be claimed that it is impossible to generate the intricate geometric with the systematic random mode.

ENDNOTES

1. Gülru Necipoğlu, *The Topkapi Scroll: Geometry and Ornament in Islamic Architecture* (Santa Monica, CA: Getty Center for the History of Art and the Humanities, 1995), 349.
2. Shiro Takahashi, "Muqarnas: A Three-Dimensional Decoration of Islamic Architecture," accessed January 2016, http://www.shiro1000.jp/muqarnas/default-.htm/.
3. Ibid.
4. Necipoğlu, *The Topkapi Scroll*, 349.
5. Ibid., 350.
6. Ibid.
7. Ibid., 46.
8. Ibid., 9.

6.0 SHELL STRUCTURE



Figure 6-1 Underground Level of Si-o-seh pol, Isfahan, Iran, 1602

A key part of the thesis design, called a contemporary stand-alone shell structure, uses vault topology as a historical precedent. This aspect leads the thesis to this area of study, exploring the history of the vault topology as a shell structure and the only way to cover long spans in the past. In this chapter, first, the vault's structural behavior and its different formal types are illustrated. From there, the research continues in order to investigate the shell structure in contemporary design culture based on computational methods of form and structural optimization.

6.1 HISTORICAL VAULT STRUCTURE

A vault is a curved shape, defined as a roof or ceiling surface covering a room. The form of each type is based on its structural principles.[1]

History shows that the vault system was used earliest in the Near East and Egypt, with the masonry method of construction later developed in Roman architecture, and expanded into contemporary architecture. This means that the vault topology and the concept of the vault were not Roman inventions and, until Roman architects by the aid of architectural and engineering advances developed the potential of the vault topology and its structural behaviour. Then, the vault structural system has been used in various areas as a shell structure and expanded and developed. [2]

Before modern vault construction with concrete, the vault system and structure was formed using masonry. For load bearing of

structure and material, the proportion of the modules in the structure is considered and shaped in a way to distribute the weight of the arch to the piers. The symmetrical form of the structure enables the behaviour of this load spreading. [3]

The structural behaviour of this kind of shell is primarily in compression only. This is because materials such as brick and stone "are strong in compression and weak in tension." Moreover, the geometry-finding "can work in compression under gravity loading."[4]

Different kinds of Vault Topology

In his book, *Vaults*, Professor Charles Babcock describes the main kinds of vault systems and their subset types as they appeared throughout history. He also describes the whole system of each kind. Below, the main kinds of vault systems are illustrated in order of construction and form. The vault systems' construction is divided into two parts of "solid" and "ribbed," and their form is divided into "simple" and "compound" categories.

1. Solid Vaulting

• Solid-Simple Vaulting: Barrel Vault
The barrel vault is the simplest shape of the vault system. The arch shape in section extends in one axis to cover a space. Other types under this category, differing in cross-sectional arch shape, include "semi-elliptical, segmental, pointed, three-centered, four-centered, etc." Some of them also extend along a curved "ridge."[5]

• Solid-Compound Vaulting: Groined Vault
When two or more simple vaults intersect each other, they make a compound vault. This type of vault is known as a groined vault and is composed of "two or more simple vaults, which may be Barrel-vaults or Expanding-Vaults." [6] This kind of vaulting has more various shapes, which can be seen in Roman and German architecture.

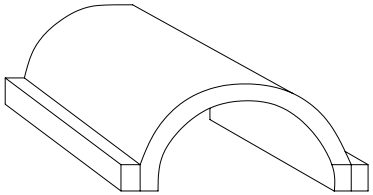
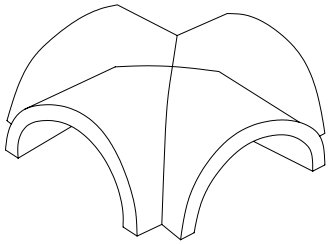
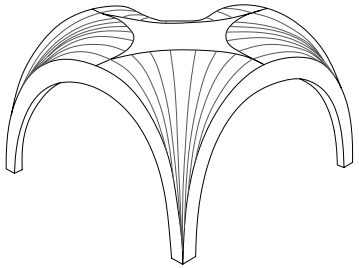
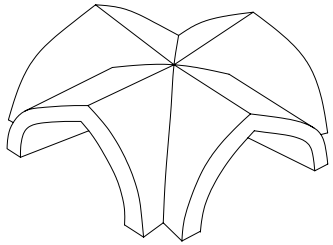
2. Fan Vaulting

In this kind of vault system, the solid vault is repeated to cover a space. Fan vaulting has two categories, "Pykamidoidal" and "Conoidal." It can be seen in late-Gothic architecture. The form is similar to rib vaulting but is differentiated from it in that it does not have a rib part. [7]

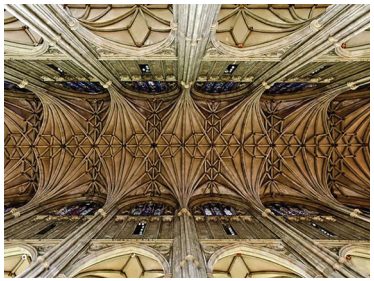
3. Rib Vaulting

In rib vaulting, the system has a structural skeleton that covers the surface. The rib material is stone, but the materials used for the surface area are lighter, such as "tufa, brick, pumice-stone, sometimes even […] wood." [8]

The Vault Topologies



From Left to Right

Figure 6-2 **Top**: Form topology of Barrel vault
Bottom: One example of Barrel Vault, Basilica Nova, Rome

Figure 6-3 **Top**: Form topology of Groined vault
Bottom: One example of Groined vault, Palladio's, Basilica,Vicenza

Figure 6-4 **Top**: Form topology of Fan Tracy vault
Bottom: One example of Fan Tracy vault, Kings College Chapel, England

Figure 6-5 **Top**: Form topology of Rib vault
Bottom: One example of Rib vault, Canterbury Cathedral, England

6.2 WHAT IS A SHELL STRUCTURE?

In this part, the contemporary shell structure and the important factors in designing a shell in architecture are investigated. At first, the complete definition of the shell structure and the importance of the aesthetic sense of the form are demonstrated. In the following sections, another critical factor in shell design, its optimization in terms of the form and structure, is researched. After clarifying the reason for choosing the vault topology in a contemporary shell structure, computational morphogenesis as multi-objective optimization is demonstrated. The latter is used as one of the main methods in this thesis (Kangaroo, a physics engine) to achieve an optimum form and shell structure.

A shell is defined as a structure composed of a curved surface. According to *Shell Structures for Architecture*, "the most obvious definition of a shell might be through its geometry. A structure or structural element of shell may be a fully three-dimensional solid object, or it might have some dimensions notably smaller than others." [9]

It contains a "beam" defined as a straight line that can carry a compression load,, or "arch" is defined as a curved line or plate. [10] More than other construction systems, a shell structure is eye catching. Because it provides freedom for exploring design and structural behavior such as load bearing and efficiency, it has an important role for architects and engineers. The shell can be formed in infinite possible ways and can be realized using so many different structural solutions. The shell designer can use different resources to create a form, such as using inspiration from nature, different precedents or exploring the various ways of form finding. The important thing in designing a shell structure is that the designer should lead the design in a way to create different paths for resisting unexpected loads They must not only think about the final appearance, but also be concerned about the design's structural behavior. [11]

The critical challenge in designing a shell structure is finding an appropriate, optimum structural form that is safe and efficient.[12]

Before investigating form and structural optimization, it is important to answer one critical question: Why use the vault as a contemporary shell structure? The primary thinking of using vault topology as a historical precedent to design a contemporary shell structure leads to a response and indicates the importance of the aesthetic and structural behaviour of this form.

Why Use the Vault as a Contemporary Shell Structure?

Form is one important parameter to achieve an optimum and efficient structure in shell design. Its development is the primary step to generating the shell structure. Today, most architects and engineers avoid dome shell design, because they think shells are mysterious and difficult to design. Arches, shells and vaults have been seen more as a risk in contemporary design than an opportunity. Many types of this structure are converted to the column and beam system because of safety concerns. The aesthetic form and structural value

of vaults are in danger of being forsaken. According to Ney and Adriaenssens, “it is not a sort of romanticism about historical structures that leads to these thoughts. Rather that shells and arches are highly efficient structures.”[13]

Optimization

An innovative shell design that is context-sensitive and uses various parameters can discover different factors and convert an aesthetic form from creative thinking to reality. But the real world has its own limitations and constraints. Structure is defined as a device to channel loads to the ground. In the structural and scientific realms, some natural regulations, such as gravity and static have important roles. In *Shell Structures for Architecture*, Laurent Ney and Sigrid Adriaenssens bring up a question about the role of gravity in shell design: “Where would be the excitement in designing a flat structure?” and continue with the argument that “the context of gravity is our playground. This design deriver is a hard constraint but gives birth to a realm of intriguing complex spatial structural shapes. No gravity, no fun.”[14]

Gravity in design is considered a constraint but because of the infinite structural solutions and possibilities, it increases the creativity and can help to define an “optimal” structure.[15]

The shell structure plays a significant role in architecture and engineering. Shells have freedom of character and an ability to create a monumental shape with load-bearing capacity. For any shell form, there are plenty of solutions, each with its pros and cons. The best solution is formed based on limitations to achieve an optimum form and result.

First it is better to come up with the definition of the optimum structure. According to *Shell Structures for Architecture*, “structural optimization is an inverse process in which parameters are implicitly/indirectly optimized to find the geometry of structure such that an objective function or fitness criterion is minimized.”[16]

Several objectives that should be considered in optimization of construction and form are investigated:

• Using economical materials or reducing the weight of materials used to achieve a lighter structure.
• Reducing the “deflections and/or dynamic vibration of a structure.”[17]
• Increasing the stiffness to reach the highest point of load bearing capacity.

Based on the solutions listed above, structural optimization can be categorized into three groups: shape optimization, topology optimization, and sizing optimization. Each of them has different actions and possibilities, depending on the topology and the purpose of the design.[18]

Form and structure can be optimized base on a single- or multi-objective method. This means that by involving one factor or multiple parameters, the system will act differently.

The form of the shell structure can be controlled based on multi-objectives and lead the design to achieve a space design and a set of feasible shapes. It helps to gradually develop the form and can be defined as “computational morphogenesis.”[19]

6.3 COMPUTATIONAL MORPHOGENESIS

Multi-objective optimization or, in other words, computational morphogenesis, is discussed as follows by Branko Kolarevic:

> The digital generative processes are opening up new territories for conceptual, formal and tectonic exploration, articulating an architectural morphology focused on the emergent and adaptive properties of form. The emphasis shifts from the "making of form" to the "finding of form," which various digitally-based generative techniques seem to bring about intentionally. In the realm of form, the stable is replaced by the variable, singularity by multiplicity.[20]

Computational methods and simulation create possibilities in different environments using a three-dimensional modeler in architecture to achieve form and geometry. After achieving the desired form by computational simulation, engineers can calculate the structural behavior by using Finite Element (FE) analysis.

Parametric tools such as Kangaroo, a Live "Physics engine for interactive simulation, form-finding, optimization and constraint solving,"[21] create methods for optimum design, but they also come with important new challenges. For example, a complex system of geometry is modeled in an environment absent of scale, material and gravity, and structural analysis should apply after freezing the geometry. In fact, the computational simulation contains modeling with all parameters as abstracts and illusions for understanding the system and its aspects.

In this thesis, the computational physics engine, Kangaroo, as a form and structure simulation physics engine, offers a method to generate multi-objective form and structure optimization. This means that the parameters enable generative design to achieve a desired form in terms of aesthetic value. Also, forces such as spring force and gravity are considered to achieve one type of structural behaviour. Moreover, varying the thickness of the solid components enables varying and balancing the weight of the body. But, it is worth mentioning that structural optimization requires external calculation and analysis which is not in the scope of the thesis.

ENDNOTES

1. Charles Babcock, *Vaults* (Boston: James R. Osgood & Company, 1884), 3.
2. Niraj Inamdar, "A Brief Overview of the Techniques of Vaulted Architecture in Rome," accessed October, 2016, http://web.mit.edu/inamdar/www/Site/Publications_and_Science_files/Roman_Vaults_Inamdar.pdf
3. Ibid., 1.
4 Sigrid Adriaenssens et al., introduction to *Shell Structures for Architecture: Form Finding and Optimization* (London: Routledge/ Taylor & Francis Group, 2014), 9.
5. Babcock, *Vaults*, 4.
6. Ibid.
7. Ibid., 7.
8. Ibid., 10.
9. Adriaenssens, *Shell Structures for Architecture*, 21.
10. Ibid., 22.
11. Ibid., 7.
12. Ibid., 11.
13. Adriaenssens, *Shell Structures for Architecture*, 17.
14. Ibid., 15.
15. Ibid., 16.
16. Ibid.
17. Ibid.
18. Ibid.
19. Ibid.
20. Branko Kolarevic, *Architecture in the Digital Age: Design and Manufacturing* (New York: Spon Press, 2003), 17.
21. Daniel Piker, "Kangaroo Physics," accessed October 2016, http://www.food4rhino.com/app/kangaroo-physics.

7.0 DESIGN STRATEGY

7.1 DESIGN SCOPE

The design scope is the parametric system of the inverse conical module composing shell type, which is generated interactively to create a componential envelope. Considering the vault as a topology is a historical precedent as a way to cover a long-span space and act as a shelter. It can be a response to the requirement for a stand-alone structure to protect people from weather conditions; it also has the potential to create various scales of space in diverse locations to host different public and private activities. The design aims to show the unity across the process from the large-scale topology to the microscale ornamental component. The system starts with one square module and generates the module continuously, based on the particular mathematical system. This is applicable in all stages.

For achieving this purpose, two strategies are proposed, each of them comprising several steps in two sections. Section one includes one step, the primary, or master, level of each strategy, and entails creating an incremental and generative topology which can grow parametrically across the sites selected for the design. This system is the basis for developing two advanced designs known as "Modular" and "Vault." These strategies are divided into three levels, each of which has various parameters, with each parameter capable of affecting the whole system because of each individual step's dependency on the whole. In the end, the design can be achieved by combining the outcome of section two for each strategy with the master level in section one.

The Design Levels

The first round involves the standard actions that are generated based on a modular arrangement compatible with the site in which they are to be realized, and are applicable to both the Modular and Vault design strategies. This is considered the first step for both design strategies.

The second section of the overall scheme is considering the design process in each plan and contains three sub-levels of design. Herein, the first step is providing the desired structural topology of a single module repeating throughout the whole system, which is considered in each design (medium design scale). The second part of this round of design is created by looking at the modular system in a loop and developing the primary concept for achieving the internal aesthetic surface on a micro scale. One possible method is to formulate a componential system compatible for each topology. This part, called "patterning," is the decoration and is inspired by *muqarnas* and mesh surface division in each Modular and Vault approach, respectively (micro scale).

The third step generates the solid spatial component based on the developed pattern. In the last level, the final result is achieved when all layers of each design are combined with the master system.

In both proposed designs, several initial parameters are involved in generating form and pattern. In the Modular strategy, the size

of the top and bottom radius as well as the height of the cone are considered, and in the patterning step the main parameters include the number of divider points, the size of the circle, and the mode of connection of the divider nodes. Two modes, random and even, are applied to each of the three proposed patterns, based on the length between the nodes on the circle. The even mode creates a shape and system like the art of knot from the past; by applying the random mode, a contemporary style of this art is generated. This two-dimensional pattern is then projected onto the form.

In the Vault strategy, parameters such as gravity, body force and mesh division are involved in the creation of the structure of the form topology, affecting the shape directly and making a heterogeneous space by creating various arches in the system.

This chapter is arranged at three levels to show the fundamental role of the associated parameters within the entire design scope. The first part provides the full details of the master system, the second demonstrates the Modular strategy, through diagrams and examples, and the third section illustrates the full details of the Vault strategy.

THE DESIGN SCOPE DIAGRAM

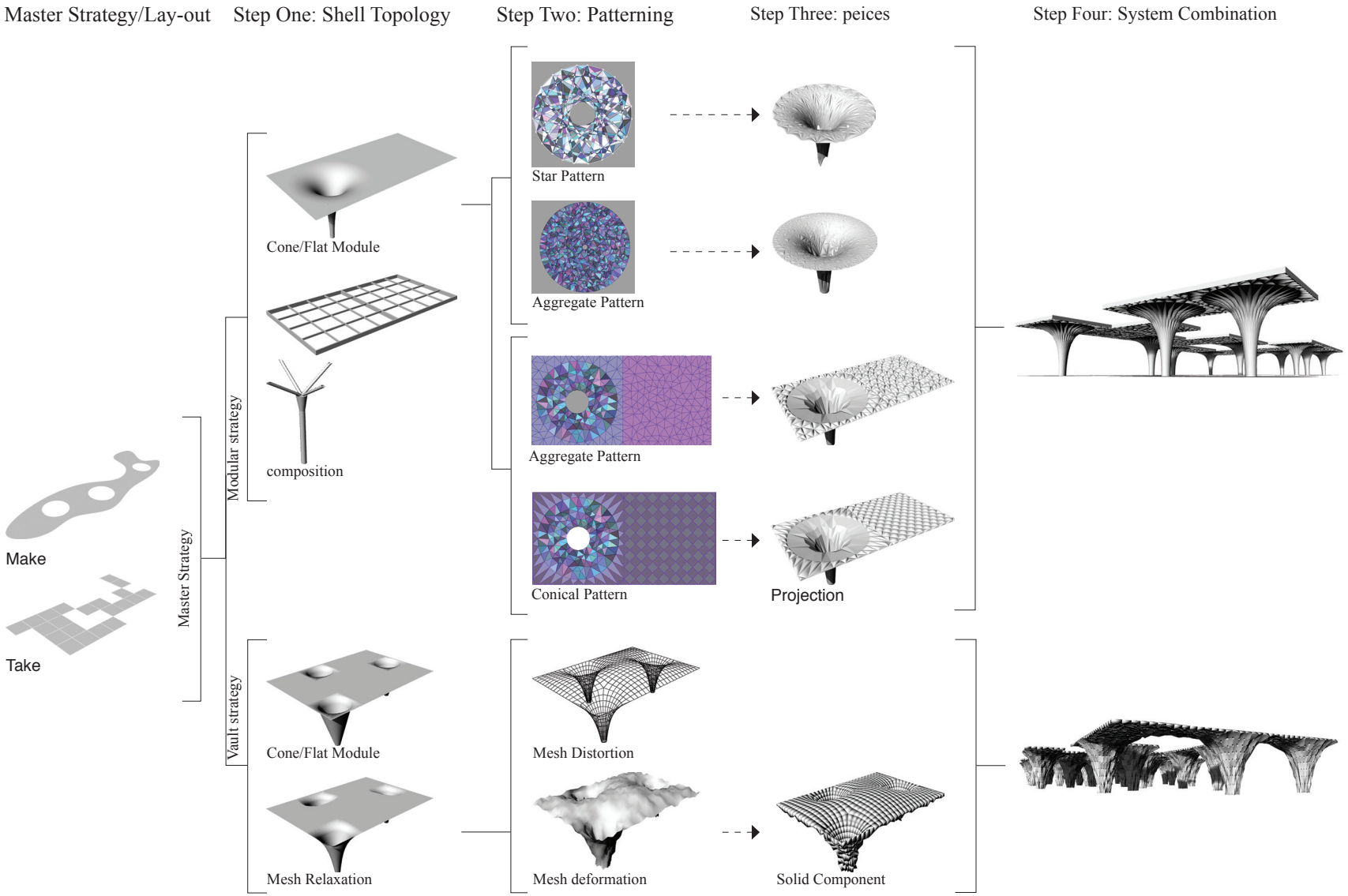
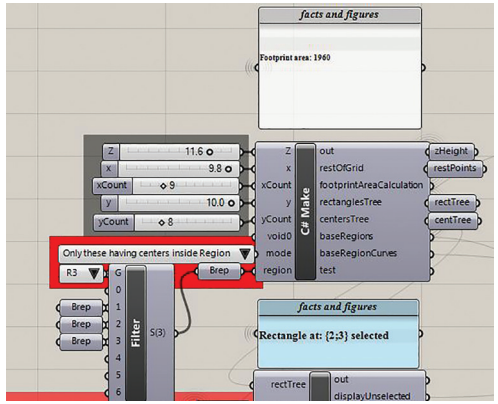
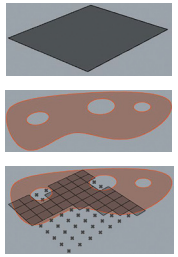


Figure 7-1 Tree diagram of the Master system, plus two proposed strategies: Modular and Vault

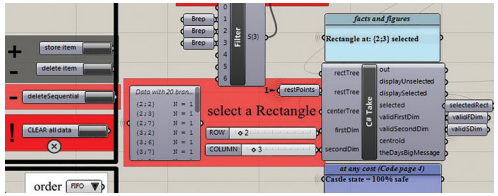
7.2 MASTER STRATEGY

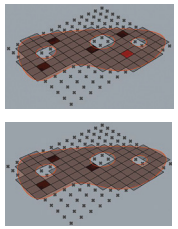
Make Part





Take Part





This part acts as the master layout for either solution (Modular or Vault). The system is generated in two parts, “Make” and “Take.” Each of them has several inputs as its parameters.

Make: This section includes the regular/irregular regions and a grid of rectangular modules defined at Z, zero. The related parameters are the site area over which the design is to be realized (with or without “holes”), the rectangular size of the grid module and the numbers of modules in the X-Y direction. Optionally, a defined region is used to “cull” grid modules. The cull mechanism is determined by the inclusion of the module’s centre within the region. Many areas are available in which the user can be active and develop the process.

Take: This section involves two actions, “storing” and “deleting.” “storing” is an interactive process used to identify modules as “columns” or “bridges” and store them in a suitable collection called a ‘‘DataTree’’ in Grasshopper. The system enables movement along the X and Y axes and picks the modules based on the choice of the user. The selected module is defined as a column and the rest of the modules act as a bridge between the columns. Then, depending on the strategy applied to the region (a set of columns and bridges), it is combined with the rest of the design. On the other hand, “deleting” involves three options to remove the selected module, which be done interactively. Two other options are suggested for this part such as sequential deletion, or clearing all data in one action. These options make the process of design faster.

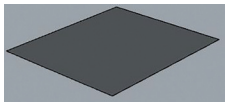
Figure 7-2 **Top** Screenshot from the Grasshopper Environment, showing the “Make” inputs

Figure 7-3 **Bottom** Screenshot from the Grasshopper Environment, showing the “Take” inputs

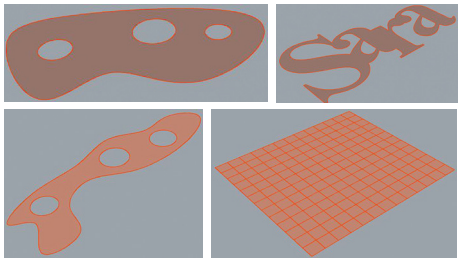
Parameter

Illustration

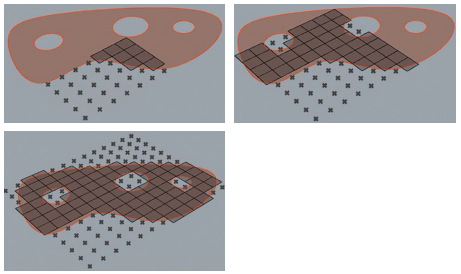
Module Size



Region



Growth



The system is infinitely variable based on defined parameters such as the module size, the shape of the region within which the grid system is arranged, and the module count in the X and Y directions. The parameters are listed on the left side, and on the right are illustrations.

Figure 7-4 **Top** The rectangular module start at (0,0,0); the size of the core module is changeable and applies to the entire grid system

Figure 7-5 **Middle** Changing the region as one parameter, such as a regular/ irregular shape with/without holes, and scale

Figure 7-6 **Bottom** Growth of the grid system across the X-Y axis

‹‹TAKE›› PART:

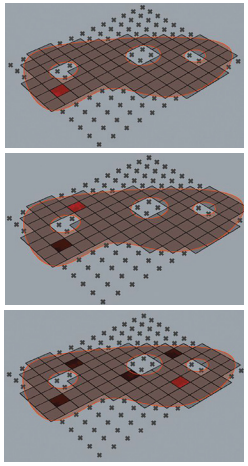
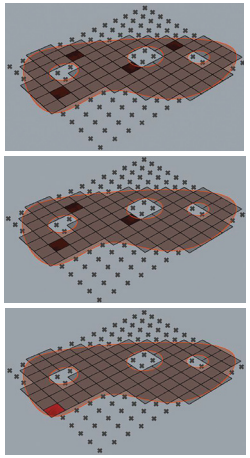
Action	Illustration
Storing	
Deleting	

Figure 7-7 **Top First-group** The interactive system of the continuous selecting and storing movement

Figure 7-8 **Bottom Second-group**
1. “Delete Sequential” action, removing the previously selected module from storage
2. “Delete Item” action, removing the ideal stored module by moving along the grid
3. “Clear all data” action, removing all stored modules at the same time

7.3 MODULAR STRATEGY

The “Modular” strategy contains three steps plus the final step, which is the combination of the system with the master layout:

Step One: Shell Topology
Step Two: Patterning
Step Three: Projection/pieces
Step Four: Combined system

Each step contains the related parameters, which can affect the whole system. The design can be split into two main parts: form, shown in the first step, and component, generated in the second and third steps.

Form, Repetition of Homogeneity

The form in this strategy has two standard modules that compose two parts: a conical one that carries the loads directly and acts as a “column,” and a planar one serving as a “bridge” between the “columns.” This form is introduced into the base grid pattern as a module that repeats across the system. Moreover, the whole system shows the same structure at selected points.

Component

The components framed through the star pattern, inspired by the system of the knot, uses the “radial” projecting mode. The system converts the two-dimensional pattern into solid spatial components on the column and flat surface with inflation parametric option, representative of a contemporary way of thinking, which alter the aesthetics.

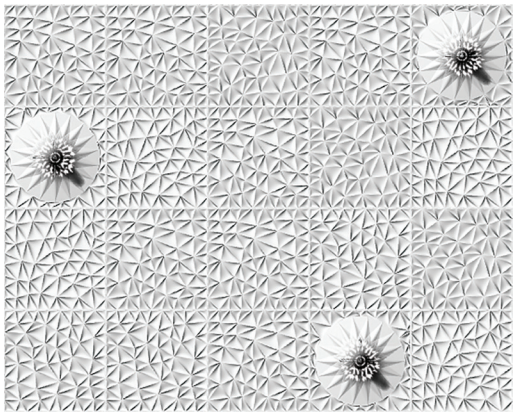
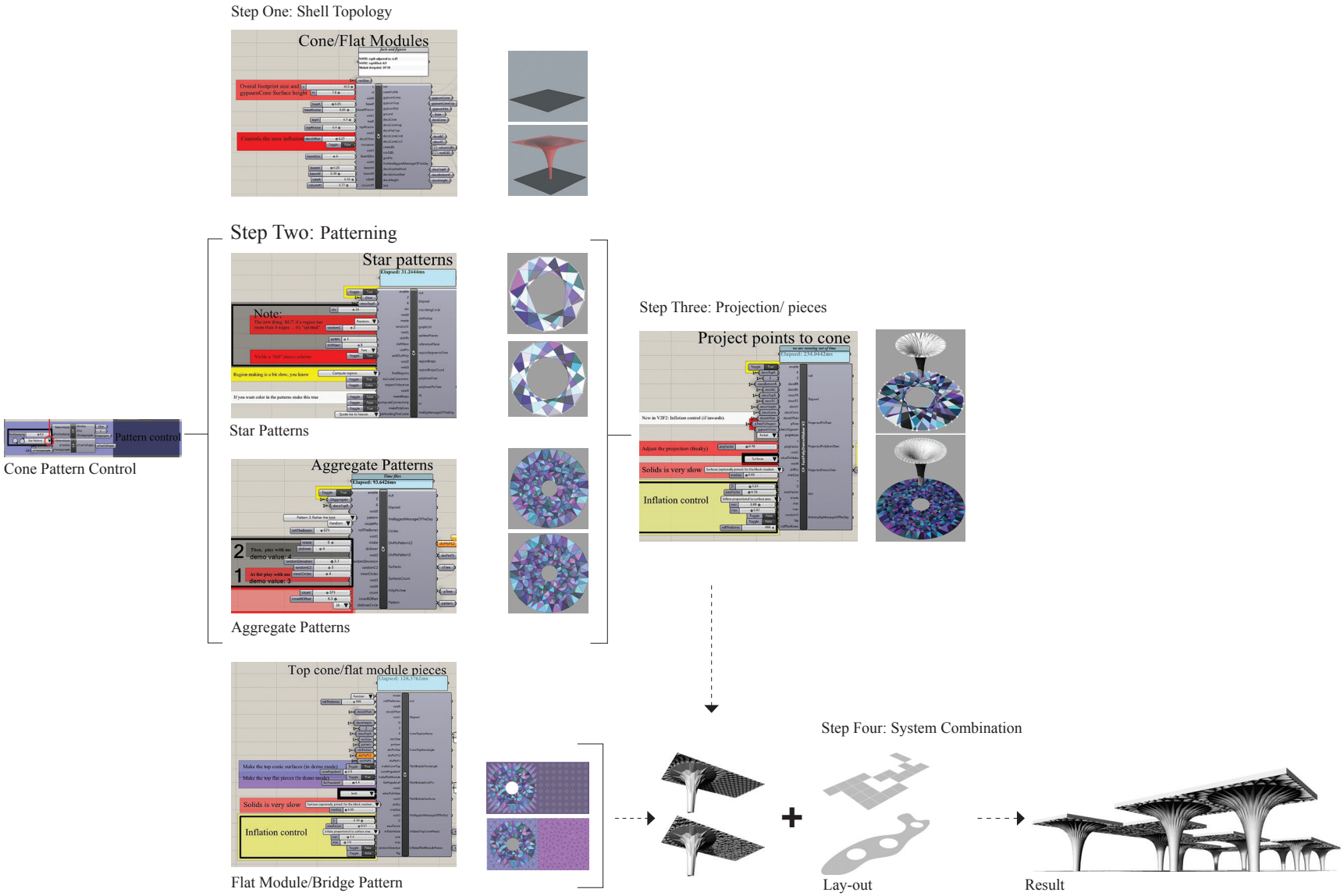
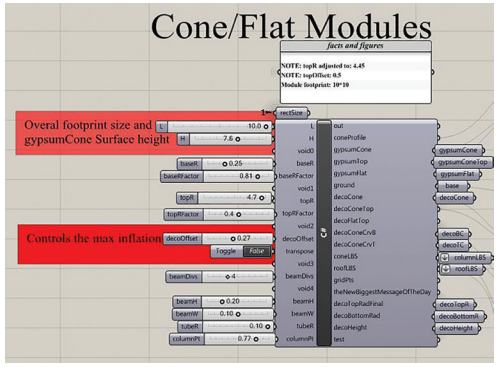


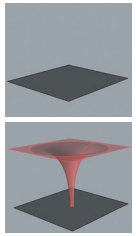
Figure 7-9 One example of Modular Strategy, Bottom View

Figure 7-10 **Group**

Showing the Modular strategy level, Grasshopper parts, and the result of each step; screenshot from Grasshopper and Rhino Environment







Step One: Form Topology

The form is composed of two modules, the conical structure as column and the flat module as the bridge to cover the space. Each part of the structure can be changed parametrically, such as the top and bottom values of radius and the height of the column. The size of the rectangular module in the master step can affect the scale of the flat module of the form. By controlling these optional parameters, the result can vary infinitely. The type of geometry used is NURBS.

After developing the shell, for static purposes, structural elements such as beam and truss are manipulated to allow the design to perform as a stand-alone shell structure. the design offers speculation on how the structural elements can be oriented in terms of form topology, which each one has its parameters such as size and division.

Figure 7-11 **Group** Showing the form and structural modules as inputs; screenshot from Grasshopper and Rhino Environment

FORM PARAMETERS

PARAMETER ILLUSTRATION

Module Size

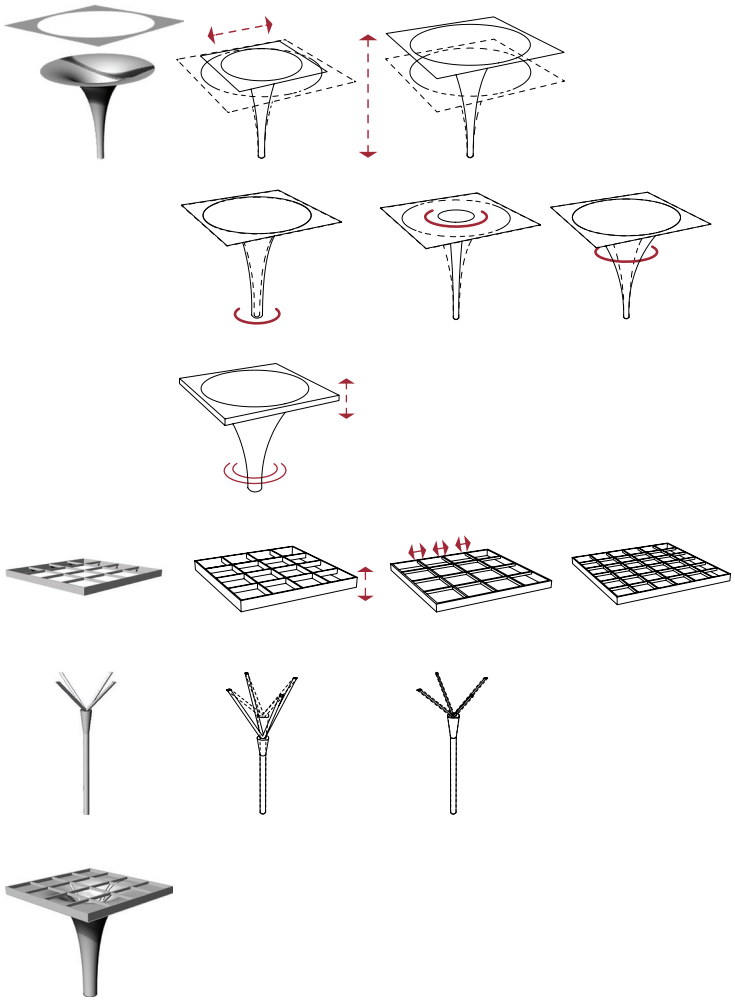
Radius Factor

Offset

Beam

Truss

Whole System



From Top to Bottom **From Left to Right**

Figure 7-12 **First-group**

1. Two compositions of the form, Conical structure and Flat Module
2. Changing the length and width
3. Changing the height

Figure 7-13 **Second-group**

Changing the radius factor such as top, middle and bottom radius

Figure 7-14 **Third**

Generating the shell offset and adjusting its thickness

Figure 7-15 **Forth-group**

1. Beam as a structural flat module
2. Changing the height
3. Changing the width
4. Increasing the beam division

Figure 7-16 **Fifth-group**

1. Truss as a static base
2. Changing the height
3. Changing the pipe radius

Figure 7-17 **Sixth**

Overall compositions of structure elements and form modules

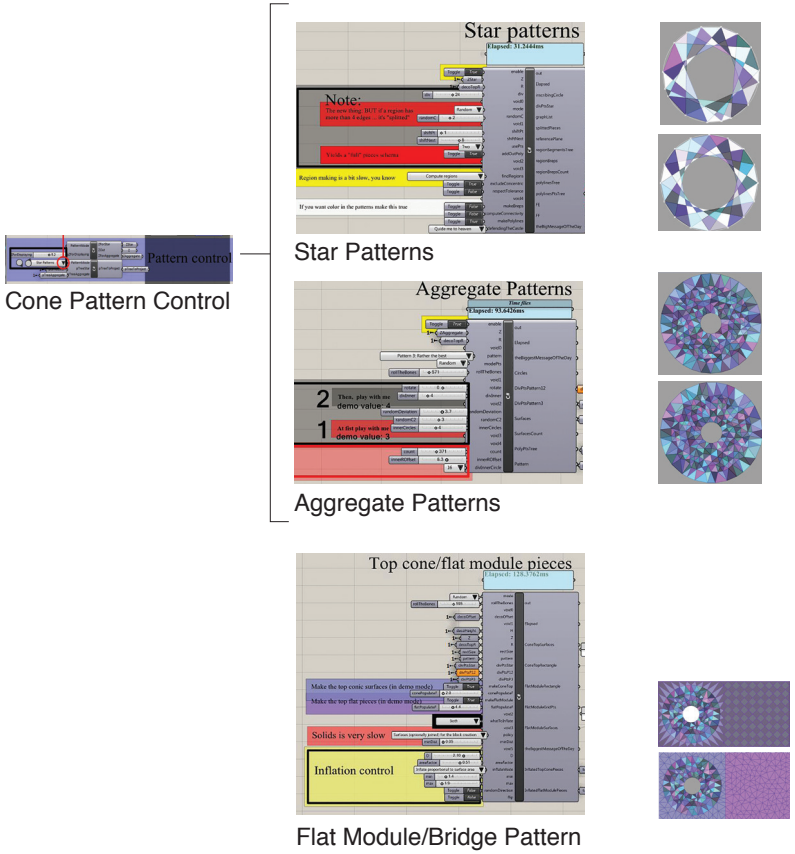


Figure 7-18 **Group**

Components relating to the patterning step and their results; screenshot from Grasshopper and Rhino Environment

Step Two: Patterning

The initial approach to achieving a componential surface in this strategy is "patterning," considered for projecting on two modules used in the form topology, conical/column and flat/bridge. The pattern is created based on surface division and is inspired by *muqarnas*. For creating a surface division to design a spatial ornament, one method is the same as the case study of *muqarnas* presented in chapter five. The creation of a pattern on the two-dimensional surface is based on the basis of the form topology, then radially project onto the object. In this design strategy, the top circle of the cone is picked and the pattern is created in that area; then, the projection rises radially to achieve the desired design. Because the bridge module is flat, the solid components are shaped in the flat mode after creating a surface division. Here, the rectangular module is the same size as the bridge used to create the desired pattern.

Pattern for Cone module: Two different decorations, the "star pattern," and "aggregation pattern" are available in a complete process with several options proposed for the conical module. Each is offered in two modes, "even" and "random."

Cone Pattern Control: Because of the two proposed patterns and dependency of the whole project, one pattern should be chosen during the work to apply to the structure. One action is offered for doing this that enables running the desired pattern on the design.

Pattern for Flat module: The division system for the flat module is the same as one of the options from the aggregation type, in the same two "even" and "conical" modes, which is explained in upcoming sections.

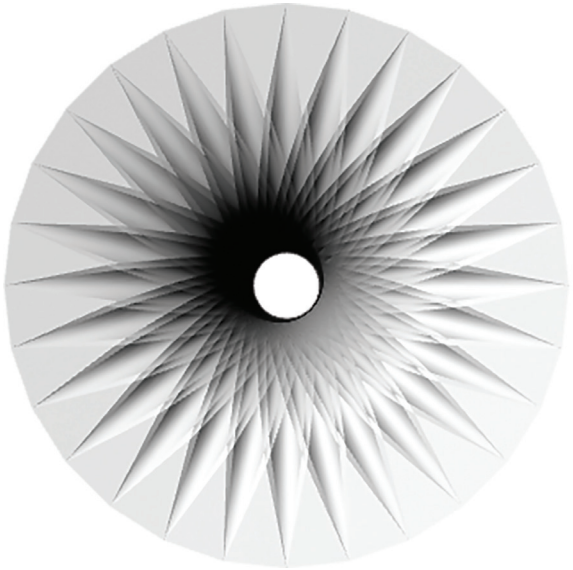


Figure 7-19 One example of Star pattern. Even Mode
ID, Division: 28, Shift: 10, Branch: 3

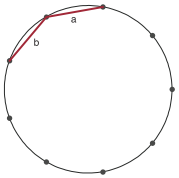
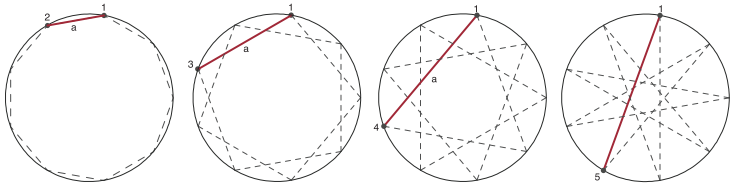
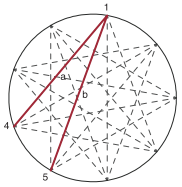
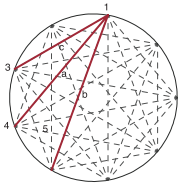
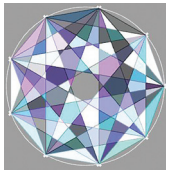
Star Pattern

The system of the star pattern is explained with full details in the “parametric arabesque dome” chapter five. In this part, the main parameters used in this system are shown. Several examples with the specified identification based on parameters such as number of points, shift and branch are illustrated. Briefly speaking, the star pattern is created from a circle, divider points, and the systematic linkage of these nodes. It is developed in the two modes of “even” and “random,” and the associated parameters are demonstrated on the next page:

1. “Division,” the division of the circle
2. “Shift,” the next connecting point
3. “Branch,” the number of branches given from each point
4. “Even Mode,” the same length between the divider nodes
5. “Random Mode,” various lengths between the divider nodes

‘‘Even’’ mode refers to the square system of arabesque art, but the ‘‘random’’ mode has the same system which by changing only one parameter it can enrich the complexity and contemplation sense of the design, and also increase the aesthetic sense. This option, because of offering infinit types of pattern, also shows the power of parametric design and tools.

STAR PATTERN PARAMETERS

PARAMETER	ILLUSTRATION
Mode	Even
Division	
Next Shift	
Branch	 
Brep Option	

From Top to Bottom

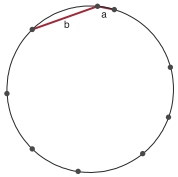
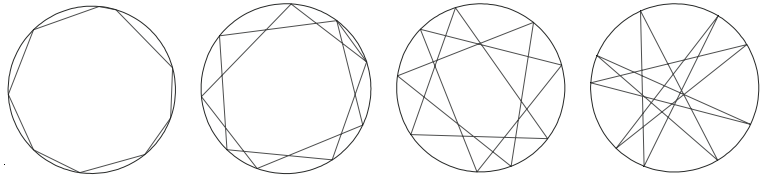
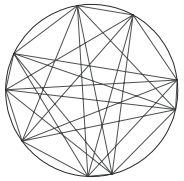
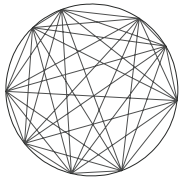
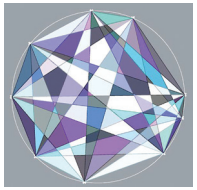
Figure 7-20 **First** — The points as dividers, the network between the points, equal length of each linkage, a=b

Figure 7-21 **Second-Group** — The next turn connecting point
From left to right, Shift, one, two, three and four

Figure 7-22 **Third-One** — The number of branches given from each point, Branch=n
In this Example, n=3 and the result is n-1, equals two

Figure 7-23 **Third-Two** — n=4 and the result is three

Figure 7-24 **Forth** — The Brep option, adding color to the parametric system during work to identify the generated region; screenshot from Rhino Environment

PARAMETER	ILLUSTRATION
Mode	Random
Division	
Next Shift	
Branch	 
Brep Option	

From Top to Bottom

Figure 7-25 **First**
The points as divider
The network between the points
The various length of each linkage, a≠b

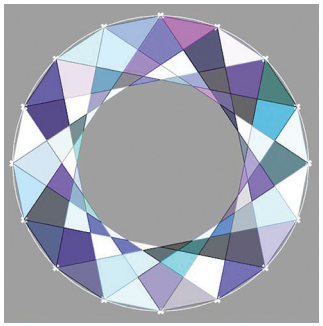
Figure 7-26 **Second-Group**
The next turn connecting point
From left to right, Shift, one, two, three and four

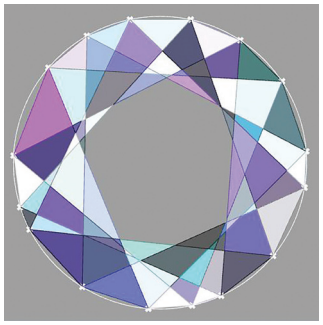
Figure 7-27 **Third-One**
If Branch identified by ‹‹n››
n=3 and the result is n-1

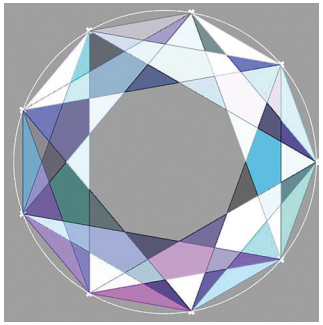
Figure 7-28 **Third-Two**
n=4 and the result is three

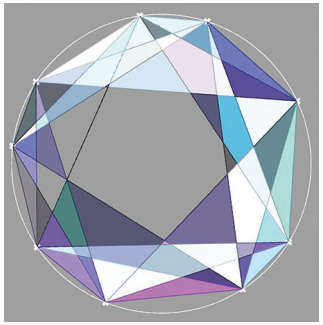
Figure 7-29 **Forth**
The Brep option, adding color to the parametric system during work to identify the generated region; screenshot from Rhino Environment

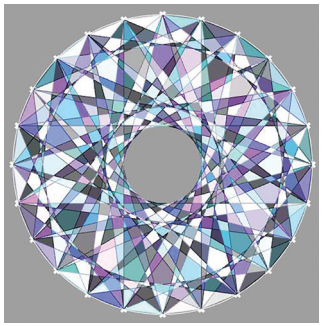
Star Pattern Examples

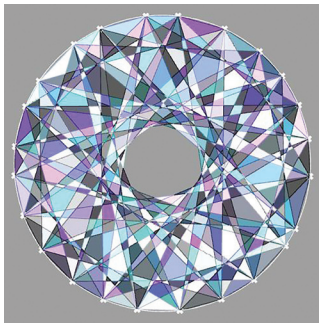












Left, Even Mode
Right, Random Mode

Figure 7-30 **Top-Group** The ID is: Division: 16, Shift: 05, Branch: 02

Figure 7-31 **Middle-Group** The ID is: Division: 09, Shift: 06, Branch: 03

Figure 7-32 **Bottom-Group** The ID is: Division: 24, Shift: 09, Branch: 04

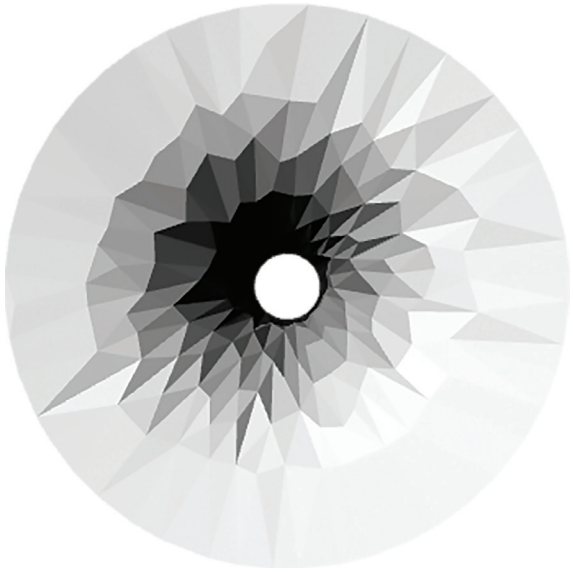


Figure 7-33

One example of Aggregate Pattern
Random Mode
The ID is: Option three, Inner radius offset: 6

Aggregate Pattern

The aggregate pattern is provided in three options, with each again available in two modes, “even” and “random.”
The three alternatives work by populating points evenly inside a given seed region with the different methods, which explains each pattern choice.

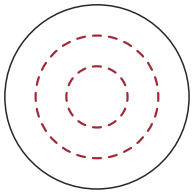
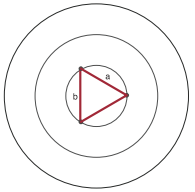
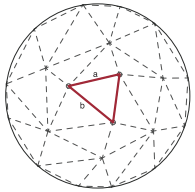
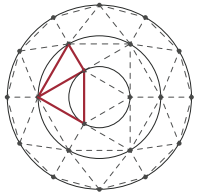
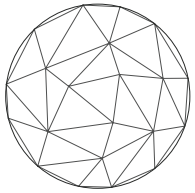
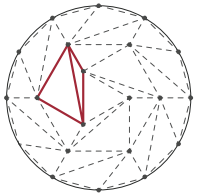
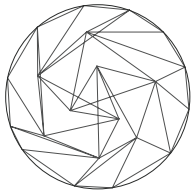
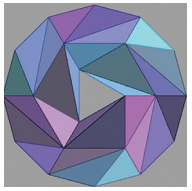
1. The first option follows the “loop” system, meaning that the first circle is offset to smaller circles inside of it, which populate points placed on each circle. Connections between the points create regions. The link starts from the inner rings and continues, point by point, to cover the whole area. According to this system, the core parameters are the number of circles and the minimum division on the last internal circle.

2. The second option is similar to the above, only the form of the connection is different, rotating the three-cornered region made by this system.

3. The third option pattern works by populating random points evenly inside a given seed region, then connecting them using a classic Delaunay triangulation. This means that the points fill an area so that each of the three points is placed on a circle and none of the points are put inside circles. The system has one circular region, constructed using two curves (inner and outer). In this option, there are two parameters such as the offset between two circles and the divider points located on the inner circle.

   The valid parameters of each option are represented by the following illustrations.

AGGREGATE PATTERN PARAMETERS

PARAMETER	ILLUSTRATION	
Mode One	Even	Random
Inner Circle		
Inner Division		
Connection First Option		
Mode Two		
Brep Option		

From Top to Bottom

Figure 7-34 **First** — Inner Circle, offset from the outer circle

Figure 7-35 **Second-Group** — Inner Division, first circle start to divide by the selected points D=3
Left, Even Mode, a=b
Right, Random Mode, a≠b

Figure 7-36 **Third** — First pattern option
The way of connection

Figure 7-37 **Forth** — Second pattern option
The way of connection

Figure 7-38 **Fifth** — The Brep option, adding color to the parametric system during work to identify the generated region

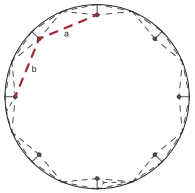
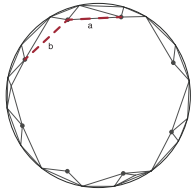
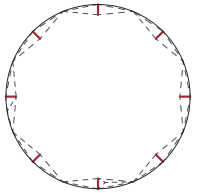
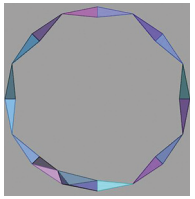
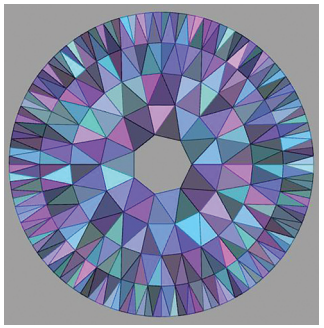
PARAMETER	ILLUSTRATION	
Mode Three	Even	Random
Division		
Inner Radius Offset		
Brep Option		

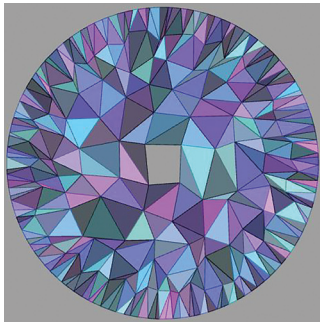
Figure 7-39 **First-Group** Division, the numbers of the points divide the inner circle, D=8
Left, Even Mode, a=b
Right, Random Mode, a≠b

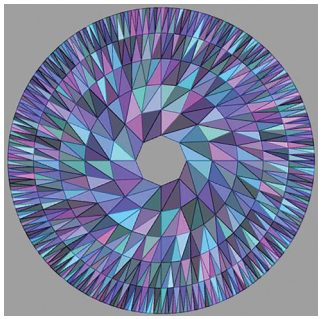
Figure **7-40 Second** Inner radius offset, the measurment between two circles

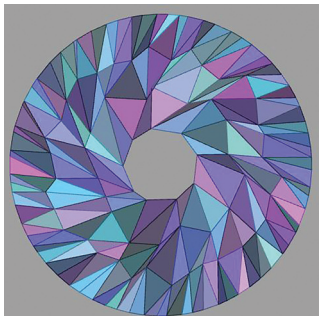
Figure **7-41 Third** The Brep option, adding color to the parametric system during work to identify the generated region; screenshot from Rhino Environment

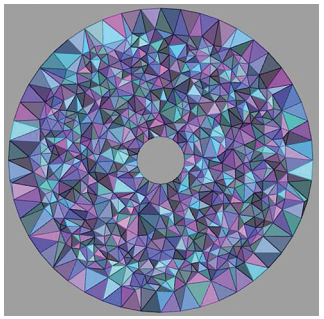
STAR PATTERN EXAMPLES











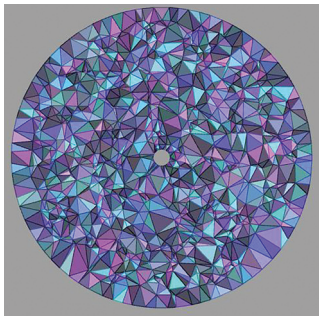


Figure 7-42 **Top-Group**
First Option
Left, Even Mode - I.D: 07, I.C: 05
Right, Random Mode - I.D: 04, I.C: 06

Figure 7-43 **Middle-Group**
Second Option
Left, Even Mode - I.D: 08, I.C: 06
Right, Random Mode - I.D: 09, I.C: 04

Figure 7-44 **Bottom-Group**
Third Option
Left, Even Mode - D: 24, I.R.O: 7.5
Right, Random Mode - D: 40, I.R.O: 09

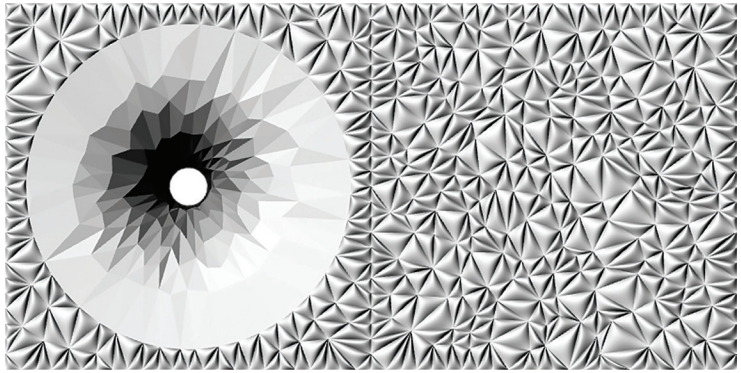


Figure 7-45 One example of proposed pattern for the bridge module
The ID for Flat Module is: Division 24, Random Mode
The ID for Cone is: Aggregate pattern, Random Mode
Option three, Division: 24, Inner radius offset: 6

Flat Module/Bridge Pattern

It is important to mention that there are commonalities between the border connections of related modules. The relationship of the cone and the flat module is one, and the meeting edge of the flat module with its neighbour is another. The system of this pattern is the same as the third option in the aggregate pattern and works by populating the points inside a given region. Two pattern modes, conical and random, are provided to create decorative surfaces either on the flat portion that meets the cone surface or across the full face of the flat neighbours (if applicable).

First, the pattern is selected by cone pattern control. Then, the populated points on the edges of the flat surface that connect to the cone, are arranged (based on user choice).

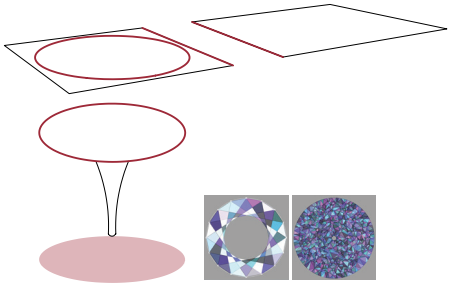
Random Mode: The populated mode of the points is random, and the length of each linkage is different from all others.

Conical Mode: The populated mode of the points is even, and the length of all connections is equal.

FLAT MODULE PARAMETERS

PARAMETER ILLUSTRATION

Cone Pattern Selection



Connection Edge

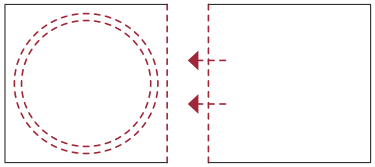


Figure 7-46 **First-Group** First step, selecting the pattern for the circle surface connecting to the flat surface

Flat Pattern mode

Random Pattern

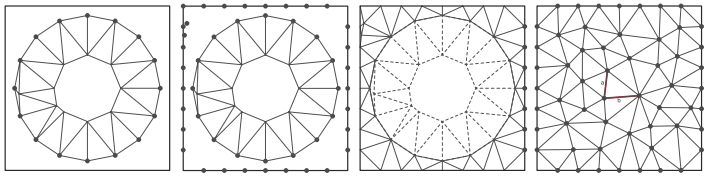


Figure 7-47 **Second** The common position of the contact points on the borders of related modules

Figure 7-48 **Third-Group**

Random Mode
1. Detecting the points on the outline of the Cone pattern
2. Populating all points randomly in the flat surface
3. Connecting the points
4. Different lengths of links, a not equal to b

Conical Pattern

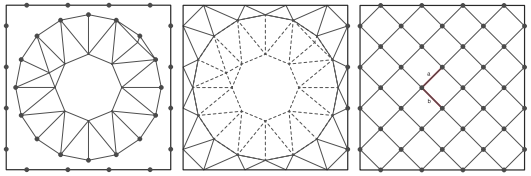


Figure 7-49 **Forth-Group**

Evan Mode
1. Detecting the points and populating all points evenly on the flat surface
3. Connecting the points
4. Equal length of links, a=b

PIECES PARAMETERS

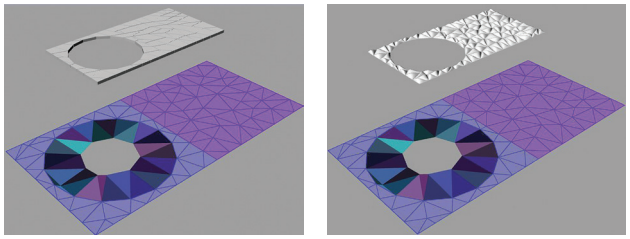
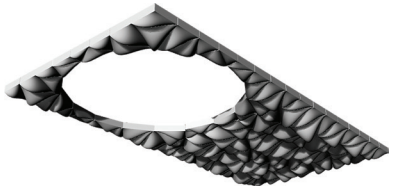
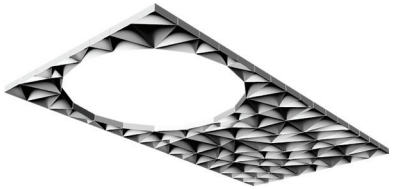
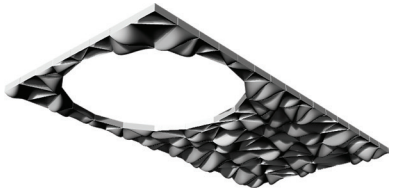
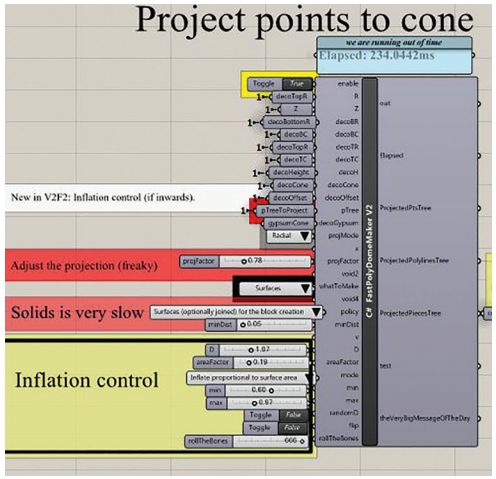
PARAMETER	ILLUSTRATION
Pieces, Solid/ Surface	
Inflation Mode Depth	
Flip Inflation	
Random Inflation/Min-Max	

Figure 7-50 **First-Group** — **left**, Solid Pieces **Right**, Surface Pieces with Inflation mode

Figure 7-51 **Second** — Depth of the pieces is vary; here the Inflation mode in outward

Figure 7-52 **Third** — Flip the Inflation mode to make it inward

Figure 7-53 **Forth** — Random Inflation of pieces between minimum and maximum depth





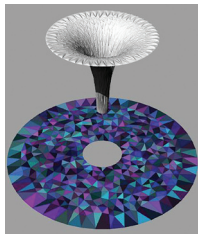


Figure 7-54 **Group** Showing the components related to Projection and their results

Step Three: Projection/ pieces

In the projection method, one cone is considered as a demonstration for applying the desired pattern and to make solids. The demo provides this possibility to change modes and parameters to achieve the best componential model. The mode is projection, which raises the flat point tiers radially and makes them as solid units. The places of the points or, in other words, the levels, can be changed by controlling the projection factor parameter. The projected points on the surface create regions. The depth of the regions is different, and they present various options such as Polyline, Surface, Solid and, lastly, Inflated.

The inflation option is the same as the bridge module pieces involved in this level of the design. This mode has parameters such as depth of the component, inward and outward inflation, and the random mode between minimum and maximum depth.

PROJECTION PARAMETERS

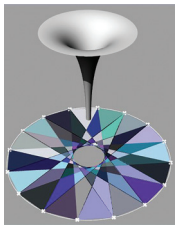
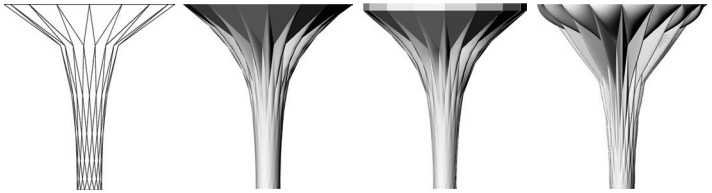
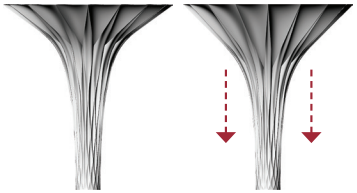
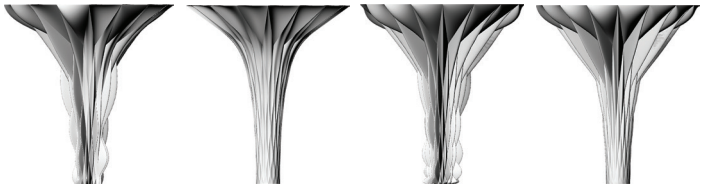
PARAMETER	ILLUSTRATION
Pattern Selection	
Depth	
Project Factor	
Inflation Mode	

Figure 7-55 **First** The demo cone shape and selected pattern

Figure 7-56 **Second**

Depth of the pieces is vary
1. Polyline
2. Surface
3. Solid
4. Inflated

Figure 7-57 **Third-Group** Changing the points row position

Figure 7-58 **Forth**

Different Inflation options
1. Random Depth
2. Even Depth
3. Inflation between Min-Max depth
4. Flip Inflation

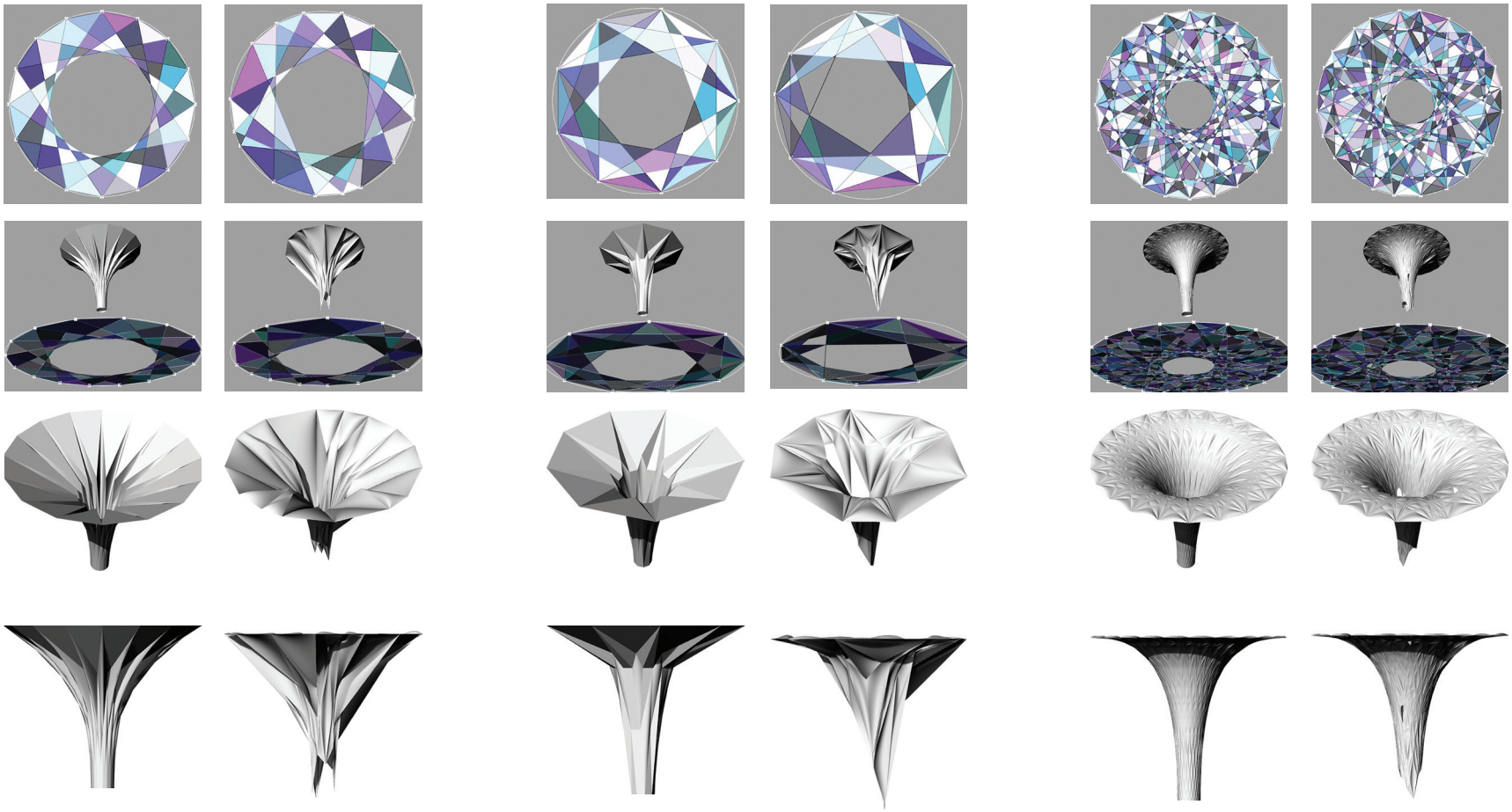


Figure 7-59 **Left-Group**

Left, Even Mode
Right, Random Mode
The ID is: Division: 16, Shift: 05, Branch: 02

Figure 7-60 **Middle-Group**

Left, Even Mode
Right, Random Mode
The ID is: Division: 09, Shift: 06, Branch: 03

Figure 7-61 **Right-Group**

Left, Even Mode
Right, Random Mode
The ID is: Division: 24, Shift: 09, Branch: 04



These examples show that there is an option available in the star patterns that allow elimination of regions that contain more than four vertices. It happens when the random options use in patterning system. And it means that in a presented decoration, some surfaces may comply with the desired deformation (the “inflate” result) and some may not.

An example of a damaged result due to making regions with more than four vertices

Star Pattern, Random Mode

Figure 7-62 **Top** The ID is: Division: 19, Shift: 9, Branch: 4

Figure 7-63 **Bottom** The ID is: Division 32, Shift 12, Branch 4

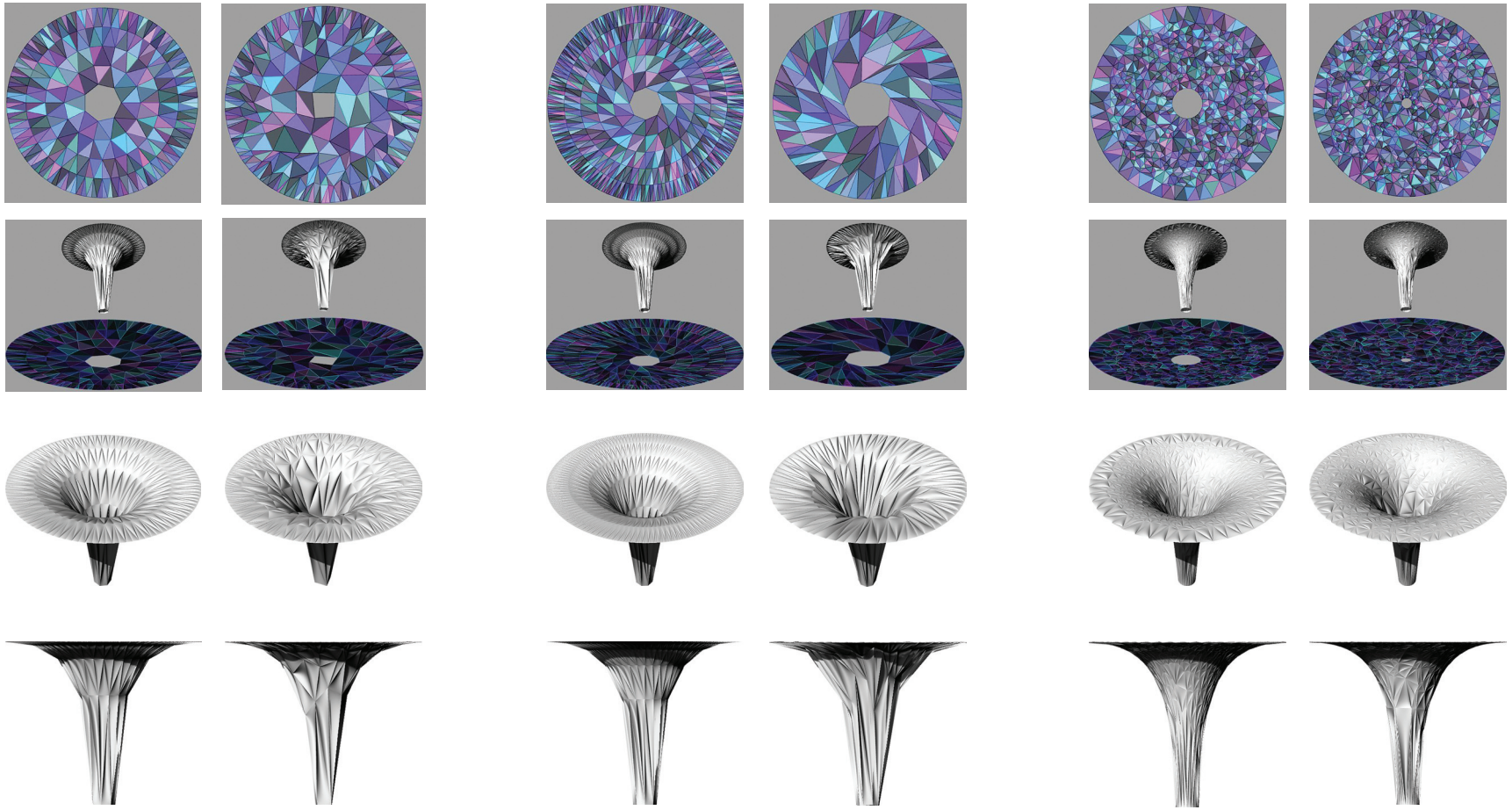


Figure 7-64 **Left-Group**

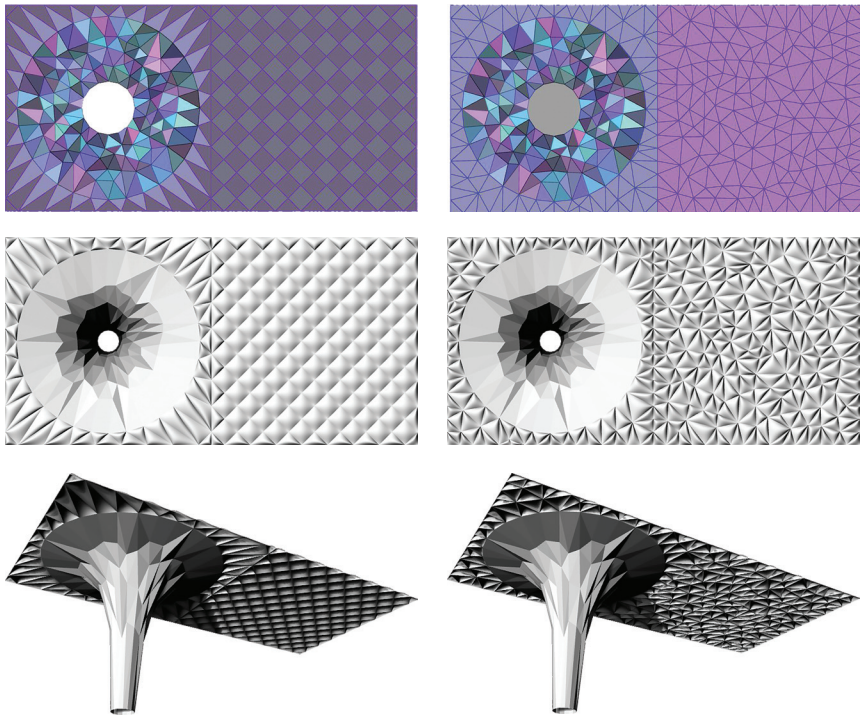
First Option
Left, Even Mode - I.D: 07, I.C: 05
Right, Random Mode - I.D: 04, I.C: 06

Figure 7-65 **Middle-Group**

Second Option
Left, Even Mode - I.D: 08, I.C: 06
Right, Random Mode - I.D: 09, I.C: 04

Figure 7-66 **Right-Group**

Third Option
Left, Even Mode - D: 24, I.R.O: 7.5
Right, Random Mode - D: 40, I.R.O: 09

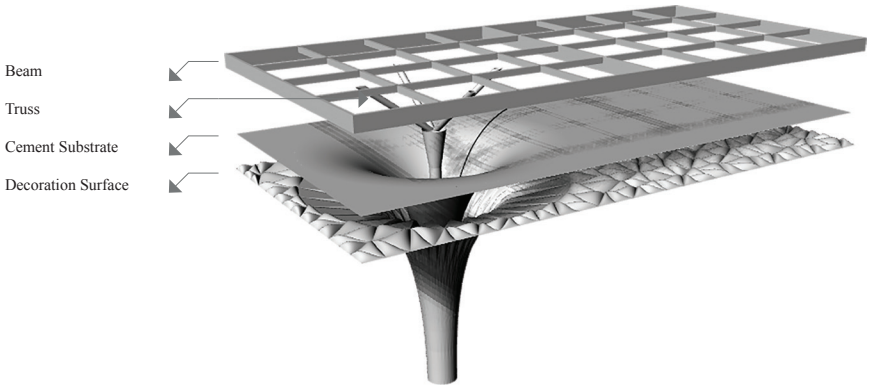


The whole system of patterning and pieces is shown in two examples.

Cone Module: Aggregate Pattern
Third Kind
D: 16, I.R.O: 6.3

Figure 7-67 **Left-Group** Flat Module: Conical

Figure 7-68 **Right-Group** Flat Module: Random



Analyzing the Members

A number of elements are assumed for supporting the decoration part in this composition, including the top structural grid and the column truss, which would be designed; a substrate, such as cement board, would be provided as an application surface. Upon this, figure 7-69 demonstrates these elements, which is proposed and manipulated.

Figure 7-69 The Composition of Modular Strategy

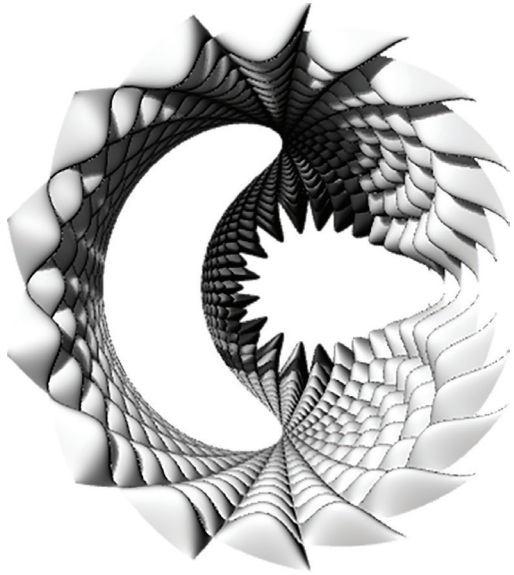
The Morphing Approach

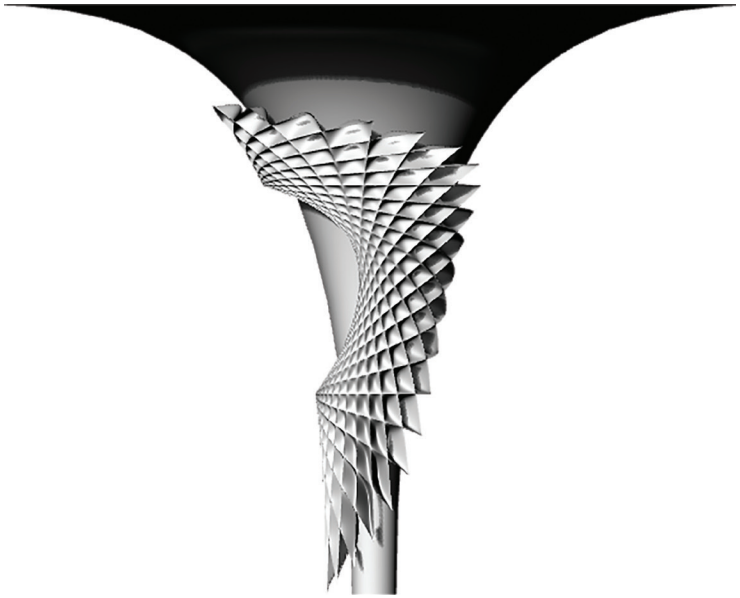
There is another way to map patterns on NURBS surfaces, called the morphing method.

The star pattern in both even and random modes enables one to apply to the surface using the morphing method. Because of the flat behaviour of this mapping technique, the inflation mode is provided as an option that increases spatial sense and recognizes each fragment.

The pattern morphs on the conical module and covers it but, by switching the toggle to the transposed mode, it allows the star pattern to run over the whole form and meets a portion of the flat roof.

In this example, there is no continuity as shown in some of the available images.The lack of continuity here means that the pattern has no connection with the neighbour's module when applied at the master level.

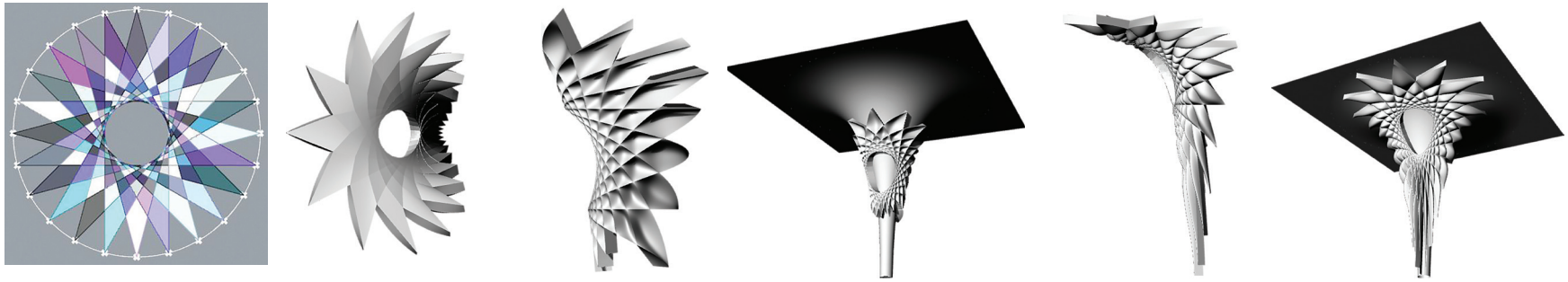


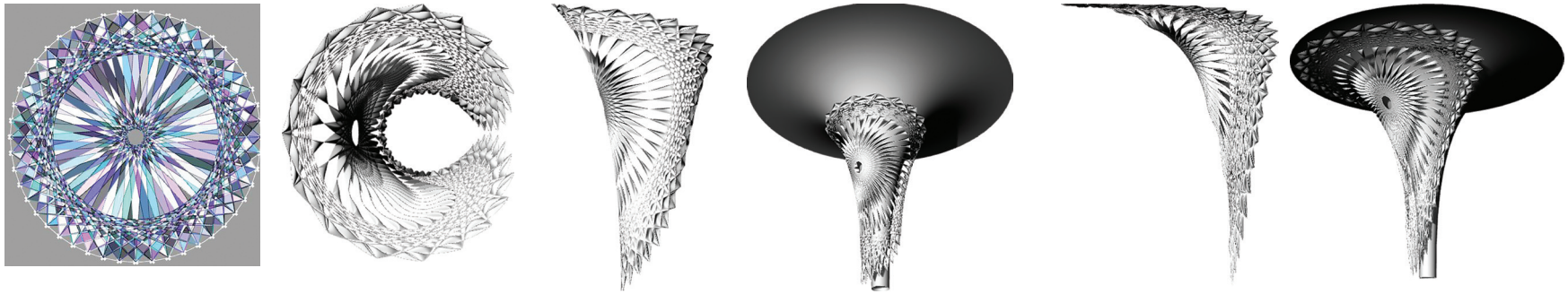


Star Pattern with morphing strategy, Even Mode
Division 42, Shift 15, Branch 02

Figure 7-70 **Top** Top View

Figure 7-71 **Bottom** Section





Star Pattern, Even Mode
Division 24, Shift 10, Branch 02

Figure 7-72 **Top-left** Top view

Figure 7-73 **Top-middle** Non-Transposed Mode, morphing the pattern across only column modules

Figure 7-74 **Top-right** Transposed Mode, morphing the pattern across both column and flat modules

Star Pattern, Even Mode
Division 48, Shift 12, Branch 04

Figure 7-75 **Bottom-left** Top view

Figure 7-76 **Bottom-middle** Non-Transposed Mode

Figure 7-77 **Bottom-right** Transposed Mode

EXAMPLE NUMBER ONE

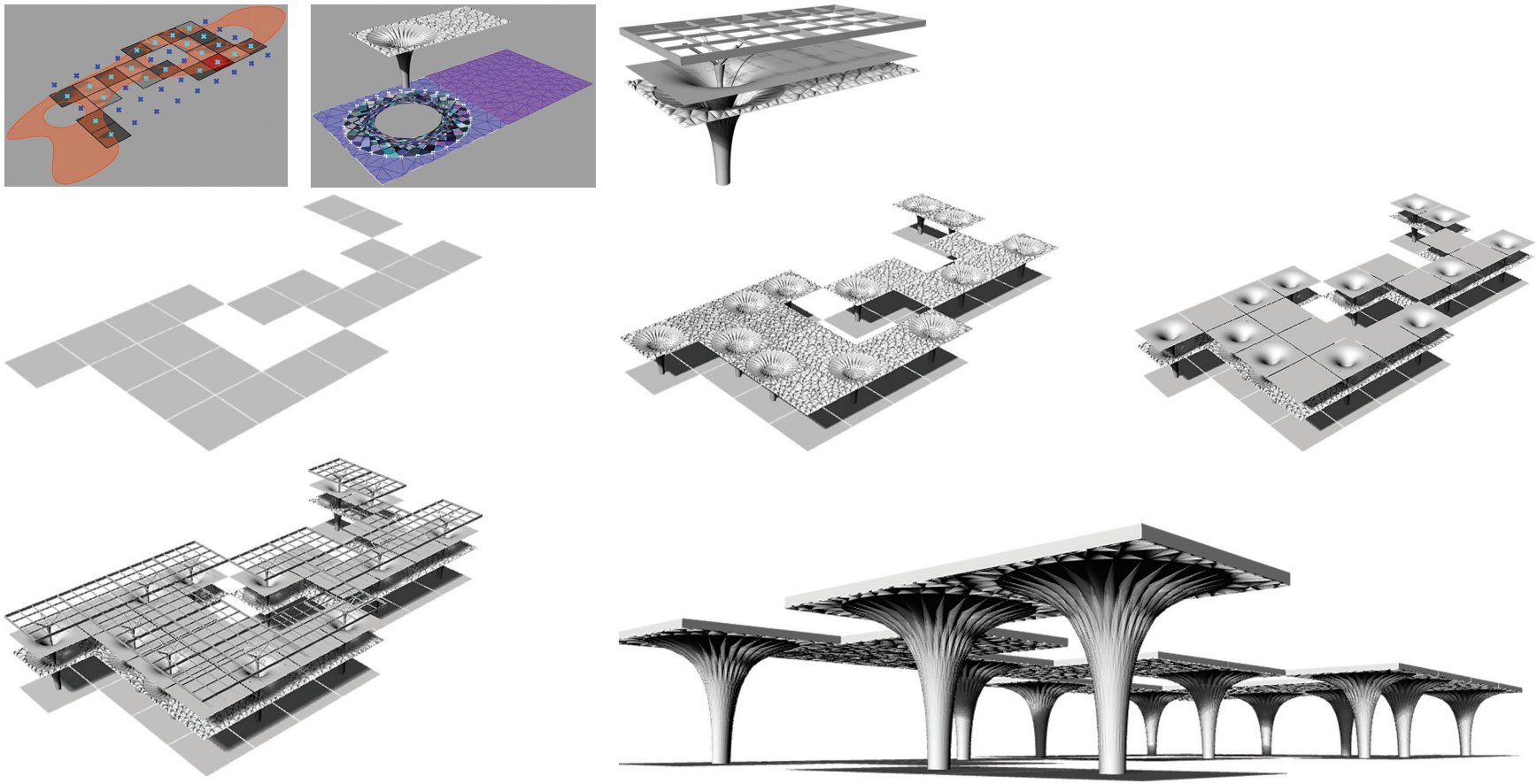


Figure 7-78 **Top-Left** Generative modular form level: Irregular Region, Picking modules randomly

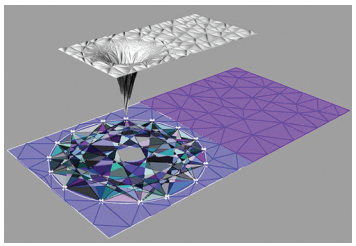
Figure 7-79 **Top-Middle** Projecting The desired pattern on the Demo
Flat Module: Conical Pattern
Cone Module: Star Pattern, Even Mode
Division 28, Shift 08, Branch 03

Illustration 7-80 **Top-Right** Applying the whole composition of the Modular strategy, standard and decorative parts

Illustration 7-81 **Bottom-Group** Implementing the developed Demo structure on the modular region and showing the entire process, level by level

EXAMPLE NUMBER TWO





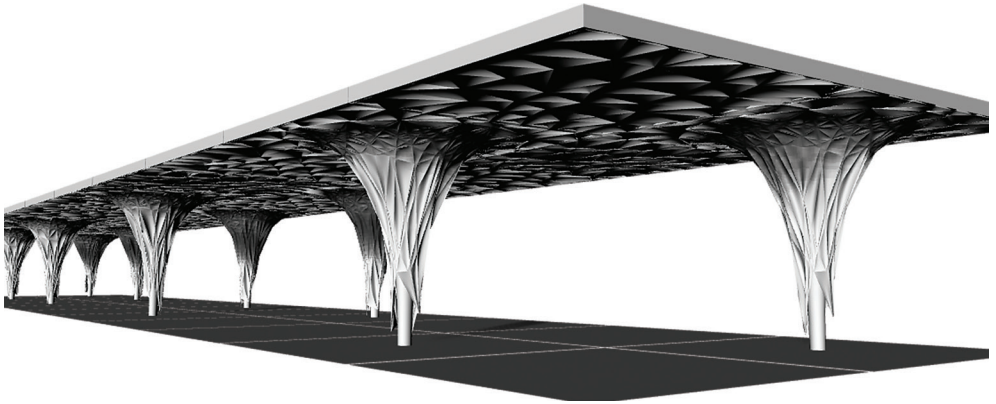




Figure 7-82 **Top-Left** Generative modular form level: Rectangular Region, Picking modules randomly

Figure 7-83 **Top-Middle** The pattern on the Demo
Flat Module: Random Pattern
Cone Module: Star Pattern, Random Mode
Division 16, Shift 04, Branch 04

Figure 7-84 **Middle** The 3D model of Example

Figure 7-85 **Bottom** Section of the Example

7.4 VAULT STRATEGY

In this strategy, the form starts from a conical module and contains a column and a bridge, similar to the first strategy. The main differences between Vault and Modular are: firstly, in Vault, each form is unique (creating variable trajectory)—there is no standard shape, but all are still based on the same system; secondly, the surface used in Vault is Mesh as opposed to NURBS.

This strategy is developed in three parts, namely, Vault Mesh Preparation, Vault Physics Engine, and Mesh distortion, which contains two options such as Mesh Deformation and Solid Creation. The first two steps make the form topology, and the last action creates the vault pieces to achieve the decorative purpose.

In this strategy, there is an option called “Inspection,” which makes the design process faster by providing a demo. Inspection gives the possibility of testing any parameter quickly, fixing it, and then applying it to the modular grid region. This ability to switch from applying to all to inspecting the results of specific changed settings, then reapplying to all, is always available.

Moreover, it is a “part to whole and whole to whole” system, meaning that during this process, control and change of the parameters in Inspection affects the overall system and vice-versa. Therefore, it should control in parallel for both. After amending the settings for one part, the new settings apply to the entire system to see the result and, if needed, they can control for all or switch to demo and change in that mode.

It is worthwhile to mention that all levels of the process are parametric and each level contains the parameters enabling change and control. Also, different options are considered during design development, such as the random elimination of vault pieces and inward/outward Inflation mode, representative of a contemporary way of thinking, which alter the aesthetics.

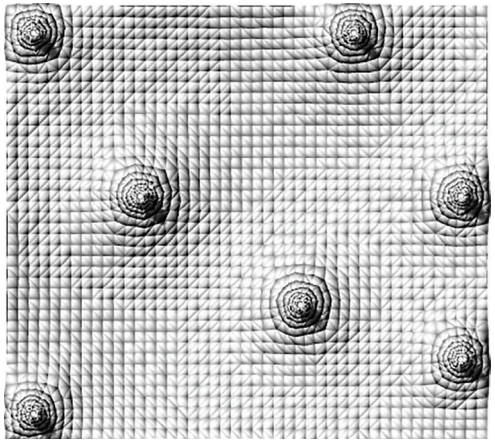
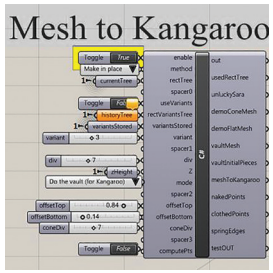
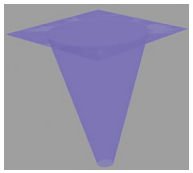


Figure 7-86 One example of Vault Strategy, Bottom View

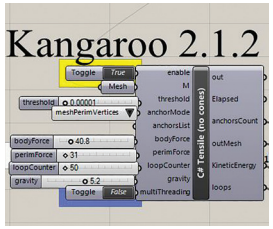
Figure 7-87 The Vault strategy levels of design, Grasshopper part and the result of each step

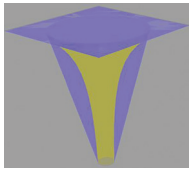
Step One: Form Topology



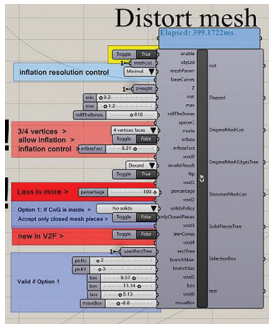


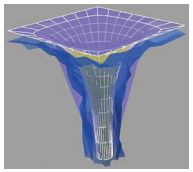
Step Two: Vault Physics Engine



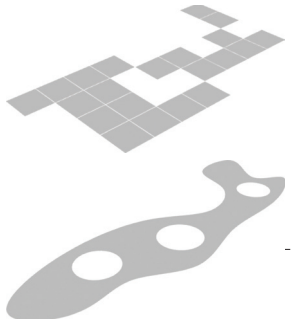


Step Three: pieces/Mesh Distortion

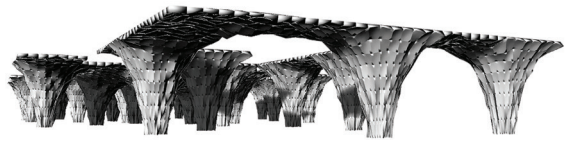




Step Four: System Combination



Lay-out



Result

Step One: Achieving the Form Topology

Vault Mesh Preparation

This mesh consists of “straight” cones and planar meshes and is deployed in space using stored data. There is a “quick” inspection mode that allows the creation of two “seed” meshes: a conical one and a flat one.

Various parameters control the mesh resolution. On the next page, the parameters are shown in inspection mode and then applied to the whole of one example. The controlling parameters are:

Radius Factor: The top and bottom radius of the cone.

Division: The divided texture of the mesh surface (solid will generate based on this division in the following steps).

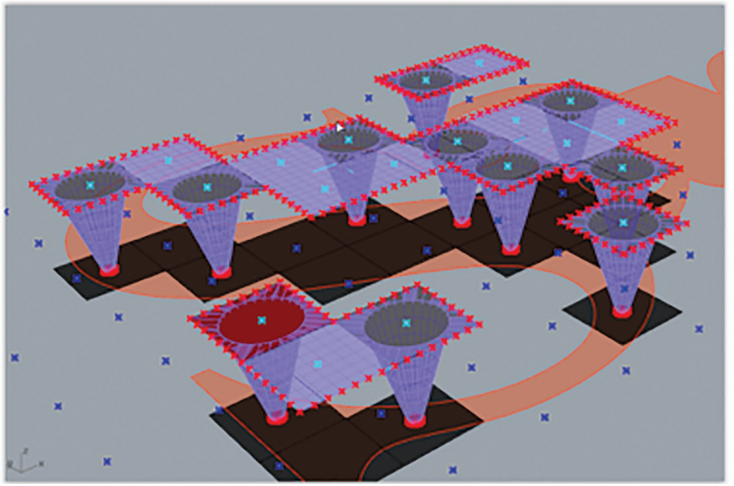
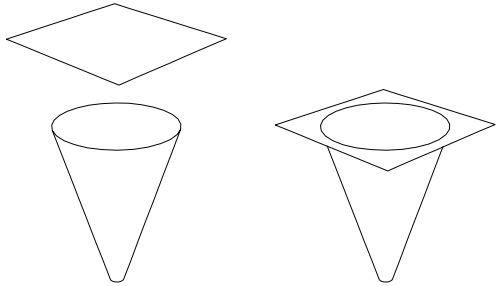


Figure 7-88 The naked mesh vertices: act as anchor points in the future mesh relaxation phase

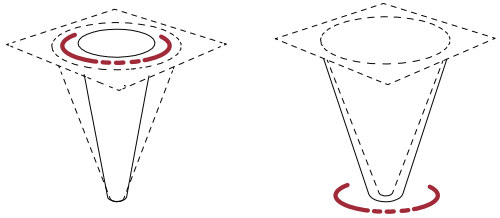
MESH PREPARATION PARAMETERS

PARAMETER ILLUSTRATION

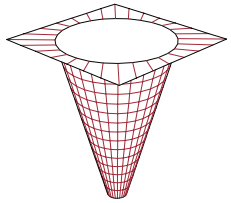
Modules



Radius Factor



Division



With the Lay-out System

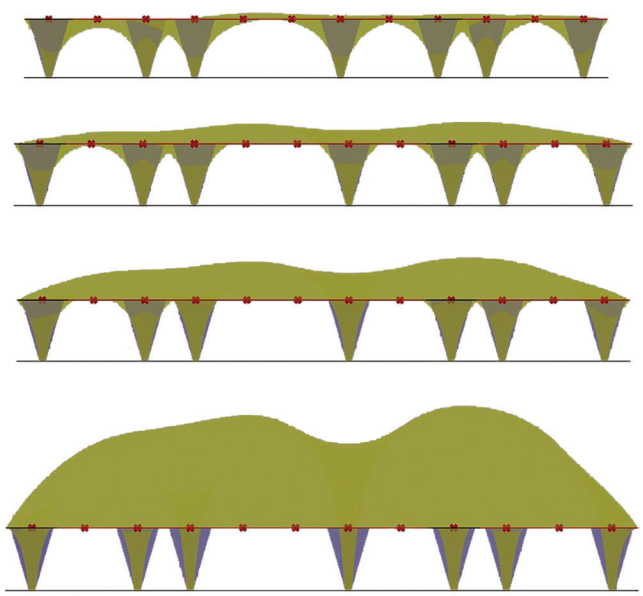


Figure 7-89 **First-Group** — **Left**, the cone and flat modules of the form **Right**, solidity of two modules

Figure 7-90 **Second-Group** — **Left**, top radius = 0.8, variable between (0.5 - 0.9) **Right**, bottom radius = 0.14, variable between (0.1 - 0.8)

Figure 7-91 **Third** — Mesh Division = 15, variable between (11-15)

Figure 7-92 **Forth-Group** — one example of the Mesh Preparation with Mater System **Left**, Plan view **Right**, Section view



Step Two: Vault Physics Engine

The whole system works based on preparing a desired Mesh using a specific physics engine (Kangaroo 2.1.2) through the aid of C# to achieve all design levels. Using this physics engine helps to achieve active form-finding and simulation.

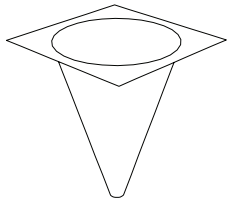
As the examples show, at this level of design, the form and the mode of relaxation is changed to give a suitable shape by controlling several parameters such as body force, gravity, and cone division.

Figure 7-93 **Group** The Interactive form changing based on the parameters in Physics Engine, Kangaroo

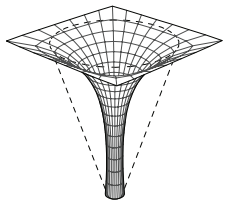
PHYSICS ENGINE PARAMETERS

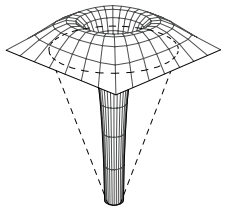
PARAMETER ILLUSTRATION

Modules

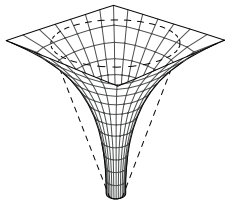


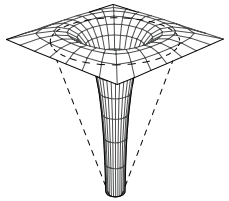
Body Force





Gravity





With the Lay-out System

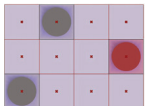




Figure 7-94 **First** The cone and flat modules of the form

Figure 7-95 **Second-Group** Body Force,
variable between (10 - 200)
Left, BF= 110
Right, BF = 14.5

Figure 7-96 **Third-Group** Gravity,
variable between (1 - 10)
Left, G= 5.2
Right, G = 9.6

Figure 7-97 **Forth-Group** One example of the Form Relaxation with Master System
Right, Section view
Left, Section view

Step Three: Vault Pieces

Mesh Distortion

After achieving the desired form in the previous level, the Mesh Distortion acts as a first step to adjusting the mesh for creating the pieces. It distorts the mesh division into three/four edges.

Mesh Deformation

After obtaining the mesh division, the deformation is applied to provide the conditions to compose the solid pieces at the next level. Various options control the topology of the pieces, most notably the number of random vertices deformation (within min/max limits) and the direction of deformation.

Pieces

Following the Mesh Deformation is the creation of the solid pieces. Different options such as depth, elimination mode and finally the possibility of Inflation (inward/outward), apply to this level. The elimination mode can provide a different visual interface, but it would be costly to build in reality. The inflation style is not necessarily used; it is only proposed as an extra mode for a further approach, which will be explained in the conclusion, act as acoustic diffusion or structural behavior.

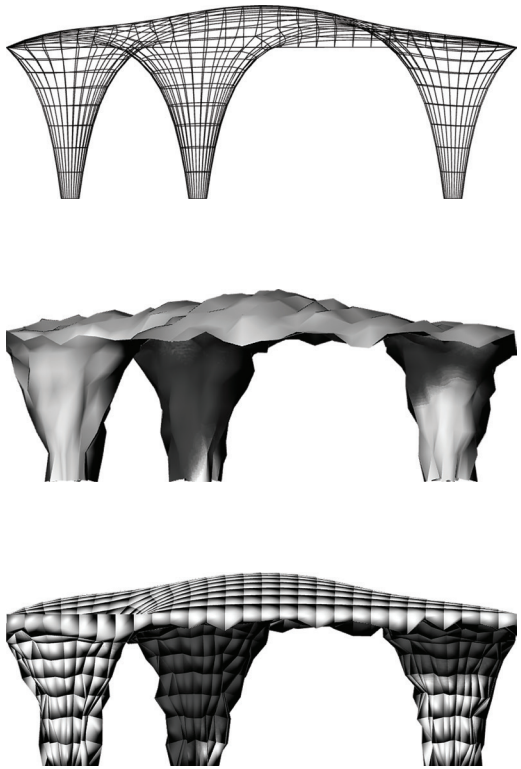
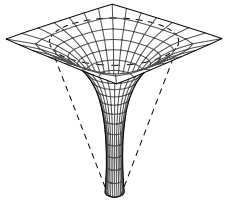


Figure 7-98 **Group** The levels of Pieces created in the Vault strategy

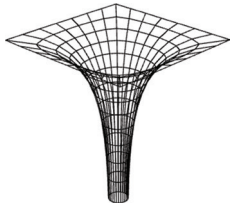
PIECES PARAMETERS

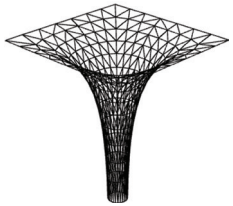
PARAMETER ILLUSTRATION

Modules

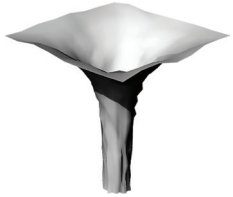


Face Vertices

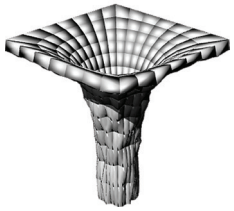




Surface/
Deformation



Solid



From Top to Bottom

Figure 7-99 **First** Desired form after relaxation

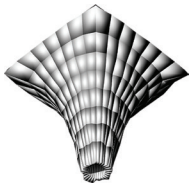
Figure 7-100 **Second-Group** Distorting the Mesh Division,
Available, three and four vertices
Left, Four edges, square module
Right, Three edges, triangle module

Figure 7-101 **Third** Deformation mode,
variable in orientation

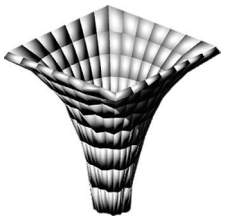
Figure 7-102 **Forth** Solid Pieces

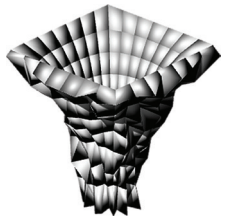
PARAMETER ILLUSTRATION

Solid Options

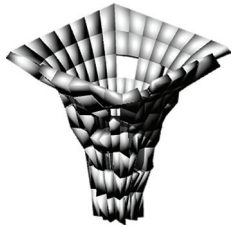


Depth

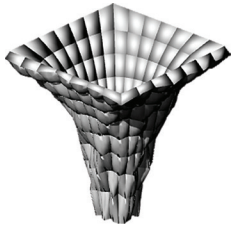


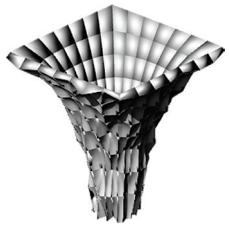


Elimination



Inflation





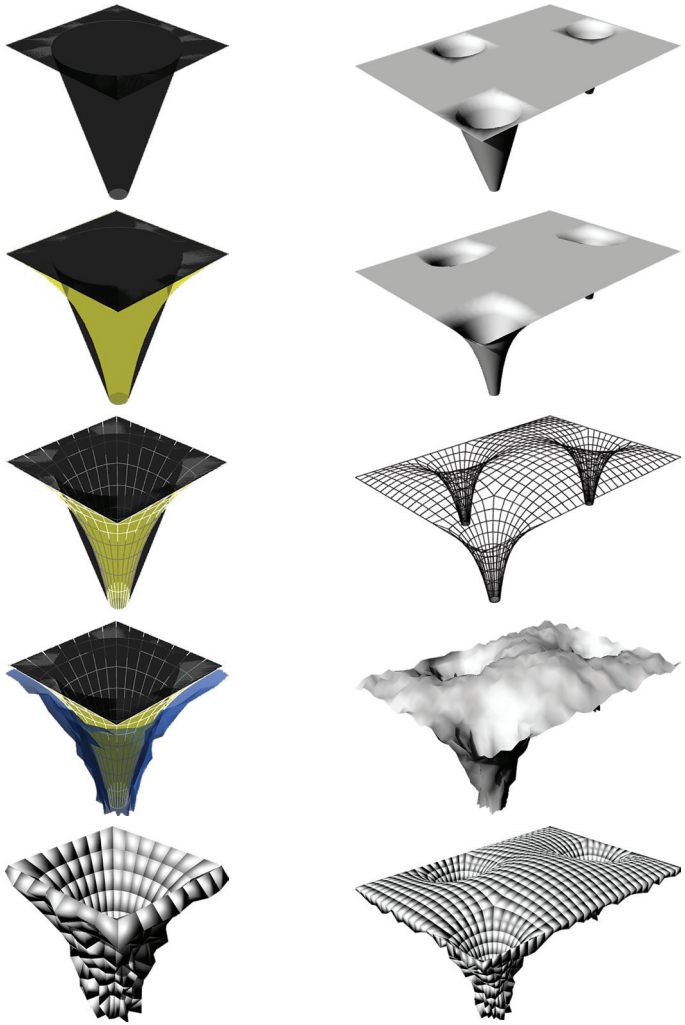
From Top to Bottom

Figure 7-103 **First** Top view of one vault demo with its pieces

Figure 7-104 **Second-Group** Different Depth,
Variable between (0.2 - 1.2)
Left, Maximum Depth = 0.3
Right, Maximum Depth = 0.8

Figure 7-105 **Third** Vault Pieces random elimination

Figure 7-106 **Forth-Group** Solid Pieces, from left to right, Outward and Inward Inflation Mode



Left: Inspection Model
Right: One Example combined with Master System

Figure 7-107 **First** Form topology and Mesh preparation

Figure 7-108 **Second** Form simulation with Physic Engine

Figure 7-109 **Third** Mesh distortion

Figure 7-110 **Forth** Mesh deformation

Figure 7-111 **Fifth** Generating the solid Pieces

EXAMPLE NUMBER ONE

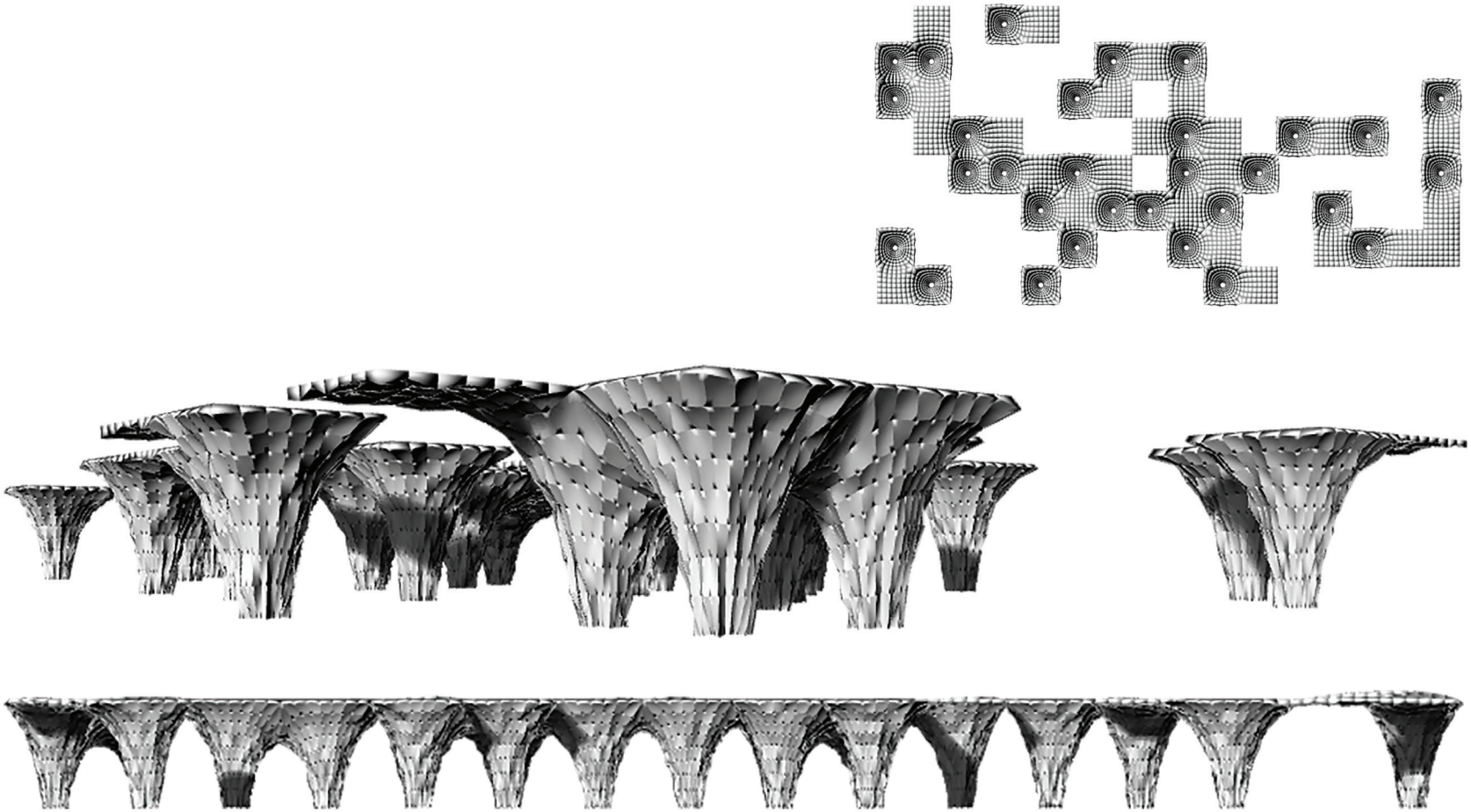
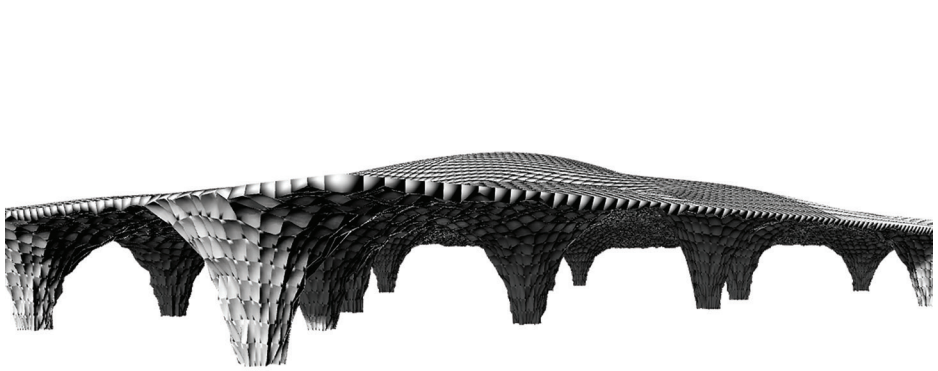
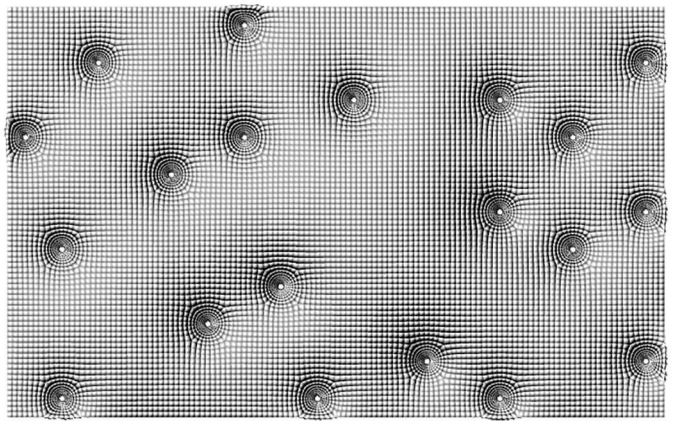


Figure 7-112 **Top** the region is ‘’Sara’’, modules are selected randomly

Figure 7-113 **Bottom** Various open, semi-closed and closed spaces are created

EXAMPLE NUMBER TWO





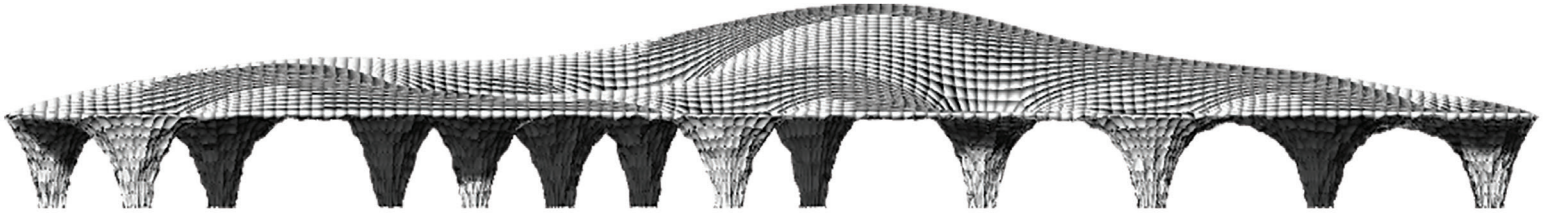


Figure 7-114 **Top** Rectangular region, Modules are selected randomly for showing dispersion and heterogeneity

Figure 7-115 **Bottom** Section of the form, addressing various possible heights

8.0 PROPOSED DESIGN

Purpose

This chapter presents four proposed designs, two using the Modular strategy and two using the Vault strategy. The purpose is to present the designs as contemporary architecture in historic sites; in other words, how contemporaneity meets history. It also aims to show the capability of the design strategies at different scales. The Modular strategy, based on arabesque art, is employed for sites in Isfahan, Iran (as an ancient city) and Dubai (as a contemporary city) at two scales, small and large, respectively. For Vault, St. Petersburg, Russia is chosen as a historic city while an empty site in Las Vegas is chosen as a contemporary place to show the potential of this strategy.

Location

The reason for choosing the specific ancient locations for both strategies is a consideration of their historic neighbours. The proposed Modular design for Isfahan is located near Si-o-she pol, famous as an ancient historic pedestrian bridge and public space. The second strategy, Vault, is proposed for Palace square in St. Petersburg, Russia as one of the most well-known squares in the world, with the selected site bordering the square. The method for selecting the two contemporary sites, in Dubai and Las Vegas, is finding an empty field, with view as a consideration. In Dubai, Al Mamzar Island is selected for its beautiful view of the Persian Gulf and in Las Vegas, the large, empty site, close to the hotels and restaurants of the city, has a perfect view of the various types of architectural language used in its neighbours' building design.

Function

The examples aim to show both open and closed public spaces at small and large scales. In the Modular strategy, a small-scale bus station located in Isfahan, Iran is proposed as an open public space. This design is intended to reveal the potential of the bus station as a public space, and the street as one of the important elements of a city's public spaces. On Al Mamzar Island, a large-scale design for a shopping mall is proposed as a closed public space. In the Vault strategy, the first design indicates a semi-open public space, a place for gathering, sitting and talking, and other social interactions. People can enjoy the beautiful view of Palace Square in St. Petersburg with protection from weather conditions. The proposed design in Las Vegas is for a large-scale shopping mall, with various restaurants and bars.

Design

The design is developed at each location after a quick site analysis. In all proposed designs, a sense of invitation and views are considered to create a form appropriate to the design's geographical region. The selection of the modules as columns are regular in the Modular strategy and irregular or random in the Vault strategy. Also, different modes are considered, such as elimination of components for sun penetration and creating holes at the large scale to achieve the desired quality of light.

MODULAR STRATEGY



Figure 8-1

Purpose: when the contemporary Architecture meets the History
Location: Isfahan, Iran
Function: Bus station
Area: 54 m^2



Figure 8-2

Purpose: Large scale structure with long span in contemporary City
Location: Al Mamzar Island, Dubai
Function: Mixed-use public space
Area: 100,000 m^2

VAULT STRATEGY

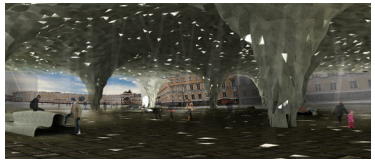


Figure 8-3

Purpose: when the contemporary Architecture meets the History
Location: Palace square in St. Petersburg, Russia
Function: Semi-open Social Space
Area: 5150 m^2

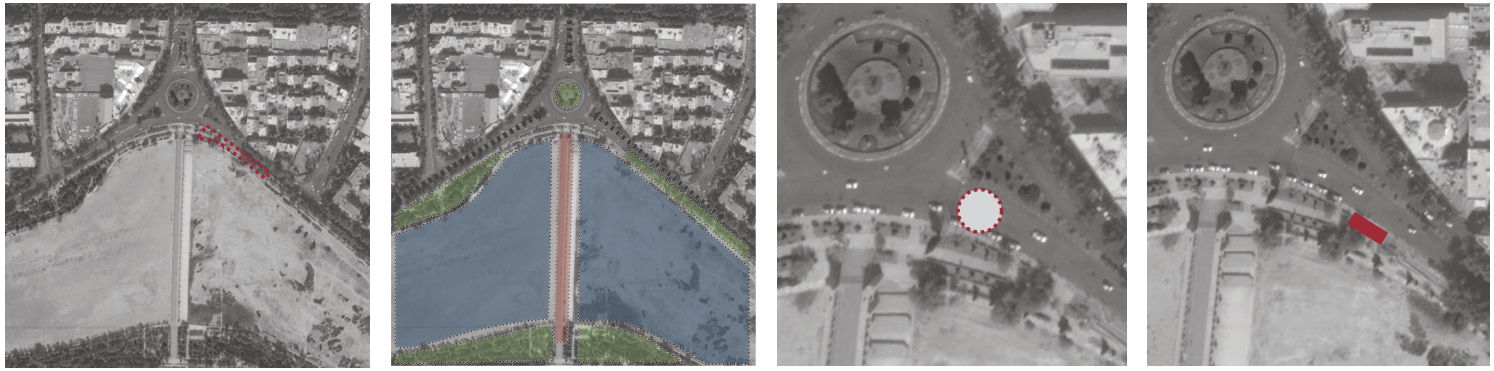


Figure 8-4

Purpose: Large scale structure with long span in contemporary City
Location: 5367-5681 Dean Martin Drive, Las Vegas
Function: Mixed-use public space
Area: 127800.500 m^2

MODULAR STRATEGY, KAMAL ESMAEEL ST , ISFAHAN, IRAN

EXPLORING THE DESIRED REGION



Pedestrian Area

Street Access

Subject Area

Existing Station

Historic Neighbors, Si-o-se pol Bridge

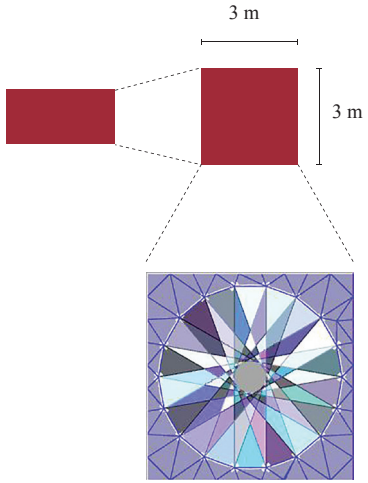
Green Area

Zayande Roud River

Figure 8-5 **Group** Site analysis demonstrating site features, neighbours and proposed boundary within the site, aerial map, Kamal Esmaeel St., Isfahan, Iran

SIZE, PATTERN AND DESIRED REGION





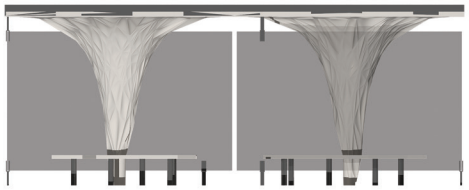


Figure 8-6 Proposed boundary for the design, Isfahan, Iran

Figure 8-7 Size and pattern of each module

Identification Charector

Flat Module Area: 9 m^2
Height: 2.4 **m**
Pattern: Star
Mode: Even
Division: 18
Shift: 8.0
Branch: 2.0

Figure 8-8 Section view of proposed bus station



Figure 8-9 Perspective rendering of proposed bus station, demonstrating its contemporary architecture close to the ancient Si-o-Seh pol Bridge in Isfahan, Iran





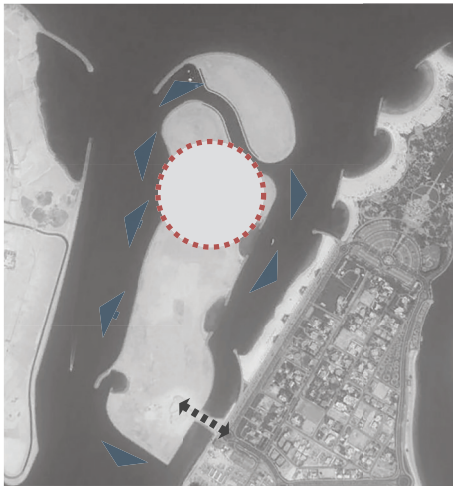
Figure 8-10 Perspective rendering of proposed bus station, demonstrating the view from the ancient Si-o-Seh pol Bridge in Isfahan, Iran

Figure 8-11 Perspective rendering of proposed bus station, demonstrating the overall view from the ancient Si-o-Seh pol Bridge in Isfahan, Iran

MODULAR STRATEGY, KAMAL ESMAEEL ST , ISFAHAN, IRAN

EXPLORING THE DESIRED REGION







Island Area

Access from Twon

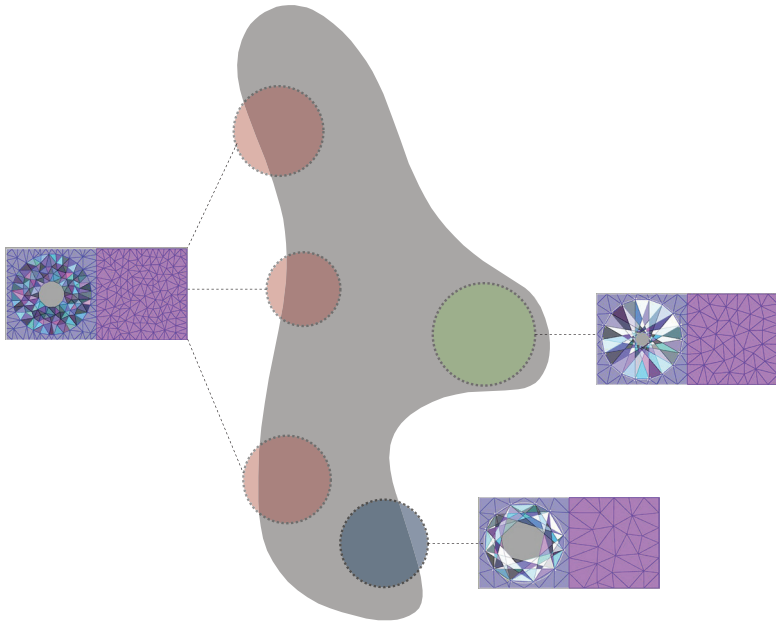
Subject Area

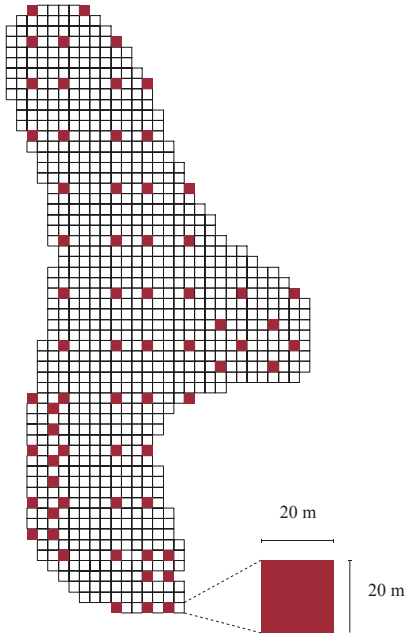
Desired Region

Sea View

Figure 8-12 **Group** Site analysis demonstrating site features and neighbours, aerial map, Al Mamzar Island, Dubai

AREA OF THE SITE, CONSIDERING DIFFRENT PATTERNS AND MODULES





Identification Charector

Flat Module Area: 100 m^2
Height: 15 **m**
Pattern: Star, Aggregate
Mode: Even, Rnadom

Aggregation Pattern, Option three
Division: 16, Inner Offset: 6.0

Star Pattern, Random
Division: 12, Shift: 08, Branch: 03

Star Pattern, eVEN
Division: 16, Shift: 08, Branch: 02

Figure 8-13 Proposed boundary for the design and positions of its three various patterns, Al Mamzar Island, Dubai

Figure 8-14 Stored modules as columns in the proposed design, demonstrating the span length and size of each module



Figure 8-15 Perspective rendering of the shell structure from inside of the proposed shopping mall, Al Mamzar Island, Dubai, demonstrating the Aggregate pattern used for decoration.



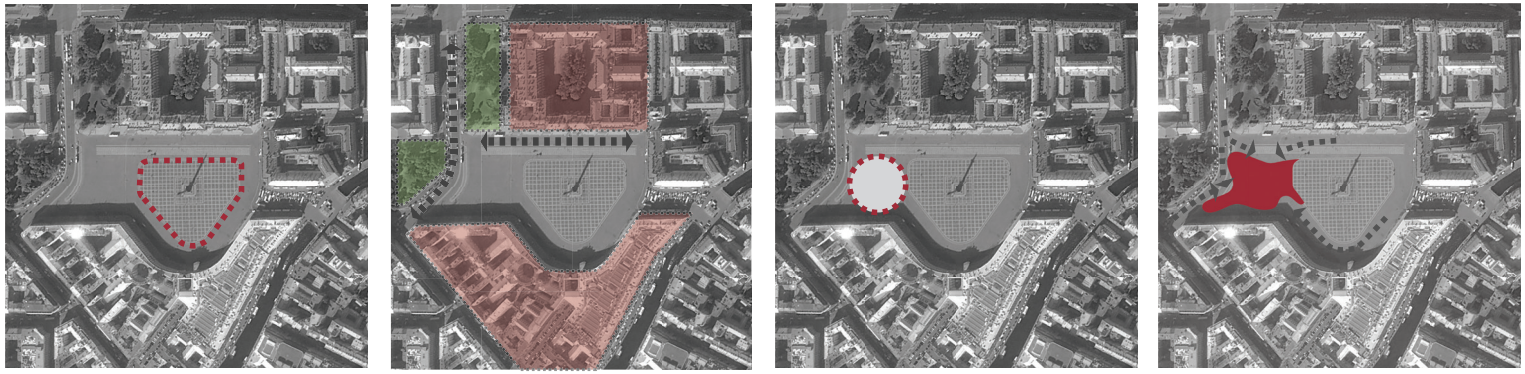


Figure 8-16 **Left** Perspective rendering of shell structure from inside of the proposed shopping mall, Al Mamzar Island, Dubai, demonstrating Star pattern (Random mode) used for decoration

Figure 8-17 **Right** Perspective rendering of shell structure from inside of the proposed shopping mall, Al Mamzar Island, Dubai, capturing the decoration part of the shell structure

VAULT STRATEGY, ST PETERSBURG SQUARE, RUSSIA

EXPLORING THE DESIRED REGION



Palace square Area

Street Access

Subject Area

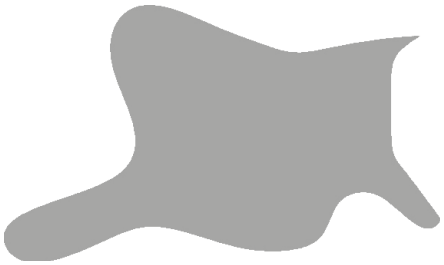
Desired Design Form based on ‘’inviting”

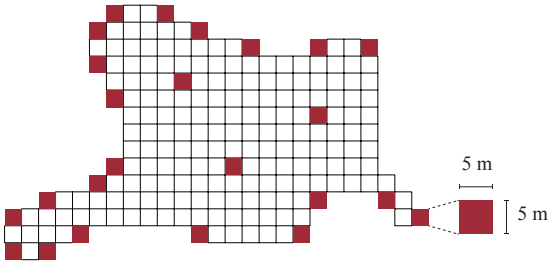
Historic Neighbors

Green Area

Figure 8-18 Site analysis demonstrating site features and neighbours, aerial map, Palace Square, St. Petersburg, Russia

AREA OF THE SITE, MODULES AND FINAL MODEL







Vault Identification Charector (All measure is Meter)

Flat Module Area: 25 m²
Height: 8
Number of Vertices: 3.0
Cone Division: 9.0
Body Force: 150
Gravity: 6.0
Top Radius: 0.77
Bottom Radius: 0.11
Thickness: (0.2 - 1)

Figure 8-19 Proposed boundary for the design, St. Petersburg, Russia

Figure 8-20 Stored modules as columns in the proposed design, demonstrating the span length and size of each module

Figure 8-21 Top view of the proposed shell structure, Palace square in St. Petersburg, Russia

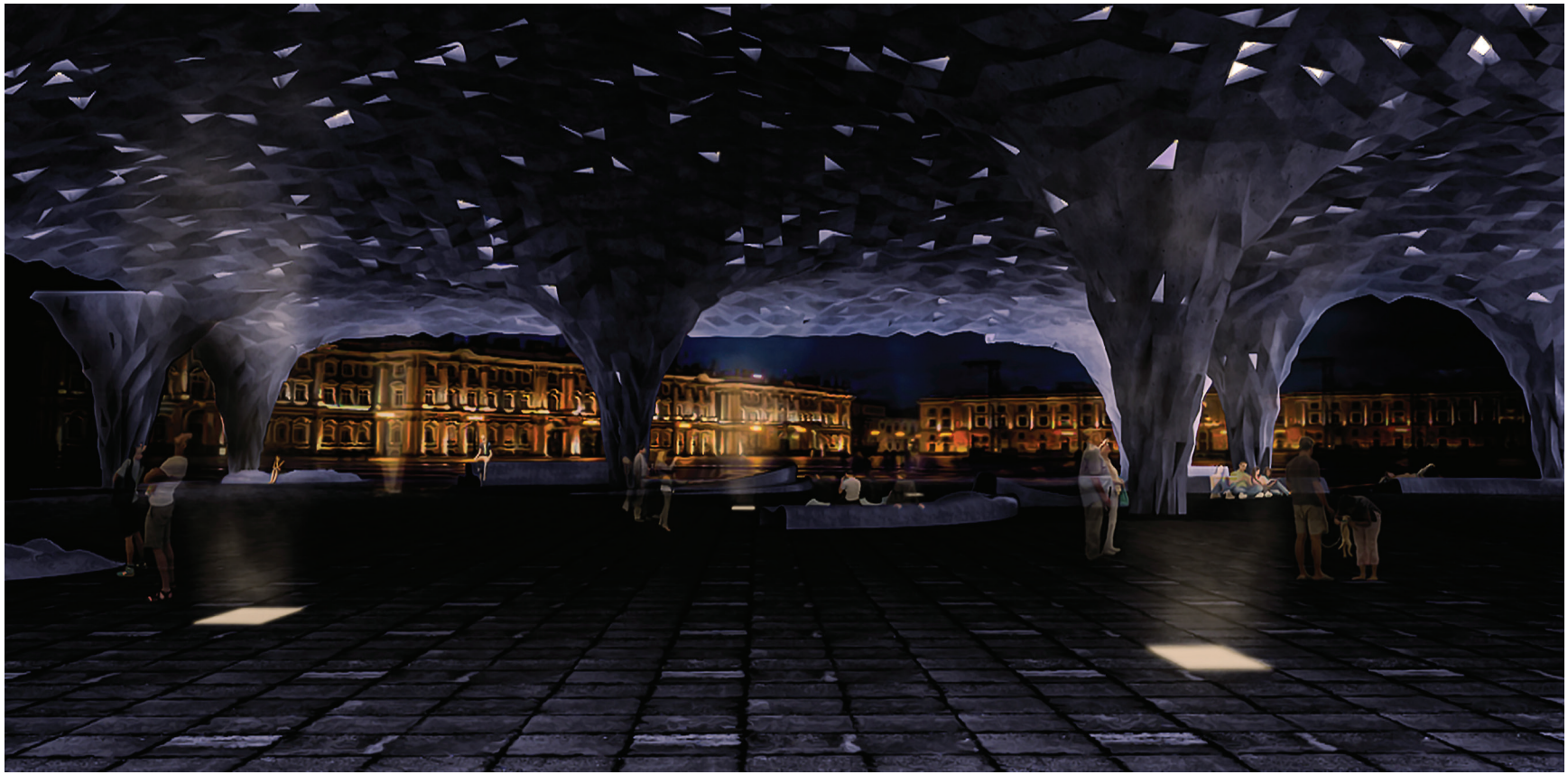


Figure 8-22 Night rendering of proposed open public space, demonstrating the contemporary vault structure located in its historic context, Palace square in St. Petersburg, Russia



Figure 8-23 Day rendering of proposed open public space, demonstrating the contemporary vault structure located in its historic context, Palace square in St. Petersburg, Russia

VAULT STRATEGY, 5367-5681 DEAN MARTIN DRIVE, LAS VEGAS

EXPLORING THE DESIRED REGION



5367-5681 DEAN MARTIN Drive Area

Street Access

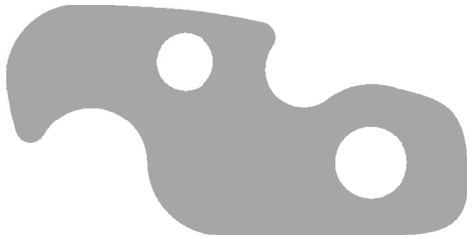
Subject Area

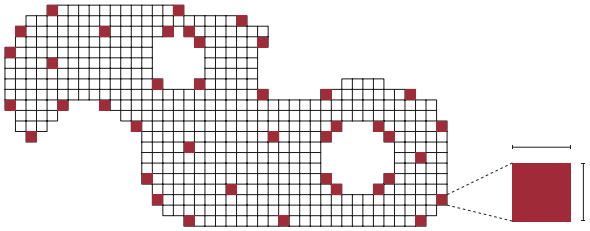
Desired Design Form based on ‘’inviting”

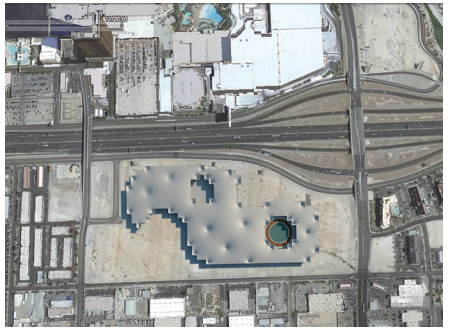
Direction to the Entrance

Figure 8-24 **Group** Site analysis demonstrating site features and neighbours, aerial map, 5367-5681 Dean Martin Drive, Las Vegas

Area of the site, Modules and Final Model







Vault Identification Charector (All measure is Meter)

Flat Module Area: 100 m^2
Height: 10
Number of Vertices: 4.0
Cone Division: 7.0
Body Force: 150
Gravity: 6.0
Top Radius: 0.77
Bottom Radius: 0.11
Thickness: (0.8 - 1.2)

Figure 8-25	Proposed boundary for the design, Las Vegas
Figure 8-26	Stored modules as columns in the proposed design, demonstrating the span length and size of each module
Figure 8-27	Top view of proposed shell structure located at 5367-5681 Dean Martin Drive, Las Vegas



Figure 8-28 Night rendering of proposed shopping mall, demonstrating the contemporary vault strategy located in the contemporary context of Las Vegas



Figure 8-29 Day rendering of proposed shopping mall, demonstrating the contemporary vault strategy located in contemporary context of Las Vegas



Figure 8-31 **Right** Interior rendering of proposed modular strategy, demonstrating Contemplation character of the design using Aggregate pattern, Third option, Random mode



Figure 8-32 **Left** Interior rendering of proposed vault strategy, demonstrating the Contemplation character of the design using four edges module and Cone Division is seven

9.0 CONCLUSION

"Several hierarchies reveal a web of inventive flow; nowhere the same but everywhere the intrigue of abstract points turning to compiling, deciding, line. The result is finally articulated, always on the move. There seems to be no edge condition or final moment, the fabrics are something to wrap around one's imagination, finite but unbounded." - *Cecil Balmond* [1]

This thesis was based on a parametric system as a new ecology emerging in architecture and design culture, combined with specific lessons from history. It considered not only the structural aspects of the design but also took into account aesthetic values to create an algorithmic, generative system, applicable everywhere based on local site shape, optimization of the structure and reaching a sublime point—space represented as media. To achieve these goals, the primary concept of the form topology emerged from the historical use of the vault system. Another reason to choose this topology is that, nowadays, the historic vault topology has been largely replaced with another formal system. The aesthetic form of this kind of shell and the value of its structural behaviour may be lost forever.

The decoration and aesthetic values were considered from local and global perspectives to create subjective values of design. The contemplation sense of the inner surface achieves through analysis of the spatial geometry of *muqarnas* of an existing example of one kind, located in Isfahan. Exploring the main parameters, based on two-dimensional drawing of *muqarnas*, and applying the projection mode based on its construction method created a conceptual form of this ornament in a contemporary way. This idea of the design is presented as a standalone shell structure protecting people from weather conditions, hosting different public and private activities, and performing as a place of social mediation.

According to these objectives, the thesis proposed a generative modular system called a Master system, which remained the same in the two proposed strategies, Modular and Vault. Both presented the same form topology, containing the column and flat modules. In the first

design, the module is replicated by defining the position of the columns in the Master system and the structural elements offered to create a standalone shell type. The pattern used for the decoration component inside the shell is inspired by an aniconic, vernacular geometrical ornament called *muqarnas*. Although in this thesis, it is applied differently from actual *muqarnas* used historically, it is the inspiration of the algorithmic system, and the psychological features of this ornament are revealed in this strategy.

In the second strategy, Vault, the form is found using the live physics engine Kangaroo, the interactive digital simulation, and constraint resolving, and replicated on various trajectories along the master system. The inner decoration is created through the deformation method using mesh division and the generated components, as well as optional modes such as inflation and elimination, representative of a contemporary way of thinking, which alter the aesthetics. The different parts of the design such as geographical region, form topology, or inner decoration include various parameters; each of them can affect the design based on project demands.

The design strategy and the critical parameters are created to respond to the primary thesis question, which is how this infinite result deals with the restrictions of construction. The parameters developed are offered based on optimizing factors such as the thickness of the components and the span distance by taking action in the Master system, which can be either shortened or extended.

Using the vault topology as the source of the form and *muqarnas* as the inspiration for the aniconic ornament, combined with computer-based techniques, addresses the second question of the thesis: how to use historical precedents in both structure and aesthetics to design a contemporary architecture, consistent with the past but still different.

After analyzing *muqarnas* as a case study, the method of construction, the relationship between the tiers of the two-dimensional pattern and their projection onto the form, the key parameters are generated. These parameters lead the design in a new area of computational desing, using multilayer characters of muqarnas integrated with a contemporary way of thinking. In this area, the system of two-dimensional pattern is defined by three parameters namely, a circle; the points, which evenly divide the perimeter; and the linked lines between points, which connect according to a particular system. In the next level of design, the traditional form of a dome or semi-dome is selected as a topology to indicate how the two-dimensional pattern can tessellate and relay onto the surface. In the next approach, ‘‘random’’ mode, the method of variable lengths on the circle is employed. It has the same system which by turning only one parameter it can enrich the complexity and contemplation sense of design, and also increases the aesthetic value.

The Modular strategy for the inner decoration was based on the vernacular ornament and geometry *muqarnas*, combined with research showing that it shares similarities with digital media art, from forming the algorithms to the perceptions of the observers, which is not the final result. In both Islamic and computer-based arts, “the work of art plays out in time, unfolding image from information and information from the infinite.”[2] It is one type of ornament based on a local culture, which is identified in a place as a familiar language and creates a sense of belonging. The suggested sites for this case are therefore places such as Iran and Arab countries.

In the second strategy, the decoration and the aesthetic sense are designed based on computational principles offered by mesh division, in a neutral, global way—it is not the symbolic art of any particular culture and can be perceived from a global perspective. Different sites are randomly offered for this strategy.

In the end the two different locations for each strategy of the proposed design are chosen based on scale and character of region. Palace Square in St. Petersburg, Russia and Isfahan, Iran present sites for the first and second strategy, respectively, to show the conjunction of contemporary design in ancient places. Las Vegas and Dubai are excellent contemporary places for showing the potential of the proposed design at a large scale. Different potential activities are illustrated in each example in the form of a place for gathering, a bus station and shopping centre, café and restaurant.

DEVELOPMENT OF PARAMETRIC *MUQARNAS*

The analysis of the physical formation of *muqarnas* is considered in one section, from the two-dimensional drawing to the formation and tessellation of the spatial modules. But the result used in the Modular strategy has more depth in the art of the knot (a 2D pattern) and the outcome was close to the *Yazdi Bandi*, one type of Persian ceiling ornament used instead of full, three-dimensional ornamentation. It is created using two-dimensional, solid components that are projected on the surface. It could be proposed as an opportunity for further research to revise this *muqarnas* form for emulation. Rethinking the generation of the self-supported modules as having more than a decorative role can be an innovative idea for the revival of this art.

COMPONENT AS ACOUSTIC DIFFUSION

In both the Modular and Vault strategies, optional modes of inflation in the first and the deformation action in the second are considered as ways to increase aesthetic possibilities and differentiation. Today, the return of ornament to the realm of architecture and the development of technologies opens a broad range of possibilities in architectural practice and theory. These possibilities guide this thesis towards the next level of thinking to consider the compo-

nents not only in the aesthetic, but also the functional sense. The application of the design to public space, the types of activities, and the topology of the vault converged to generate an idea to design based on acoustic raytracing. This means the sound rays creates by the outer and inner activities can be controlled by spreading and absorbing them. The deformation and inflation of the solid component and, as Peter Fotiadis has said, at an even more advanced level for dealing with this problem, the specific type of coating, can absorb a percentage of noise. This approach would require specific simulation and calculation of the raytracing, which is a costly process for this level of research.

INNOVATIVE METHODS OF AFFORDABLE FABRICATION

In recent decades, besides computational design, the two fields of materiality and fabrication technologies have started to significantly redefine the theoretical and practical principles of designing architecture. The precedents analyzed in this thesis presented two examples of fabrication based on design and purpose that can be taken into account for this practice step. The physical fabrication of the strategies proposed in this thesis would be costly based on the use of material, because of the variation of components such as scale and thickness in each outcome. Further research and prototyping at different scales, as well as analysis of material behaviour, could further develop the design. The way to realize the thesis design strategies is using the digital fabrication methods such as large-scale 3D printing, CNC machines, or other innovative methods of fabrication using performative robotic devices. Just as the proposed design strategy aims to innovate in the area of design, it will require innovative construction methods for its realization.

REFLECTION AND FUTURE DIRECTIONS

Besides its potential in achieving different possible design solutions, the complex parametric design system proposed in the thesis has several constraints and limitations. These limitations appear at all levels of design, stimulating rethinking of the design and changes in approach in some parts because of the limitations of the parametric and algorithmic techniques employed. These limitations of the computational design, due to its virtual aspect, appear not only in the process of design, but also in its potential real-world construction. The design is faced with structural and fabrication problems, which require additional calculations and simulation for structural analysis, material behaviour and fabrication techniques at different scales.

In reflecting on the objective of the thesis research and design, the development of the intelligent character of the design was successfully achieved. This factor can be seen in different aspects of design from the infinite solutions achieved by the system as an outcome to the infinite sense of contemplation given to each beholder.

This means that using parametric design and an algorithmic system in the thesis represented a new design ecology and culture in architecture, affecting the system of thinking in practical and theoretical aspects which have an effect on the design principles. One important aspect of using parametric design is the sense of unity which arises from infinity, meaning that the thesis represented the design with “one” system (unity), which generates various possibilities (infinity). This unity-infinity feature is demonstrated at two levels of design:

First, the various possible solutions achieved by one parametric and generative system are demonstrated through the proposed designs, and each of them tries to open a new potential of the system as an illustration. From a small-scale bus station in Iran to a large-scale shopping

mall in Las Vegas, the designs demonstrate the capability of the contemporary shell structure in ancient places as well as newer contexts, as well as the potential of the generative system, which can easily expand from a small to a large scale.

Second, learning from the algorithmic principles used in arabesque art as well as the algorithmic system of parametric design techniques, using the universe of code and data which both have one principle, empowered the subjective character of the design. The depth of the design is not represented as one readable image or final, perfect, glossy surface perceived in the same way by all. It invites people to gaze, touch and feel this haptic space in infinite ways. Some viewers will be reminded of a memory, some will feel it deeply but not perceive the infinite plane of data, and a small group of people will travel into the depth of the space to reach the abstract lines and infinity. This aspect of the design converts it to the deductive universe of time, contemplation and senses.

ENDNOTES

1. Ferda Kolatan and Jenny E. Sabin, *Meander: Variegating Architecture* (Exton, PA: Bentley Institute Press, 2010), 12.
2. Laura U. Marks, *Enfoldment and Infinity: An Islamic Genealogy of New Media Art* (Cambridge, MA: MIT Press, 2010), 61.

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GLOSSARY

Arabesque Art

Aniconism The absence of human, animal or material symbolism in the art of various culture.

Arabesque Art A kind of decorative art for religious and ritual intents, or not strictly religious intents, often associated with Islamic art. A rhythmic, linear pattern composed from surface division, based on algorithmic and mathematical principles in organic and non-organic ways.

Art of Knot Interweaving method of two-dimensional patterning, a subcategory of arabesque art.

Contemplative space The impersonal and subjective character of a space generated based on algorithm and code, meaning that it is perceived differently based on human senses and wisdom.

Muqarnas One kind of spatial geometry and ornament, mostly used for the interior of domes or semi-domes, originating in Persian architecture. The pattern system is based on tessellation.

Strong Primitive Name used for the style of square muqarnas, located in the Jami Mosque, Isfahan, Iran.

Yazdi-bandi A kind of semi-spatial geometry and ornament, used mostly for the interior of domes or semi-domes, originating in Persian architecture. The pattern system is morphing.

Parametric Design and C# control Data

Spring force The amount of force applied to relate two points against each other. In this thesis, this is named "body force" and refers to non-naked mesh points processed at the Kangaroo mesh relaxation phase. If it is bigger, the springs are "stiffer" and the deformation (how much the mesh is "relaxed") is smaller. In this thesis, the mesh naked points are considered as anchors.

Bool Boolean type used in C# language (true/false or 0/1).

CAD Computer Aided Drafting, software used mostly for drafting geometries.

Computational morphogenesis "Computational morphogenesis is a design process that takes advantage of the two main features of evolutionary algorithms: exploration of a wide set of possiblities, and exploration, of the best solutions generated, in analogy with natural evolutionary process." [1]

C# Programming language developed by Microsoft, currently at level 7.

CPU Refers to the central processing unit of any computer. Works under the instructions of a compatible chipset. May have multiple cores.

DataTrees Proprietary complex/nested List management feature used exclusively in Grasshopper.

Double signifies a simple type that stores 64-bit floating-point values

Face Vertices	The vertices of a given mesh face.
Generative Components	Parametric add-on (the equivalent of Grasshopper), developed by Robert Aish, used in Bentley Systems BIM software (Microstation/AECOSim).
Grasshopper	Parametric Plugins developed by David Rutten, hosted in Rhino CAD software.
Int	signifies a simple type that stores 32-bit integers.
Kangaroo	A physics engine used interactively for form optimization and structural stimulation.
NURBS	Non-uniform rational Basis spline (or B-spline), a mathematical model for creating curves or surfaces in computer 3D modeling.
Rhinoceros [Rhino]	Computer-aided design software developed by McNeil.
Physics Engine	Software that deals with point (node) collections. As one example, Kangaroo is used in order to relax (optimize) the vault mesh according to the anchors and forces specified for the springs (point to point "connections") and the ''unary forces'' i.e. gravity (the factor that "shapes" the mesh "upwards"). On the other hand, the whole topology (how curvy the vault is) should be addressed in correlation with structural analysis. ''Unary force'' means a vector with amplitude 1 entered in some sort of calculations related with points in Kangaroo

Design Strategy

Branch	The connection mode between divider points in the patterning step in the Modular strategy, as one parameter, it is the number of line connections that start from one point.
Brep	Boundary representation, used in computer modeling software and referring to the surface or poly-surface.
Decorative parts	The interior decoration part of Modular strategy.
Delaunay triangulation	''A Delaunay triangulation of a set of points is a trangulation of the convex hull of the points considered, such that none of the points lie within the circumcircles of the triangle.'' [2]
Division	One of the main parameters inspired by the art of knot, used in the Star pattern of the Modular strategy. It refers to the points on a circle which divide it in into even or random lengths.
Elimination	One specific mode added to the Vault strategy to remove solid components from the body.
Even Mode	Used to create equal lengths of lines in the patterning step.
Inflation Mode	A specific mode in the pieces step to create deformation in two modes of outward and inward, in both design strategies, representative of a contemporary way of thinking
Inner Circle	Offset from the outer circle

Inner Division	The first inner circle which begins division.
Inner Radius	The measurement between two circles.
Inspection	Used as a demo to test parameters that can later be applied to all modules; it eases control of the system and enables faster outcomes.
Random Mode	Creates unequal lengths of lines in the patterning step.
Region	In the Master system, refers to the desired area for design and expands the grid system.in projection, refers to the surface made by several lines.
Mesh	A type of surface used in computational modeling containing infinite length in a finite boundary.
Mesh Distortion	Exploiting the mesh pattern (surface division) to create a deformation on them.
Non-Transposed Mode	A morphing approach in whichh the pattern morphs only on the cone module.
Shift	A parameter used in the Star pattern, showing the position of the next point to connect to.
Transposed Mode	The morphing approach, when the pattern morphs over the whole cone and flat modules.

ENDNOTES

1. Sigrid Adriaenssens et al., introduction to *Shell Structures for Architecture: Form Finding and Optimization* (London: Routledge/ Taylor & Francis Group, 2014), 235.

2. Adriaenssens, *Shell Structures for Architecture*, 179.

APPENDICES A

The Contribution of Peter Fotiadis

Without the contribution of Peter Fotiadis, who wrote the dedicated C# code related to the design scope, this thesis would have been impossible. Based in Athens, Greece, Fotiadis is an architect with a MSc degree in Computer Science. He kindly shared pertinent information regarding the thesis and its desired purpose, and I appreciate his help, experience, and assistance.

I met Peter several years ago, when he helped me with my parametric design problems and replied to all my questions on the Grasshopper community website. After starting to generate the system to be used in this thesis in Grasshopper by using the native components, I faced problems regarding patterning and modes of connection. This time, I did not pose my questions to the online community, but emailed Peter directly about a solution to the problem. In our first conversation via Skype, I thoroughly described the idea and the purpose of the thesis, after which Peter's contribution began. Because of his experience in both construction and parametric design, Peter shared initial tips regarding the features and limitations of parametric design and also the importance of an optimum compromise between idea and real life.

APPENDICES B

C#- CONTROL DATA

In this section, the C# Control information of each level of the two strategies are documented in the same order as the design strategy chapter. The reader can follow all the parameters used in each technique and process.

In Modular strategies, four C# control data are offered with regards to the system of levels of the process. Similarly, in the Vault strategy, the essential three C# control data are demonstrated with a separate illustration and table, showing related parameters used. The documents recorded in this chapter are gathered by the author of the thesis with the collaboration of the author of the C# code, Peter Fotiadis.

Modular Strategy:

Star Pattern-Control C#
Aggregate Pattern-Control C#
Top Conical/Flat Modules Pattern-Control C#
Projection-Control C#

Vault Strategy:

Vault Mesh Preparation-Control C#
Vault Physics Engine-Control C#
Vault Pieces Creation-Control C#

Star Pattern-Control C#

Star pattern is actually a line Graph post processed in order to generate regions out of all intersection events (the so called CCX events) that occur within the Graph members. A list samples all the available options/parameters and their meaning follows (WIP).

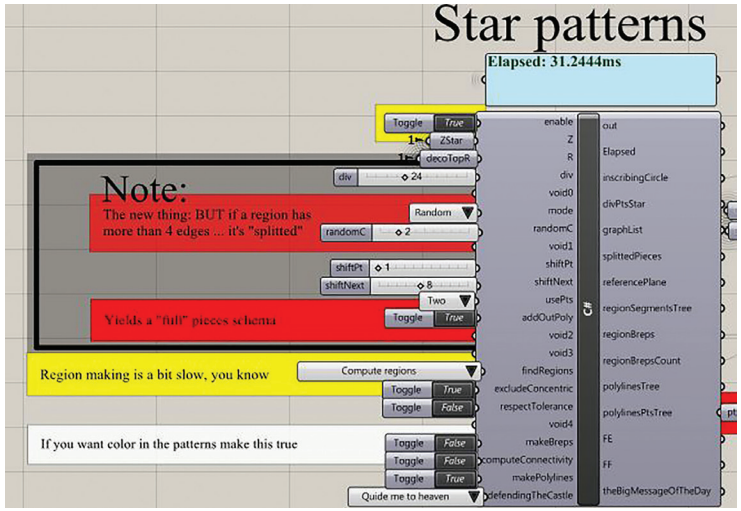


Figure Ap-1 Showing the computational environment created for Patterning step, Star Pattern

Variable	Type	Usage	Importance
Enable	Bool	Activate C#	Critical
Z	Double	Position of demo pattern	Minor
R	Double	Radius of the circle	Critical
Div	Int	Divisions of the circle	Critical
Mode	Int	Division mode (Random,Even)	Important
RandomC	Int	Coarse random division control	Important
ShiftPt	Int	Shift List items	Critical
ShiftNext	Int	Shift Branches	Critical
UsePts	Int	Pattern complexity (2/3/4) control	Critical
AddOutPoly	Bool	Add the perimeter points to the collection	Important
FindRegions	Bool	Compute regions from CCX intersections	Critical
ExcludeConcentric	Bool	Exclude regions concentric to center	Critical
RespectTolerance	Bool	Respect model tolerance	Important
MakeBreps	Bool	Make Breps (trimmed Surfaces)	Minor
ComputeConnectivity	Bool	Compute point to point connectivity	Important
MakePolylines	Bool	Make polylines out of CCX points	Important

Table 1 Star Pattern-Control C# demonstrating in four columns the parameters (variable), data type to present the values of parameters (type), application of parameters (usage) and, in the last list, the level of importance given to parameters (importance).

Aggregate Pattern-Control C#

Aggregate pattern-control C# manages an aggregate pattern as a way to link points at creation time, thus making regions. Accordingly, no post process is required as in star patterns, meaning that the procedure is considerably faster. An option makes patterns via triangulation. A list that samples all the available options/parameters and their meaning follows (WIP).

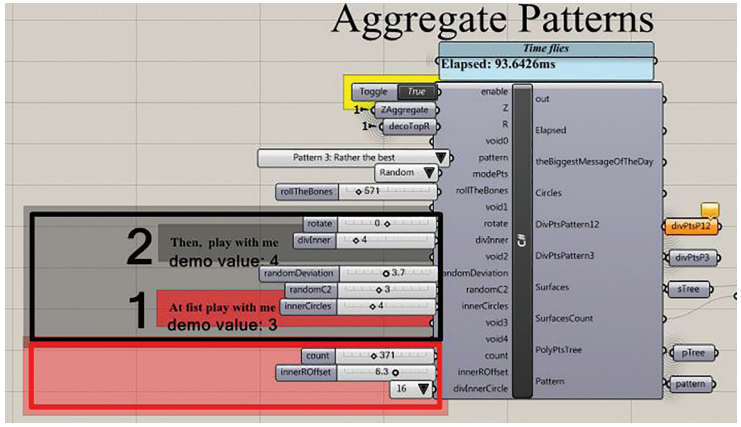


Figure Ap-2 Showing the computational environment created for Patterning step, Aggregate Pattern, in Modular strategy

Variable	Type	Usage	Importance
Enable	Bool	Activate C#	Critical
Z	Double	Z Position of demo pattern	Minor
R	Double	Radius of the circle	Critical
Pattern	Int	Pattern mode (3 options)	Critical
ModePt	Int	Division mode (Random,Even)	Critical
RollTheBones	Int	Random seed	Important
Rotate	Int	Rotate divisions	Minor
DivInner	Int	Start divisions	Critical
RandomDeviation	Int	Randomness control	Important
RandomC2	Int	Coarse control	Important
InnerCircles	Int	Circle count for divisions	Critical
Count	Int	Random point counter	Critical
InnerROffset	Int	Distance from outer circle for the region	Critical
DivInnnerCircle	Double	Inner circle “start” divisions	Critical

Table 2 Aggregate Pattern-Control C# demonstrating in four columns the parameters (variable), data type to present the values of parameters (type), application of parameters (usage) and, in the last list, the level of importance given to parameters (importance).

Top Conical/Flat modules pattern-Control C#

Top conical/flat modules pattern-control C# manages the pattern creation related with the top flat conical portion and the flat module bottom surface. A list that samples all the available options and their meaning follow (WIP).

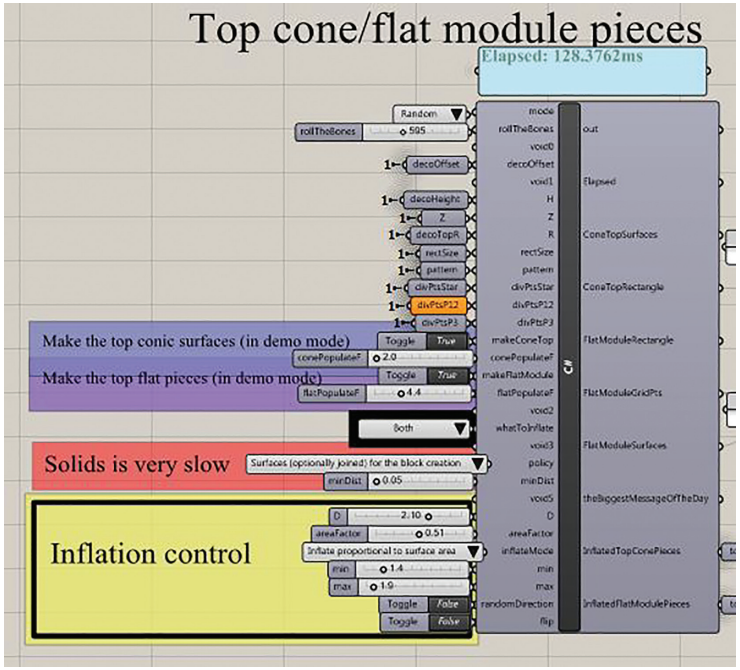


Figure Ap-3 Showing the computational environment created for Patterning step, Top cone Pattern, Modular strategy

Variable	Type	Usage	Importance
Mode	Int	Pattern mode (even, random)	Critical
RoolTheBones	Int	Randomness control	Important
H	Double	Height of cone to map	Critical
Z	Double	Position of demo pattern	Minor
R	Double	Radius of the circle	Critical
RectSize	Double	Module size	Critical
Pattern	Int	Pattern mode (3 options)	Critical
DivPtsStar	Int	Star division points	Critical
DivPtsP12	Int	Aggregate division points (options 1,2)	Critical
DivPtsP3	Int	Aggregate division points (option 3)	Critical
MakeConeTop	Bool	Make patterns on the top cone part	Critical
ConePopulareF	Double	Randomness control	Important
MakeFlatModule	Bool	Make patterns on the flat module	Critical
WhatToInflate	Int	Top/Cone pattern activation control	Critical
D	Double	Inflation deviation	Critical
AreaFactor	Double	Inflation deviation secondary control	Critical
InflateMode	Int	Inflation options	Critical
Min	Double	Inflation min	Critical
Max	Double	Inflation max	Critical
RandomDirection	Bool	Inflation control	Critical
Flip	Bool	Inflation control	Critical

Table 3 Top Conical/Flat modules pattern-Control C# demonstrating in four columns the parameters (variable), data type to present the values of parameters (type), application of parameters (usage) and, in the last list, the level of importance given to parameters (importance).

Projection-Control C#

Projection-control C# manages the projection of a DataTree of points made out of regions (patterns) to conical NURBS surfaces. The projection is of a “radial” type. A list that samples all the available options and their meaning follows (WIP).

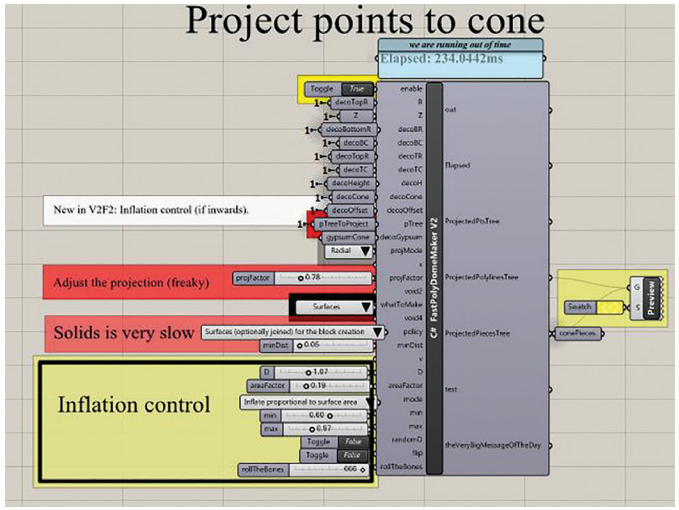


Figure Ap-4 Showing the computational environment created for Projection step, Modular strategy

Variable	Type	Usage	Importance
Enable	bool	Activate C#	Critical
R	Double	Radius of the circle	Critical
Z	Double	Position of demo pattern	Minor
DecoBR	Double	Cone bottom radius	Critical
DecoBC	Curve	Cone bottom curve	Critical
DecoTR	Double	Cone top radius	Critical
DecoTC	Curve	Cone top curve	Critical
DecoH	Double	Cone height	Critical
DecoCone	Brep	Cone	Critical
PTree	DataTree	Points to project	Critical
ProjMode	Int	WIP	
ProjFactor	Double	Projection control	Important
WhatToMake	Int	Projection result	Critical
DivPtsP12	Int	Aggregate division points (options 1,2)	Critical
DivPtsP3	Int	Aggregate division points (option 3)	Critical
D	Double	Inflation deviation secondary control	Critical
AreaFactor	Double	Inflation deviation	Critical
Mode	Int	Inflation option	Critical
Min	Double	Inflation min	Critical
Max	Double	Inflation max	Critical
RandomD	Bool	Inflation control	Critical
Flip	Bool	Inflation control	Critical
RollTheBones	Int	Randomness control	Critical

Table 4 Projection-Control C# demonstrating in four columns the parameters (variable), data type to present the values of parameters (type), application of parameters (usage) and, in the last list, the level of importance given to parameters (importance).

Vault mesh preparation-Control C#

Vault mesh preparation-control C# manages the capacity of the mesh required by the physics engine for mesh relaxation. A list that samples all the available options and their meaning follows (WIP).

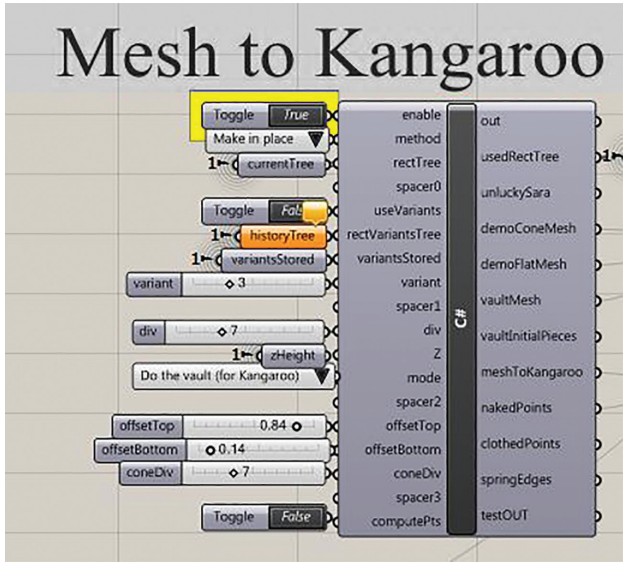


Figure Ap-5 Showing the computational environment created for form topology called Mesh prepration, in Vault strategy

Table 5 Vault Mesh Preparation-Control C# demonstrating in four columns the parameters (variable), data type to present the values of parameters (type), application of parameters (usage) and, in the last list, the level of importance given to parameters (importance).

Variable	Type	Usage	Importance
Enable	Bool	Activate C#	Critical
Method	Int	Mesh creation method	Critical
RectTree	DataTree	Modules from procedure as in #4	Critical
UseVariants	Bool	History activation as in #4	Important
RectVariantsTree	DataTree	History modules from procedure as in #4	Critical
VariantsStored	Int	History variants	Critical
Variant	Int	History variants index	Critical
Div	Int	Flat mesh resolution	Important
Z	Double	Height of mesh	Critical
Mode	Int	Inspect or fully deploy mesh	Important
OffsetTop	Double	Conical mesh top radius offset	Critical
OffsetBottom	Double	Conical mesh bottom radius offset	Critical
ConeDiv	Int	Conical mesh resolution	Critical
ComputePts	Bool	Compute/display naked points (anchors)	Minor

Vault Physics Engine-Control C#

Vault physics engine-control C# manages the mesh relaxation via the physics engine.

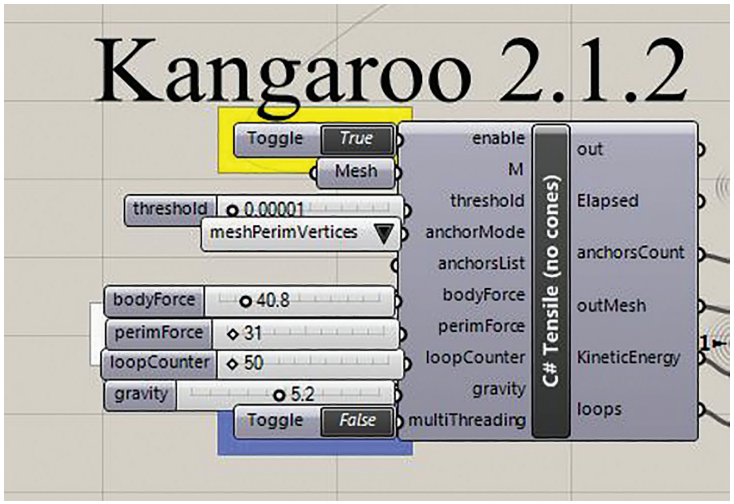


Figure Ap-6 Showing the computational environment created for form topology called Physics Engine, Kangaroo 2.1.2, in Vault strategy

Variable	Type	Usage	Importance
Enable	Bool	Activate C#	Critical
M	Mesh	Mesh to process	Critical
Threshold	Double	Kangaroo stop control	Critical
AnchorMode	Int	Anchor policy	Important
anchorList	Point3d	Optional additional anchor points	Important
BodyForce	Double	Kangaroo spring goal control	Critical
PerimForce	Double	Kangaroo spring goal control	Critical
loopCounter	Int	Kangaroo stop control	Important
gravity	Double	Kangaroo unary force goal control	Critical
multithreading	Bool	Parallel processing on/of control	Important

Table 6 The table of the Vault Physics Engine-Control C# demonstrating in four columns the parameters (variable), data type to present the values of parameters (type), application of parameters (usage) and, in the last list, the level of importance given to parameters (importance).

Vault Pieces Creation-Control C#

Vault pieces-control C# manages the creation of closed meshes that generate the vault itself. These closed meshes are obtained from mesh faces by randomly moving their vertices along the mesh face normal. Various options control the procedure whilst the user can choose working with quad or triangular mesh faces. A random elimination option is available. A collection of options controls an optional “inflation” mode related with the full mesh face, making a “textured” visual effect. A list that samples all the available options and their meaning follows (WIP).

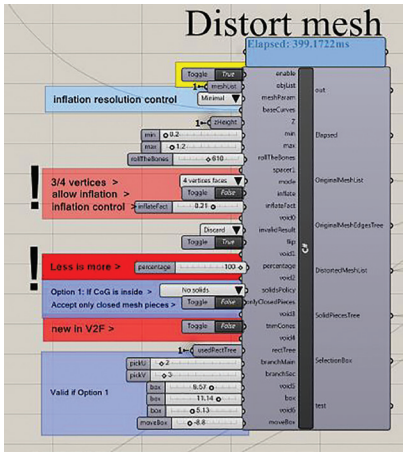


Figure Ap-7 Showing the computational environment created for Pieces Creation step called Mesh Distortion in Vault strategy

Variable	Type	Usage	Importance
Enable	Bool	Activate C#	Critical
ObjList	Mesh	Meshes to distort	Critical
MeshParam	Mesh	Mesh resolution control	Critical
BaseCurves	Curve	Trimming boundary	Important
Z	Double	Mesh height	Critical
Min	Double	Vertex distort min distance	Critical
Max	Double	Vertex distort max distance	Critical
RollTheBones	Int	Random seed	Important
Mode	Int	Quad/Triangular mesh output	Critical
Inflate	Bool	Inflate outmost mesh face	Important
inflateFactor	Double	Inflation control	Important
Flip	Bool	Flip inflation direction	Important
Percentage	Int	Random elimination control	Important
SolidsPolicy	Bool	Closed meshes control	Critical
OnlyClosedPieces	Bool	Closed meshes control	Critical
TrimCones	Bool	Trim meshes at base	Important
BranchMain	Int	Constraining box control	Important
BranchSec	Int	Constraining box control	Important
Box	Double	Constraining box domains	Important
MoveBox	Double	Constraining box Z control	Important

Table 7 The table of the Vault Pieces Creation-Control C# demonstrating in four columns the parameters (variable), data type to present the values of parameters (type), application of parameters (usage) and, in the last list, the level of importance given to parameters (importance).