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Applications of Parametric Design in Lightweight Shell Structures

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Abstract: Parametric Design is a powerful design approach that has been widely applied to architectural design in recent years. Designers may create rules using parametric design tools that consider the aesthetics, functionality, and performance needs of a design. The purpose of the study is to analyze the impact of parametric design patterns in producing unique, well-structured, and aesthetic shell lightweight structures. Achieve that by firstly defining the shell lightweight structure, its types of geometries, and Objectives for form finding of the shell structure. Secondly defining the parametric design, Characteristics of the parametric design process, and parametric patterns. thirdly studying and analyzing different five distinct global examples, in terms of the structure's form-finding technique using parametric patterns, used materials, fabrications, and installation. Finally making an analytical comparison of the five examples to achieve the main objective of the study. From this analytical comparison find that the parametric design and parametric patterns has a critical role in form-finding shell lightweight structures.

Keywords: Lightweight Shell Structures, Parametric design, Parametric patterns, Digital Fabrication.

1. Introduction

Lightweight structures are widely employed in architecture, engineering, and building construction. They are recognized for their aesthetic appearance and their innovative character. The lightweight structure can be defined as "A shape is created by an optimization process to efficiently bear the loads from a main load condition, regardless of the type of material used" [1]. "As light as feasible" is the goal of any well-designed and properly constructed structure. There are some challenges and difficulties for lightweight structures, like high labor costs, as they need specialized skilled technicians, and the unwise use of natural resources, because of this, the tendency to massiveness and limiting finesse [2]. There are many types of lightweight structures such as cable, membrane, shell, and folded structures as well as space grids, braced vaults, and domes, arched, stayed, and trussed systems [1]. For this paper we will focus on lightweight shell structure. They make the best harmony of architectural and structural forms. they also known as "surface structures", shells resist and transfer loads within their minimal thicknesses. Their structural performance is dependent on their three-dimensional curved shape and the proper orientation and positioning of supports [3]. Using parametric design methodologies in the construction of the architects' designs makes them now able to give solutions at an earlier stage of the design process, which has obvious benefits for engineering and manufacturing processes, by combining parametric modeling techniques with architectural design [4].

2. LIGHTWEIGHT SHELL STRUCTURES

Shell structures are constructed systems that are characterized by three-dimensional curved surfaces. They are form-passive and resist external loads mostly through membrane stresses. A shell distributes external loads to its supports primarily through membrane stresses, which are forces acting in the plane of the shell surface and can be compression, tension, or a combination of compression and tension. Shell structures can be built as a continuous surface or from discrete components that follow that surface [5].

2.1 Types of geometries for shell structure

There are three types of geometries for shell structures, namely Freeform (free-curved or sculptural) shells, Mathematical (geometrical or analytical) shells, and Form-found shells shown in (table 1) [5].

3. PARAMETRIC DESIGN

According to Patrick Schumacher (Zaha Hadid Architects), he defined the parametric design as "A computer-based design approach that treats geometric properties of the design as variables. Parametric Design is an approach that uses parameters in the form of constraints to solve a design problem. The parameters and the final design may have a direct relation, but this relation may not always be obvious since the parameters might be utilized in complicated ways to create complex designs [6].

3.1 Parametric Patterns

There are many patterns of parametric design, such as: Controller, Force Field, repetition, tiling, recursion, Subdivision, Packing, Weaving, and branching shown in (table 2) [7].

TABLE 1. Types of geometries for shell structure

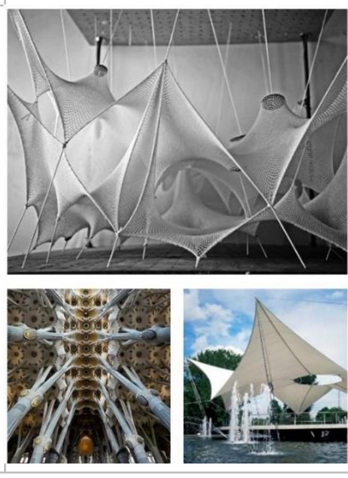
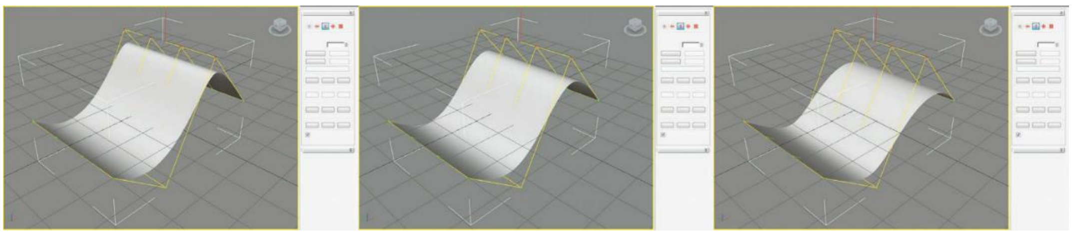
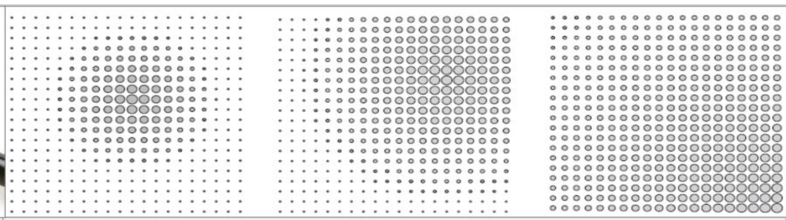
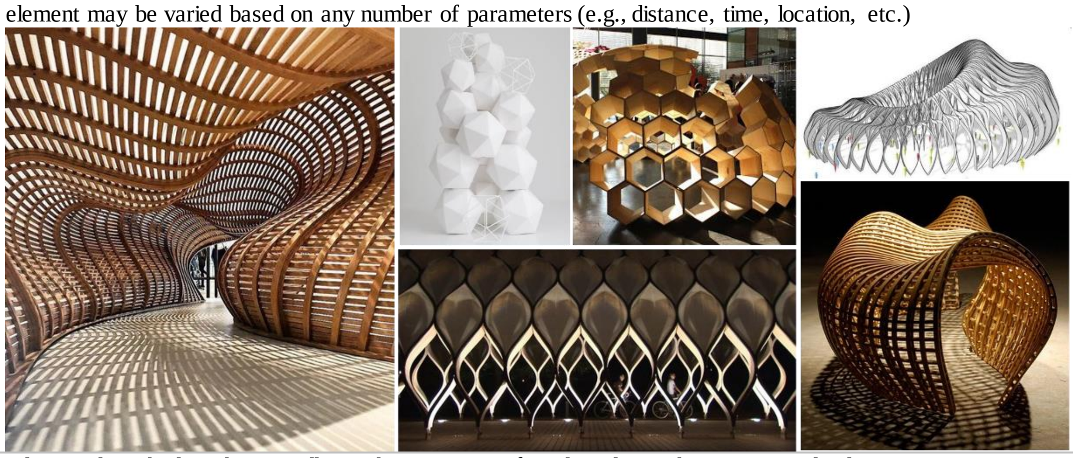
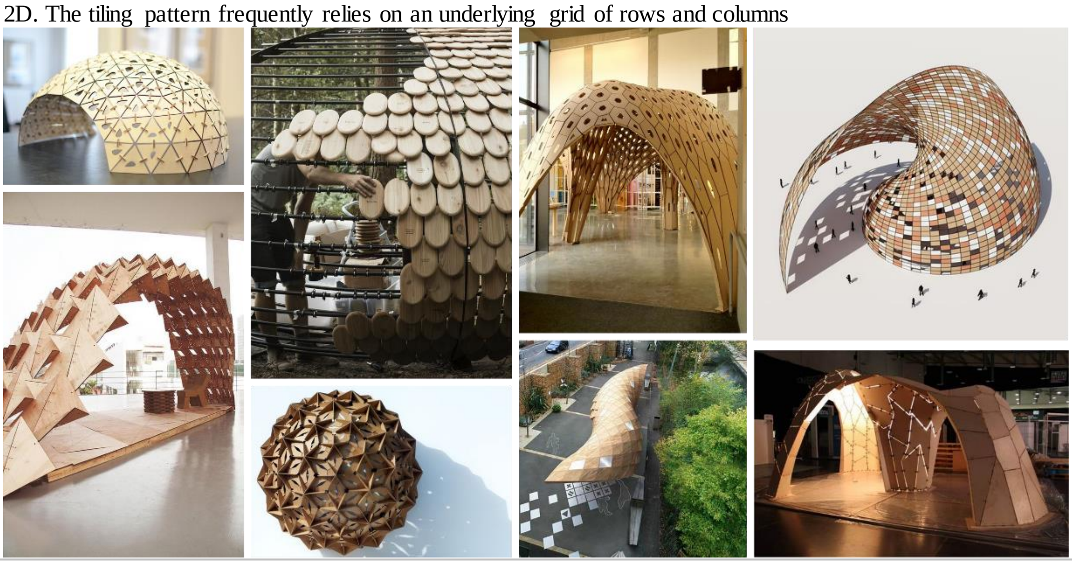
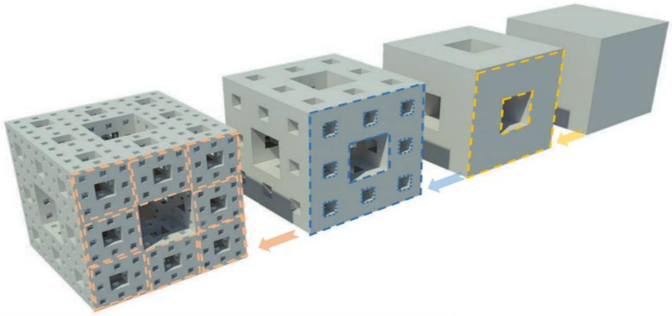
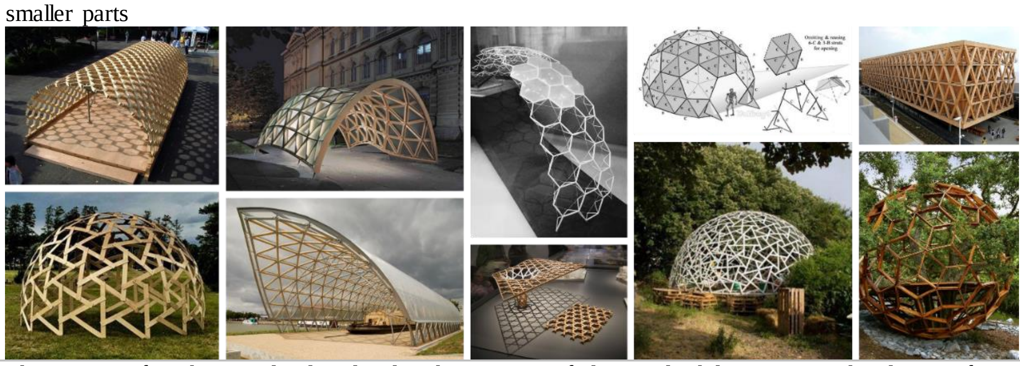
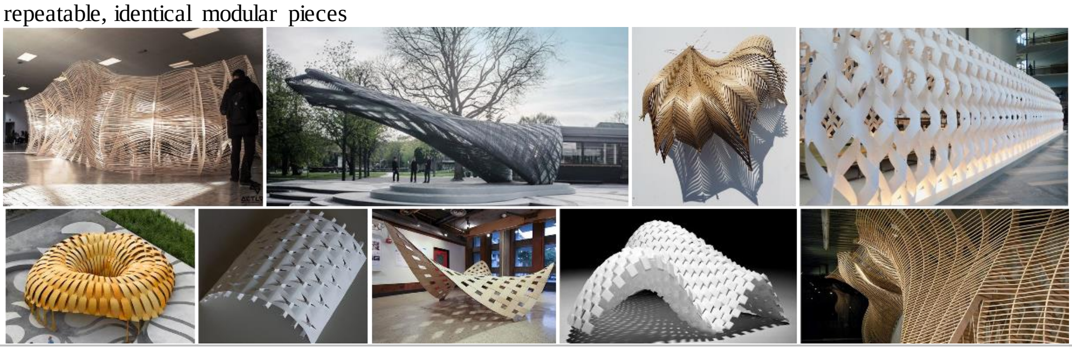
Shell's types	Freeform shells	Mathematical shells	Form-found shells
Another name	Free curved shells Sculptural shells	Geometrical shells Analytical shells	
Description	They are created without taking structural performance into consideration -function follow form	Analytic functions are used to directly describe them. These functions are frequently used because they make it easier to undertake more analytical computations and because they can define the geometry of a shell for fabrication needs. <u>-Form Follow Function</u>	Their shapes are inspired by nature (Biomimicry) <u>-form follow nature</u>
Formation Digitally	Higher degree polynomials	Lower degree polynomials	Higher degree polynomials
Examples	Patches of NURBS	- Hyperboloids - Ellipsoids - Hyperbolic or Elliptic paraboloids - Trigonometric or hyperbolic functions	Natural hanging shapes like Antoni Gaudi, Frei Otto, and Heinz Isler's structures
			

TABLE 2. Parametric Patterns

Parametric Patterns	Description
Controller	The main concept of the controller pattern is to define the mechanism which influences the primary model's change. a NURBS surface's undulation may be altered by moving a few controlling vertices that are connected to the model 
Force Field	The force field is a common pattern in parametric design methods. When considering what affects the form of an object or structure, it is common to visualize various forces pushing and pulling on it. These vectors change direction, form, and strength in a rhythmic manner depending on their location in the force field and the presence or absence of various forces acting on them

	 The concept of a magnifying glass affecting a field of circular panels.  Parametric variations.
Repetition	In parametric systems, repetition can be more significant since a repeated element can keep the basic topology of its predecessor while not being completely identical to it. Using a rule-based approach, the repeating element may be varied based on any number of parameters (e.g., distance, time, location, etc.) 
Tiling	Tiling is described mathematically as the arranging of similar planar shapes to completely cover a given area without overlapping. Thus, tiling may be thought of as a natural extension of the concept of repetition, but in 2D. The tiling pattern frequently relies on an underlying grid of rows and columns 
Recursion	Recursion is a type of repetition in which the repetition is accomplished by having a process call itself to create the following iteration. Recursion is defined as the practice of repeating elements in self-similar ways. A Menger sponge is a well-known example of a mathematical concept with clear recursion 

Subdivision	Surface subdivision is the technique of dividing a continuous surface into smaller components by tracing, scoring, or cutting lines through it. To unfold smooth surfaces and shapes into flat components that may be digitally manufactured on CNC machines or laser cutters, designers frequently need to divide them into smaller parts 
Packing	The concept of packing is closely related to the concepts of tiling and subdivision, it is the placing of several items in an area so that little or nothing of it is left behind. unlike tiling and subdivision, which are likely to be governed by a global ordering system, packing is frequently an opportunistic procedure. That is, components in a packing system seek vacant space to occupy, and the pattern is governed by a first-come, first-served procedure 
Weaving	Weaving is the interlacing of two threads at right angles to one other that results in a textile. The weft are the lateral threads that do not undulate, whereas the warp are the longitudinal threads that interlace the weft. In contrast to tiling and subdivision, a weave, particularly the warp component, cannot partition the surface into repeatable, identical modular pieces 
Branching	Branching is a fundamental topological growth strategy in nature that is used to maximize surface area, manage resources, and respond to structural force. Like a tree's limbs, an onion's fibrous root system, human lungs, or coralline algae. Branching systems in nature are self-similar and recursive, so likely to be fractal 

3.2 Digital Fabrication

For architectural and industrial design, the connection between design and manufacture has always been critical. New manufacturing techniques, assembly techniques, and materials frequently cause design paradigm shifts. For example, the incorporation of structural steel manufacturing into structure design permitted new formal goals while necessitating additional detailing and pre-fabrication capabilities. This new technique, based on component design, gradually eliminated craftsmanship and made the designer indispensable in the building process [8].

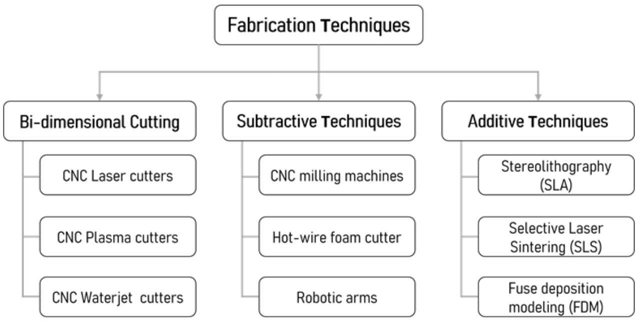


Fig 1. Digital Fabrication's different technique

4. APPLICATION OF PARAMETRIC DESIGN IN LIGHTWEIGHT SHELL STRUCTURES

4.1 Precedent 1: BOWOOSS-summer pavilion

BOWOOSS combines computer-aided, fuliginous lightweight technology with traditional timber-type of structures. and focuses on new parametric architecture-based methodologies and their applicability to traditional material and craftsmanship skills. It has been certifying old manufacturing technology design tools that can meet current computing requirements. The architects used generative form-finding and optimization methods to produce a composition of volume and material, lightweight and space in one. It has a self-stabilizing effect because to the organically formed ribs composed of 60-80mm laminated wood that are firmly bonded to the 30mm plywood folding [10].

The shell acts as a filter, controlling natural lighting, ventilation, and visibility. Hole structures are placed into the folds of the timber shell pavilion, which are generically recognized and optimized. The pores are in low-load regions, and their oval form was determined by structural analysis and the physical model. Pores are responsible for reducing structural weights, as seen by the reduced transportation and installation weights. Individual pores are non-continuously bent, which may be seen in plant load-change structures. The cut-out oval plywood parts were joined to furniture in order to preserve as much material as possible [9].

location	2012, in Saarbrucken, Germany
Created by	Craftsmen as part of a biomimicry research project at the School of Architecture Saar, SAS
Parametric patterns	Subdivision- Repetition
Formation	Geometrical formation (Geometrical shell structure)
Structure	multi-layered: primary and secondary Wooden ribs, and self-sustaining modules (surfaces with holes)
Used Materials	Glued laminated Timber and laminated veneer timber struts
Fabrication and Installation	Using Industrial cutting machines to cut timber elements, and the pavilion was installed by craftsmen

Fig 2. BOWOOSS Summer Pavilion [9]

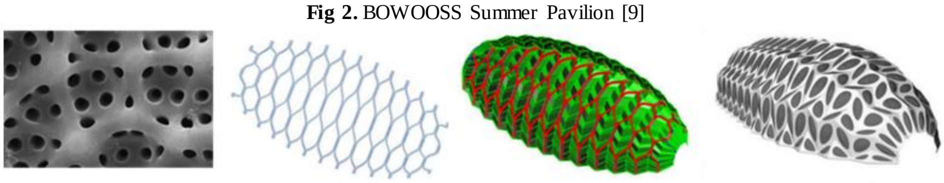


Fig 3. Natural form-finding of the pavilion design [9]

Fig 4. Fabrication and Installation of the pavilion [9]

4.2 Precedent 2: Steampunk pavilion

Fig 5. Steampunk pavilion

location	2019, in Tallinn, Estonia
Designed by	Soomeen Hahm Design, Gwyllim Jahn, Igor Pantic, and Cameron Newnham (Fologram) with Format Engineers.
Parametric patterns	Controller- Tilling
Formation	Kinetic formation (Freeform shell structure)
Structure	Free form parametrized shell /self-sustaining curved modules (steam-bent timber elements)
Used Materials	Straight 100x10mm Steam-bent timber boards
Fabrication and Installation	Steam-bent timber elements were prefabricated and assembled following holographic construction information viewed in augmented reality through Microsoft's HoloLens device

Steampunk is a pavilion constructed from steam-bent timber elements using primitive hand tools augmented with the precision of intelligent holographic guides. the installation size is 8.0m*8.0m*4.6m (w*d*h) and its area 25 m2 [11]. The boards should be wrapped and steamed to make them malleable before being bent into the form and using the digital model as a guide in the installation stage. The pavilion's varying surface effects are the result of bending three-dimensional curves from straight 100x10mm boards, which causes the timber profile to twist along its length [12].

In the beginning, the design team wanted to construct the pavilion by designing lines and drawings for CNC machine, but they found it very difficult to cut, print, and assemble the parts of it, so they turned to think of another way of manufacturing. the team took the risky route of building everything by hand, utilizing augmented reality design information sent to fabricators via the Fologram hologram platform [13] [14].

Fig 6. Installation of Steampunk pavilion by using Microsoft's HoloLens headset.

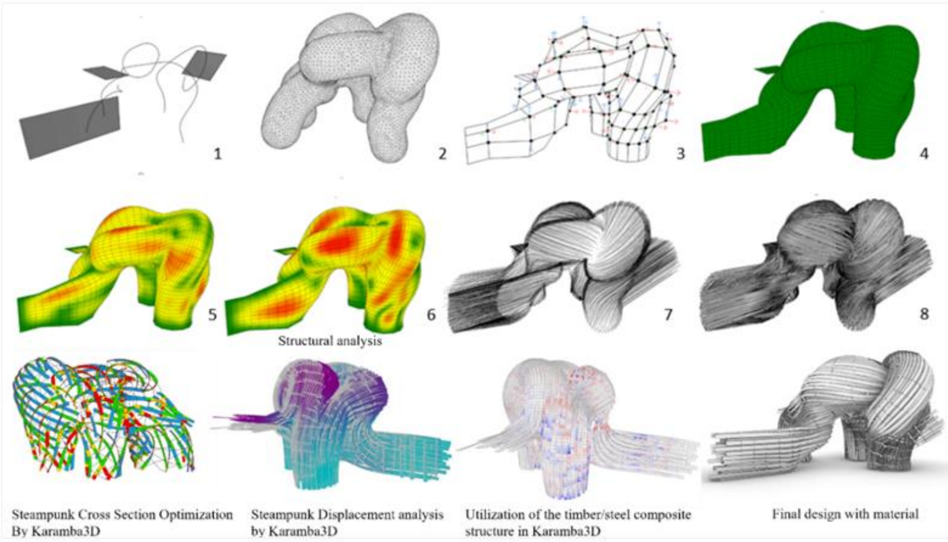


Fig 7. Form generation, structural analysis, and optimization [15]

4.3 Precedent 3: Shellstar pavilion

Fig 8. Shellstar pavilion [16]

location	2012, in Hong Kong
Designed by	the architects Andrew Kudless and Riyad Joucka (Matsys. Design Development) and was Fabricated and Assembly by Ricci Wong (Art Lab)
Parametric patterns	Subdivision-Force field- tilling
Formation	Geometrical formation (Geometrical shell structure)
Structure	Steel Reinforcement Arches, and self-sustaining modules (hexagon surfaces with circular holes)
Used Materials	4mm Translucent Coroplast, Nylon Cable Ties, Steel Foundations, PVC, and Steel Reinforcement Arches
Fabrication and Installation	Each cell was folded flat and readied for fabrication using further customized Python scripts. The cell orientation was assessed and turned to match the flutes of the Coroplast material with the surface's main bending direction.

The shellstar is a lightweight temporary pavilion that enhances spatial performance while minimizing construction and material requirements. The pavilion size is 8m x 8m x 3m, created by Rhino, Grasshopper, Kangaroo, Python, Lunchbox, and Rhino script modeling tools. The design process may be divided into three stages facilitated by advanced digital modeling techniques [16] [4].

The form is created by a digital form-finding method inspired by historical techniques pioneered by Antonio Gaudi and Frei Otto, and others. The form self-organizes into the catenary-like thrust surfaces that are aligned with the structural vectors and allow for minimal structural depths using Grasshopper and Kangaroo. The curve is formed by a shape that is suspended beneath its own weight by two fixed ends. For surface optimization, the structure is formed of almost 1500 separate cells that are all slightly non-planar. as the cells must bend slightly to fit the form's overall curvature. However, the cells cannot be excessively non-planar since this would make cutting them from flat sheet materials problematic. Using Python script, each cell is optimized to minimize any internal seams and make it as planar as possible, to simplify fabrication [16] [17].

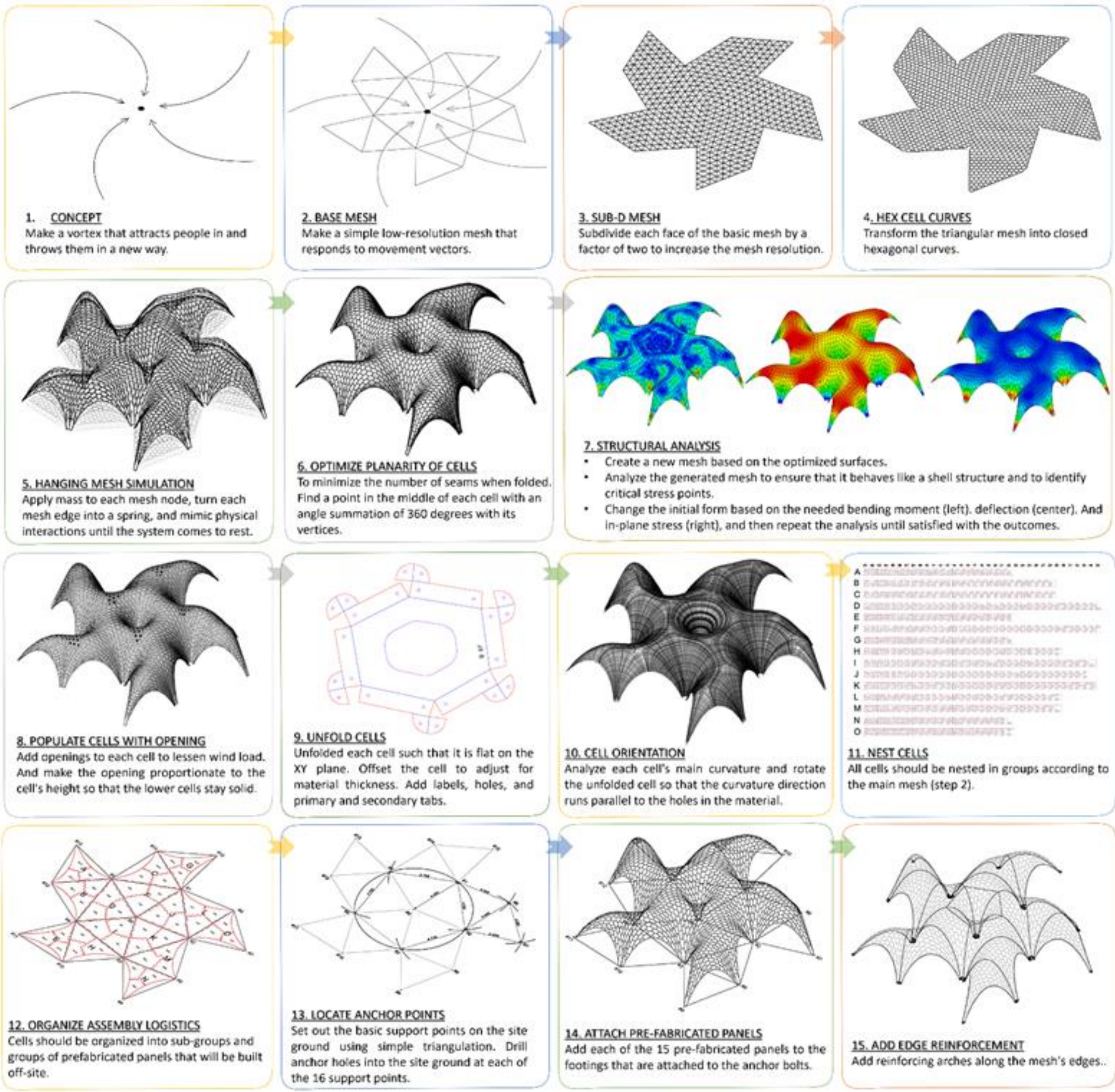


Fig 9. Form-Finding, Surface Optimization, and Fabrication Planning of shellstar pavilion [16]

4.4 Precedent 4: Serpentine pavilion 2016 (BIG)

The structure is a parabolic wall that unzips, splits, and bends to generate a huge interior area, made of hollow fiberglass 'bricks' arranged in a way that defies gravity. The structure was made up of two surfaces that started as independent harmonic walls at ground level and raised to merge as a straight, horizontal line at the elevation14 meters above the ground. Bjarke describes his pavilion as "a structure that is free-form yet rigorous, modular yet sculptural, both transparent and opaque, both box and blob". The Pavilion is fully opaque and material in the East-West direction. It is completely transparent and essentially inconsequential in the North-South direction. Lay Light is a transparent composite that allows light to penetrate through its layers of glass fibers. which was then linked with aluminum connectors and bolts. The bricks stepped so that people could sit or climb on the bottom rows, which was considered during the loading. The final optimized design consists of 1,800 boxes of 16 different lengths, as well as 3,500 connectors of 126 different typologies and more than 25,000 bolts [18] [19].

Fig 10. Serpentine pavilion [18]

location	2016, in Hyde Park, London
Designed by	Bjarke Ingels Group (BIG)
Parametric patterns	Controller, Repetition
Formation	Modular formation
Structure	Self-sustaining kinetic modules
Used Materials	500 mm by 400 mm- hollow fiberglass bricks (Lay-Light)
Fabrication and Installation	Each brick's length was designed such that it overlapped its neighbors sufficiently to form an enclosure while also giving a suitable connection length between neighboring bricks for structural purposes. The boxes were arranged in alternate chequerboard patterns on either side of the wall

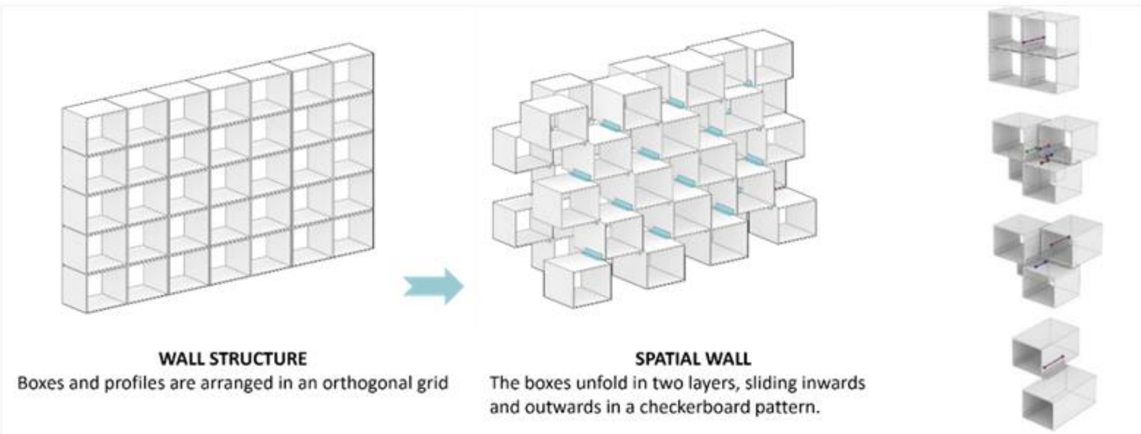


Fig 11. Structure of the pavilion [19]

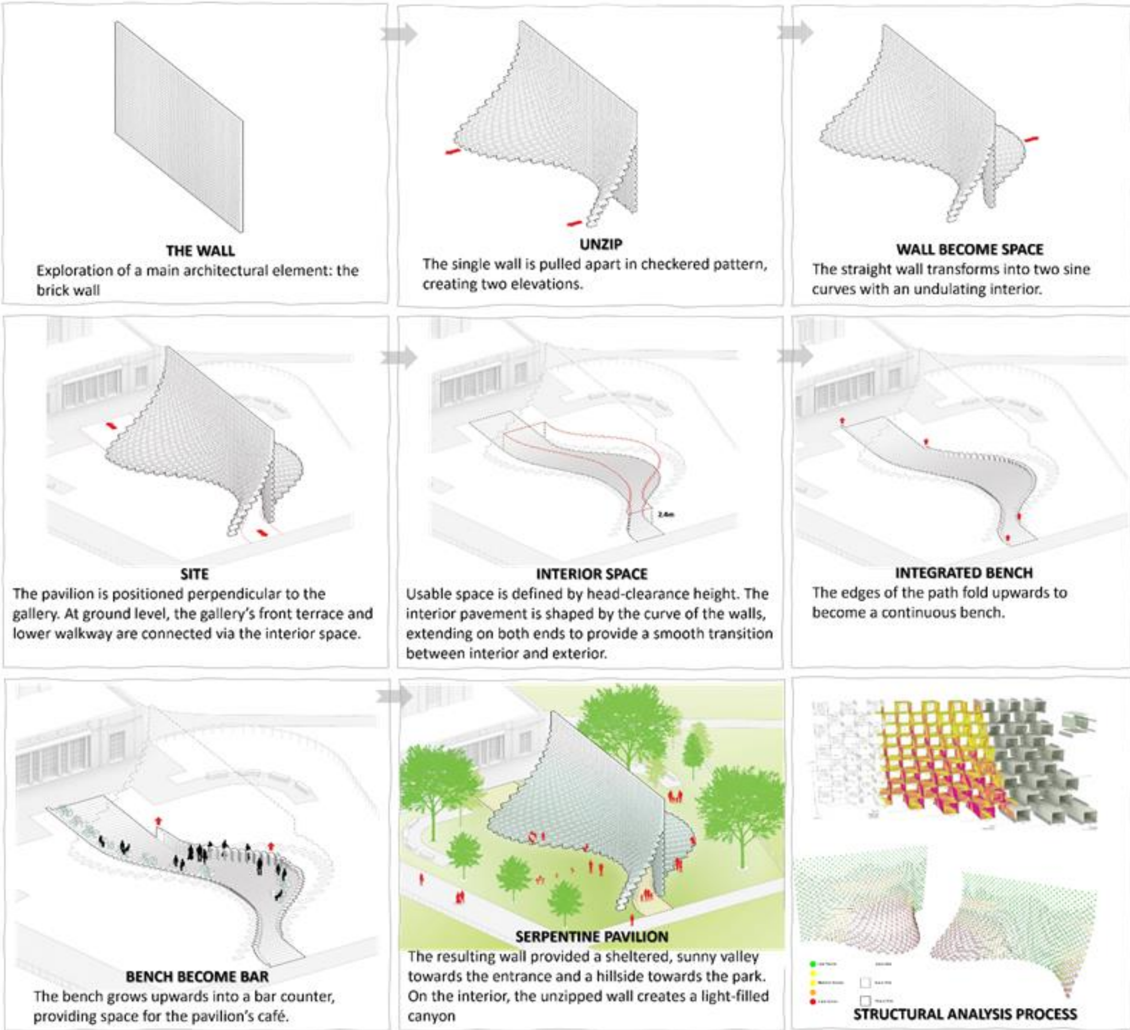


Fig 12. Form finding and structural analysis of Serpentine pavilion [18]

4.5 Precedent 5: Bubble pavilion

Fig 13. Bubble Pavilion

location	2018, in Spain
Designed by	Roberto Narvaez and his team of academics and students in the Higher Technical School of Construction Engineering at the University of Seville
Parametric patterns	Subdivision- Tilling
Formation	Geometrical formation (Geometrical shell structure)
Structure	Self-sustaining modules
Used Materials	Plywood panels
Fabrication and Installation	Using Digital CAM (Computer Aided Manufacturing) techniques and technologies to cut the elements, then they were assembled in the site due to the require form

The "Bubble Pavilion" is an experimental pavilion that was built using plywood panels provided by Garnica as the basic building material. which is characterized as High-strength, high-density panels with a wonderfully eye-catching natural eucalyptus finish. The pavilion was built using a technique based on clusters of spherical bubbles with an identical radius, which allowed for the creation of self-supporting walls and vaulted ceilings. The pavilion's structure is characterized by its sustainability, strength, aesthetics, and simplicity of fabrication. The project's goal was to carry out a real-world study into innovative approaches to architectural design using computational or parametric design tools. CAD (Computer Aided Design) tools were used as part of the parametric and algorithmic design [20].

The structure consists of two parts, the first of them is the hexagonal frames and the other is the curved triangular patterns. To manufacture them, determine their dimensions precisely and cut their elements using Digital CAM (Computer Aided Manufacturing) techniques and technologies. Then for the hexagonal frames, the six parts relate to wooden side angles to connect them with each other and form the hexagonal frame, then connect the hexagonal frames next to each other by Wooden angles also and installed on the site according to the required form of the pavilion. for the triangular pattern, the triangles are assembled, and a composition is formed to cover the hexagonal frame, using the shape of the bend to be identical to the design.

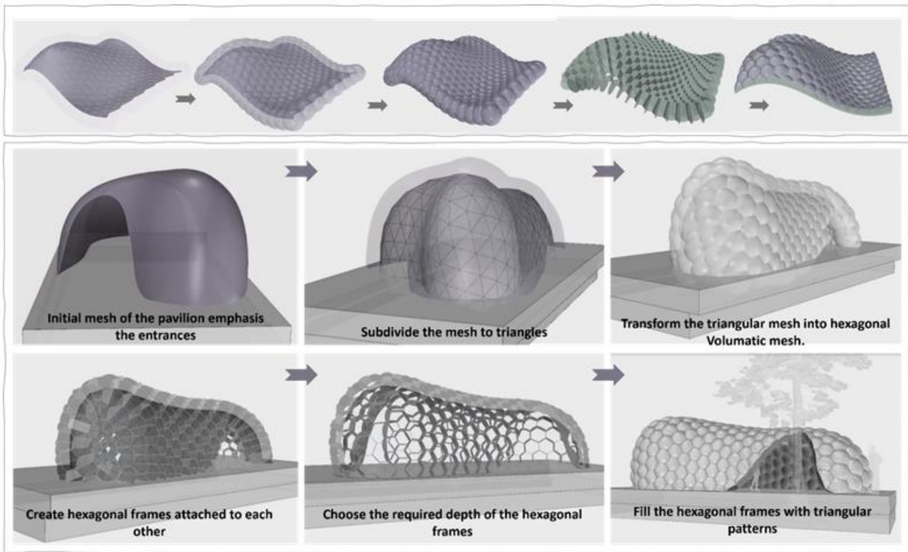


Fig 14. form finding process of the pavilion's mesh [21]

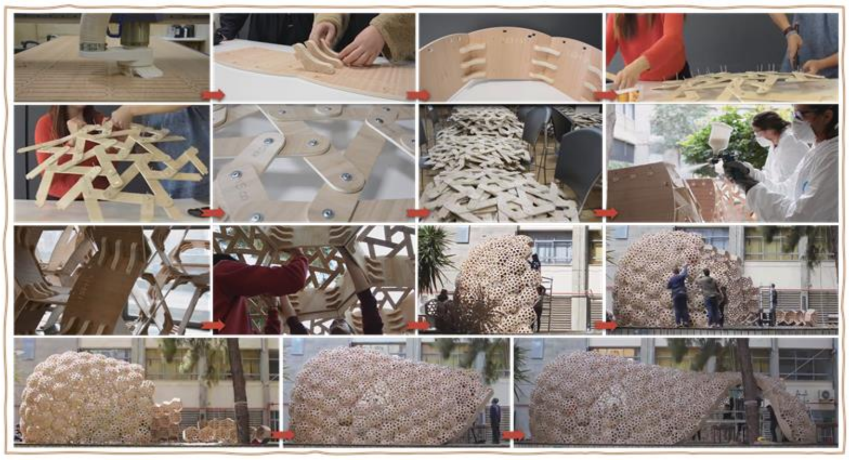
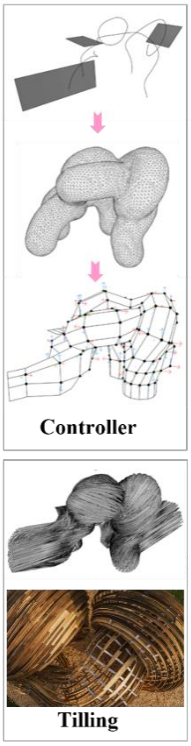
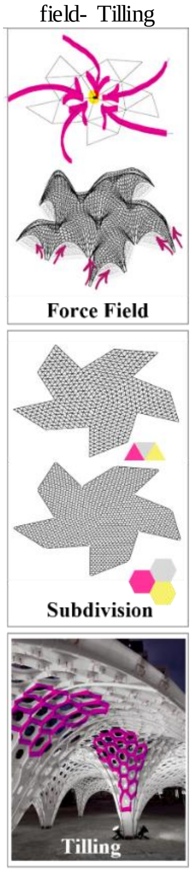
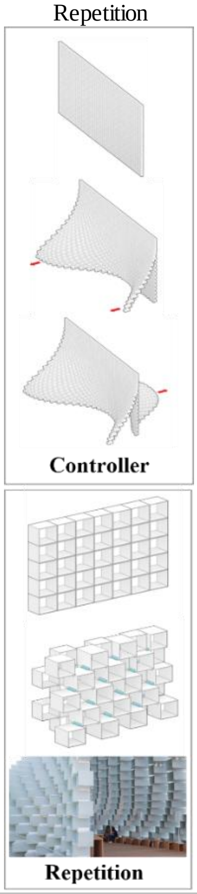
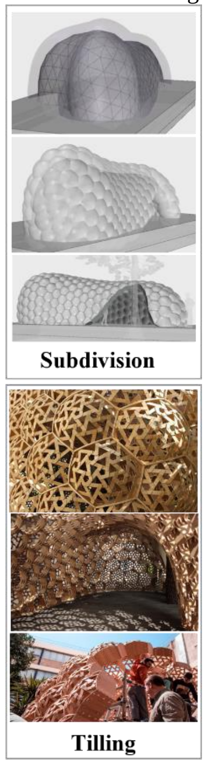
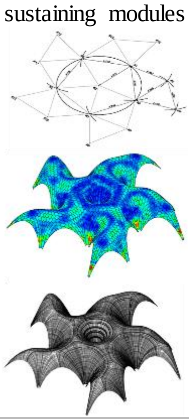
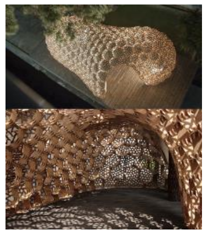


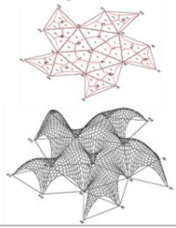
Fig 15. manufacturing process from laser cutting to the installation [21]

5. DISCUSSION

The following is an analytical comparison between the five precedents in terms of: used parametric patterns, formation of the structure, type of structure (all of them is lightweight shell structure), used materials, fabrications, and installation.

TABLE 3. Analytical comparison between the five pavilions in terms of: parametric patterns, formation, structure, used materials, and fabrication & installation

Evaluation criteria	BOWOOSS pavilion	Steampunk pavilion	Shellstar pavilion	Serpentine pavilion	Bubble Pavilion
	Subdivision-Repetition- Tilling  	Controller- Tilling  	Subdivision-Force field- Tilling  	Controller, Repetition  	Subdivision- Tilling 
Formation	Geometrical formation	Kinetic formation	Geometrical formation	Modular formation	Geometrical formation
Structure	Wooden beams & self-sustaining modules 	Freeform parametrized shell 	Steel Reinforcement Arches & self-sustaining modules 	Self-sustaining kinetic modules 	Self-sustaining modules 

Used Material	Glued laminated Timber and laminated veneer timber struts	Straight 100x10mm Steam-bent timber boards	4mm Translucent Coroplast, Nylon Cable Ties, Steel Foundations, PVC, and Steel Reinforcement Arches	500 mm by 400 mm- hollow fiberglass bricks (Lay-Light)	Plywood panels
fabrication and installation	Using Industrial cutting machines to cut timber elements, and the craftsmen assemble pieces and install the pavilion 	Prefabricate Steam-bent timber elements and assemble them following holographic construction information viewed in augmented reality through Microsoft's HoloLens device  	Each cell was folded flat and readied for fabrication using further customized Python scripts. The cell orientation was assessed and turned to match the flutes of the Coroplast material with the surface's main bending direction. 	Each brick's length was designed such that it overlapped its neighbors sufficiently to form an enclosure while also giving a suitable connection length between neighboring bricks for structural purposes. The boxes were arranged in alternate chequerboard patterns on either side of the wall.	Using Digital CAM techniques and technologies to cut the elements, then they were assembled on the site due to the required form. 

6. CONCLUSION

This paper discusses firstly the definition of lightweight shell structure, the three types of geometries of shell structures (Freeform shells, Mathematical shells, and Form-found shells). Secondly discuss the parametric design, and the nine parametric patterns (controller, force field, repetition, tilling, recursion, subdivision, packing, weaving, branching) and present different applications of them in lightweight structures. Thirdly present five different precedents, different in the used parametric patterns to formation the structure, in the used material, in the type of geometries of shell structure, and in the fabrication's techniques and installation. Discuss the different materials like different types of timber, pvc, and fiberglass bricks, and fabrication's techniques that can used for shells like CNC laser cutting, Industrial cutting machines, and prefabricated units. Present the power of traditional techniques in manufacturing and it is not necessary to create a distinct parametric structure to use modern methods, but it is possible by using traditional craft methods to implement this structure intelligently. From analytical comparison find that there are parametric patterns often used in generating the form of lightweight shell structures like subdivision, Repetition, Tilling, Controller, Force field, Branching, and Weaving. And there is a lack of using some parametric patterns in lightweight shell structures like Recursion, and Packing.

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