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Parametric architectural design using shapes and structures

ABSTRACT

This paper explores the creation of architectural structures through parametric design tools. The proposed methodology presents an alternative framework of using digital tools for the product design development from the design thinking point of view. The main core of the suggested design process includes a great number of theoretical issues from design identity, design language and architectural design areas. As a result, designers can develop constructions for public spaces that are based on innovative morphologies by using new digital design techniques such as computational design (Rhino3D© and Grasshopper©). The development of an architectural structure that aims to bring greenery into the city and increase the rest and action spaces is presented. A valuable aspect of this exploration is in positioning the proposed design framework inside - to aid in the creative process and better leverage downstream outcomes. The final steps of the proposed methodology include the production of the final architectural structure through rapid prototyping, laser cutting and engraving techniques.

KEY WORDS
Design thinking, design language, computational design, design development, architectural structures, prototyping

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Introduction

Sketching is the essential language of architecture and product design. Design language is used to express concepts through simple planar or spatial entities, correlated to forms generated by geometric thought (Rossi, 2006). In the sequence of cognition, shapes are the one that the human brain acknowledges and remembers. Therefore, the product shape portrays product identity and gives significant impact to its user/customer's perspectives (i.e., brand connection, emotional experience, consumer needs) (Wheeler, 2003). Design thinking process implicates the ability to synthesize inspiration from variety of sources (e.g., mind-map, mood-board, empathy maps, persona, etc.). Design thinking methodology is a unique tool in a holistic product design (Manavis & Kyratsis, 2021). On the other hand, Conceptual Product Design approach is perceived mainly as an art than an actual science. The main theme of Conceptual Product Design methodology is based on the design thinking principles: empathize, define, ideate, prototype and test (Manavis et al., 2020). Architecture has always embraced innovative ideas, materials, and techniques. Contemporary architecture and product design are no exception (Caetano & Leitão, 2019). Architectural design is essentially characterized as a collective process that unifies a great number of different professions. Architectural and product design make necessary the collaboration between designers, engineers, and technicians (Herr et al., 2011). Furthermore, the new role of architecture requires the creation of innovative shapes- from the geometry point of view (Casale et al., 2013) and at the same time – it is important to refresh the creative process towards the development of architectural forms. This is true and it is achieved by using the possibilities of new digital tools i.e., computational design (Oxman, 2017) and enhance communication between architects and potential users (Ņitavska & Mengots, 2018). The present article combines two different design approaches. Specifically, the ideation sketches and prototypes from the designer's sketchbook in correlation with advanced digital techniques of parametric design. The core reason of this experimentation from authors point of view is about the development of innovative and unique architectural structures.

Parametric modelling in architecture

Parametric design or modelling is a method applied in various areas and has gained an important role even in architecture. The digital model is created automatically based on a series of computer-generated rules. Digital technologies perform a crucial task, to translate the architect's idea through virtual spatial models. Bearing in mind that through FEA analysis models or systems can be evaluated in a virtual environment in order to fix various issues occurring during simulation, thus raising the performance of the virtual model, their role is determinant in increasing accuracy, reducing time and increasing productivity. Moreover, by using FEA analysis, avoiding any failure that might occur with the physical model. Since architecture is constantly looking for innovative ideas, new techniques, and materials-designers are increasingly using methodologies of computational design and digital production. Computational design endeavours to quantify the desired properties, characteristics, and behaviours of a building organism, which may be considered as a system – structured set of spaces and building components designed to satisfy certain goals (Fioravanti, Loffreda & Trento, 2011). In addition, through parametric design, it is easier to calculate and form a basic shape in variable structures, even if its geometry is strange and indeterminate. Use parametric strategies results successful for designing interactive motion facades (Panya, Kim & Choo, 2020) and is effective in combination of form parameters with various assessment tools in different analysis (Suyoto, Indraprashta & Purbo, 2015). Moreover, the combination of parametric methods for designing with optimization algorithms can be used to solve various design problems in architecture (Liang & Wenshun, 2019).

There are different possibilities and approaches of parametric modelling, which are adapted by artists and architects in the realm of urban art. As a result, they bring new possibilities and future directions of parametric modelling in both fields of architectural design and urban art (Leung, 2019). Inspirations from nature combined with computational modelling display a great importance in the reflection of biomimesis on architecture, and that this multi-dimensional and multi-disciplinary concept could be transferred to another discourse – architecture –accurately and efficiently (Sorguç & Selçuk, 2013). Due to a rapid development occurring in technology, makes it necessary to respond these changes by introducing them in educational level, in order to offer students new skills acquired. As a result, introduction of parametric modelling at educational level presents advantages in enabling conversation among students (Symeonidou, 2019), between disciplines (Woodbury, Williamson & Beesley, 2011; Jancart & Stals, 2019), and creating a digital continuum from concept to physical object (Gallas et al., 2015; Agirbas, 2018).

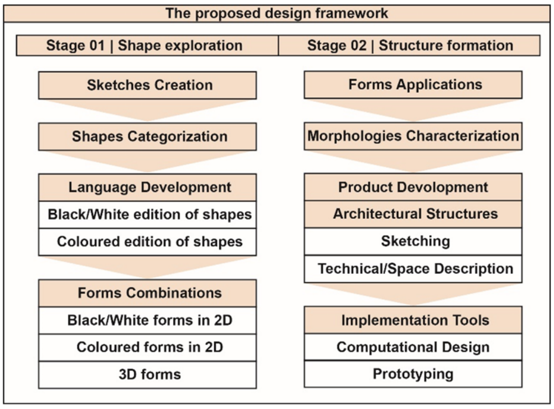
Digital manufacturing in architecture

Creating prototypes is the first step of architects. These prototypes are further used to evaluate them aesthetically, structurally, etc. The widespread use of rapid prototyping techniques (RP) or 3D printing in architecture modelling seems to have an important role. 3D printing technologies are easy, rapid, and economic to create and build models. It can serve in the field of architecture by replacing traditional modelling methods (Gibson, Kvan & Wai Ming, 2002), (Bayar & Aziz, 2018). These applications are present including kinetic architecture as well (Ferschin, Di Angelo & Brunner, 2015). As one of the advantages of 3D printing is production of complex geometries which can be parametrically controlled results in creating architectural structures for landscapes (Bañón & Raspall, 2020). 3D printing also results useful to have a better view of the design idea (Howeidy & Arafat, 2017) and by reducing material wastage resulting as a great advantage for sustainability (Beyhan & Selçuk, 2017). Projects created and implemented by various researchers results in an effective application of 3D printing in architecture (Raspall & Bañón, 2018).

An example application of the three-dimensional representation is the urban design, whose morphology and layout are studied, determining the character of the city (Bonivento et al., 2011). Projects developed using subtractive and additive manufacturing systems, together with robotic process are necessary to produce object difficult to be produced using conventional processes, this due to their irregular geometry (Sousa, 2017). A particular urban element that can take many forms in design is the square, where through 3D illustrations it allows designers to provide the optimal solution (Charlton, Giddings & Horne, 2008) so as to achieve the upgrading of these public open spaces, offering comfort and indulgence to both the inhabitants of the city and its visitors, (Pezzica, Lopes & Paio, 2016) considering the design and cultural heritage of each area. Reflecting therefore the overall image of the city and through the implementation of various activities, the arts are highlighted along with cultural activities. At the same time, it is important in these spaces to achieve through social inclusion and communication between people (Dormidontova & Belkin, 2020). Finally, understanding the importance of the squares, it becomes necessary to design and build more urban spaces, which reflect the modern image of society.

Design methodology

According to the following design process (Figure 1) any designer can follow the proposed methodology in order to create a personal design language that can be used in the creative design context by using parametric tools. The framework is separated into two design phases.

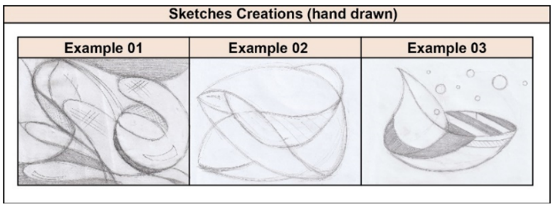


» **Figure 1:** *The proposed design framework*

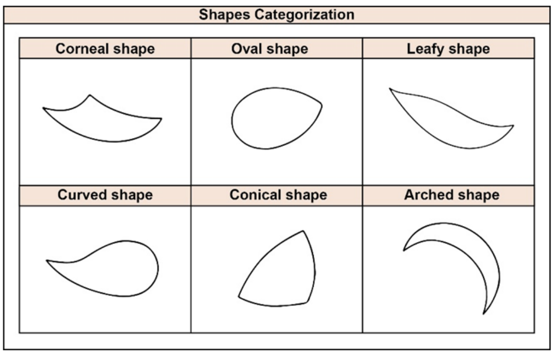
The first phase includes all the specific steps of creation of abstract sketches by hand. The classification of sketches includes two different approaches. The first categorization separates the drawings by the representation goal from the designer's point of view. Specifically, the basic types of the sketches are ideation, explorative, explanatory, and persuasive sketches (Manavis et al., 2020). The second taxonomy concerns the technical features of the sketches. Notably, a) the descriptive lines, which designers draw to convey the form of an object and the b) intermediate construction lines, which help designers draw the descriptive lines with accurate proportions and perspective (Gryaditskaya et al., 2019). The produced abstract designs from designer's point of view was categorized and grouped based on their repetitive patterns. These groups of abstract shapes develop a novel design language. The produced design language consists of individual elements (black/white and coloured editions), through which new combinations of abstract forms are formed. The designer himself is responsible for the creation and selection of these final combinations of forms. The second phase includes all the compositions, which were formed based on these evolving the reasoning process, creating new possible forms, through which the final proposal will be materialised. Furthermore, three-dimensional designs will emerge through the use of parametric programming and source code rules that are formed according to the commands, parameters, constraints, and options to be defined each time by the designer. Finally, it is presented an illustrative case study which includes architectural drawings, photorealistic illustrations, and a prototype model.

Stage 01, Shape exploration

A couple of designers created forty different abstract drawings inspired by nature formulas. The core concept of all these random sketches is about the designers couple unique sketching style (creator's artistic style). Figure 2 shows three different and representative examples (Figure 2). Creating a series of sketches with specific morphological details, a pattern of repetitive forms is developed, with the aim of a final series of individual elements- the letters of the proposed design language. The process of grouping these patterns was done with visual criteria. All the sketches were categorized into six specific and unique formations. Each shape is a primitive form with all these unique features: angles, curves, direction and weight(Figure 3). In particular, with the use of transparent layer of paper and through the search for each design, the patterns that made them up were isolated. In this way, large groups were created with common characteristics (such as cornea, oval, leafy, convex, conical, and arched). Through this process, new subgroups emerged, which would form the basis for further processing.

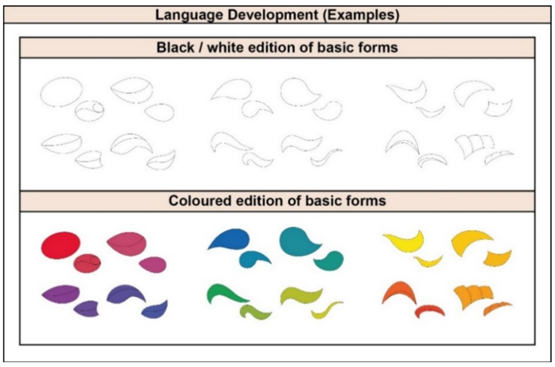


» **Figure 2:** *Sketches creations*

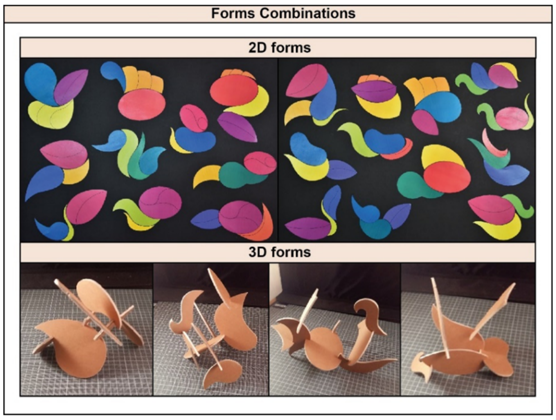


» **Figure 3:** *Shapes categorization*

Comparing the common patterns with each other, the resemblance and repetition of some of them is even more pronounced, with small design differences. The proposed language is consisting of a specific number of individual elements, representing the general identity of the designer. In this way, it is possible to compose new forms from the creation of specific pure forms. The proposed design language is composed of twenty-eight shapes. All shapes include two kind of morphologies – big shapes represent the upper-case letters of the design language and the small ones, the lower-case letters (Figure 4). The transition, modification, change in their form is done design smoothly, starting from a circular element and ending in an identical circular element. In order to give one more information and property to each individual element, the colouring of the linear elements based on the colour wheel was chosen. Starting with the red colour and the first element, a new specific colour was assigned to each shape gradually. The combinations of the shapes are up to designer's aesthetics criteria (Figure 5). All the new morphologies are created randomly according to designer's instinct about future structures that will be transformed into products and/or architectural applications. Designers created twenty-two different combinations of 2D shapes according to geometrical and connectivity criteria of each pair of shapes. Furthermore, the designers updated the two-dimensional shapes into 3D forms. Specifically, twenty different abstract 3D forms were created by the couple of the designers. Figure 5 shows three unique examples of forms. For the proposed 3D transformations designers kept the same criteria as a previous stage (geometry and connectivity). Finally, creators selected two different options of the twenty alternatives. In this paper only one structure is presented as a case study.The final proposal represents morphologies and structures from both 2D and 3D perspective. Finally, having created all the new two-dimensional and three-dimensional abstract forms, some benefits arose for the designer: the development of critique in terms of aesthetic perception, the acquisition of freedom in the formation of new compositions, the management of freedom in composition along with the constraints that arose, as well as the possibility of using this process as a new design methodology, with a wider range of ideas.



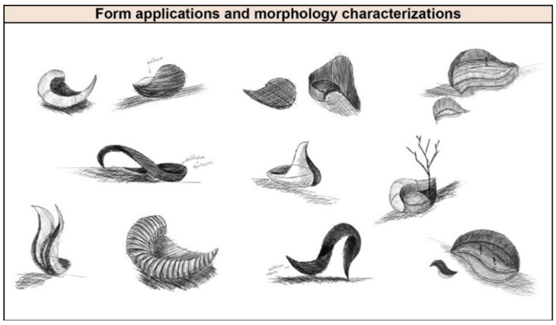
» **Figure 4:** *Examples of language initial forms*



» **Figure 5:** *Form combinations*

Stage 02, Structure formation

The proposed second stage of product design involves four critical substages (Figure 1). First stage is about discovering forms and structures from specific morphologies of applications point of view. This stage focuses to designer's creativity. Furthermore, in this stage designer uses a great number of inspiration tools (i.e., mind map, mood board, sketching, storyboard, and prototype) to explore and visualize the final concept of product. All inspiration tools were used as creative techniques in order to explore the range of different ideas and concepts (Manavis et al., 2020; Manavis & Kyratsis, 2021). Specifically, the mind-map was used for the idea exploration of the main concept (parametric architectural design using shapes and structures according to designers unique sketching style). On the other hand, the mood-board and the free-hand sketching are special tools and techniques for the holistic approach of design. First, the mood-board was used for the idea's visualisations and after that, free-hand sketching for the main concept representation.

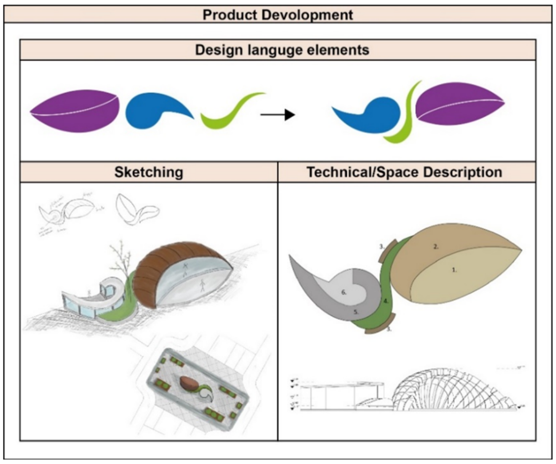


» **Figure 6:** *Form applications*

Finally, the tool of prototyping is a crucial step for the creation of the final concept forms as physical entities- the prototypes were crafted by paper. In structure development stage is presented a detailed architectural structure. The implementation tools area digital sketching software for first concept approach (Figure 6), a vector design application for the technical description of the structure- including the environment space (Figure 7), a parametric design tool for 3D digital modelling development (Rhino3D™ and Grasshopper™) and finally, a specific rendering tool for photorealistic images of the final structure (Kyratsis, 2020; Kyratsis, Kakoulis & Markopoulos, 2020).

Case study: Architectural structure

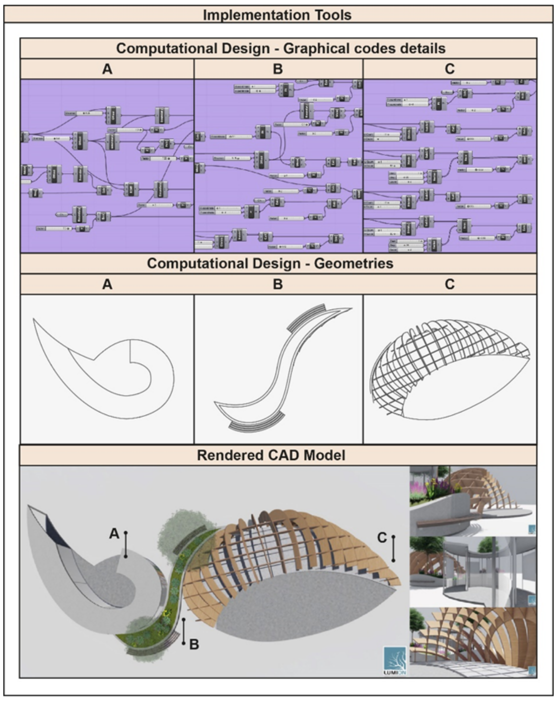
According to the previous design framework, the designers selected three different 2D shapes in order to build a three-dimensional structure. The criteria that were used fits with the geometrical features of each form and finally with the connectivity perception. Figure 7 shows the combination of the design language elements. Furthermore, Figure 7 notes the final sketching approach from the architecture structure. The architectural construction presented in this work with total maximum dimensions, of height 25,35m, width 12,00m and depth 4,90m is formed by the combination of three coloured shapes (Figure 7). The placement of the construction due to its shape is suitable for open elongated public spaces. The large construction on the right is the main platform for people's free movement or for an organization of a public event. The main base of this structure is made of cast material for the formation of curves, with a height of 0,15m and 0,10m above, of a different grey shade to stand out. The wooden construction is a modular connection between the curved wooden planks, thickness 0,04m - maximum construction height is about 4,90m (C).



» **Figure 7:** *Product development (1. Free space and podium, 2. Shell, 3. Rest point, 4. Greenery section, 5. Exhibition space and 6. Yard)*

The middle part of the architectural synthesis is served as a resting point, and it includes wooden benches and a green space through the trees and flowers into a curved shape (B). In addition, the third structure houses an exhibition space that anyone can visit to see periodical art events (A). This construction is placed on a cast base.

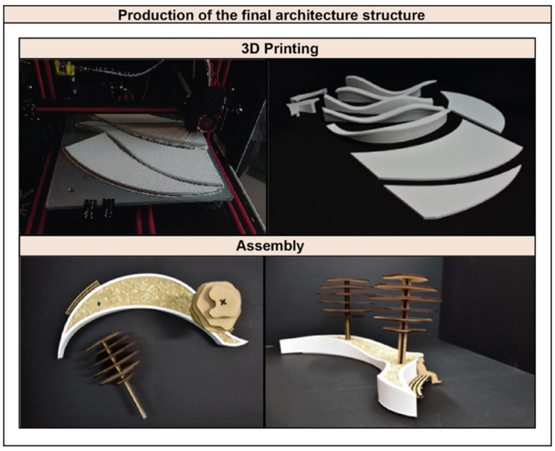
In the parametric modelling, the design process is based on algorithms which are a set of steps for a computer program to accomplish a task, and often come from computer programs such as Rhino3D™ and Grasshopper™. Normally in parametric design, the formation of the three-dimensional form is based on algorithms and rules, which result from the computer programs used. During the design process- it is worth to write down that the designer himself becomes responsible for the final decision of the resulting form, through all these conditions, parameters, and rules. Figure 8 presents view of the created code for the design of the first architecture structure, which has three sections.



» **Figure 8:** *3D digital model*

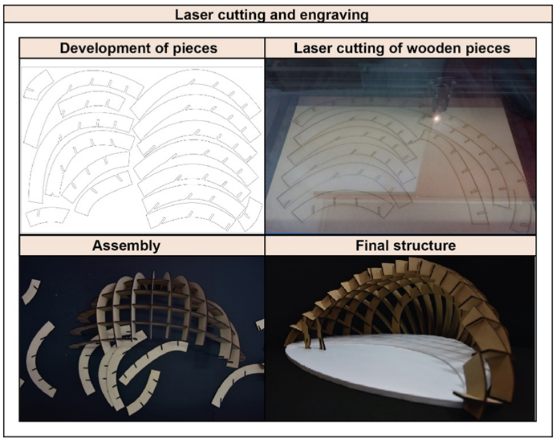
The commands Boundary Surface, Offset Surface and Extrude were used for the creation of the Section A (exhibition space). These specific commands are suitable for the proposed design and building approach. The development of Section B (green space) was based again on parameters on Boundary Surface, Offset Surface and Extrude. The reason of this decision was the similarity of these two forms (curved morphologies). On the other hand, the Section C (shell) is more complex and unusual geometry. The development of Section C was based on Python™ programming language (usage of rhinoscriptsyntax module for Grasshopper™) . Some of the commands were used for the script are: ExtrudeCurveStraight (inserts values for extrude), OffsetSurface (inserts values for offset), MoveObject (moves planars for layering) and IntersectBreps (creates segments). The suggested example of Section C is based on laser CNC cutting techniques – in order to create wooden structures for architectural and product design purposes. All three structures are properly lit with spotlights, so that they are accessible to the public at night. Moreover, the rendered 3D model is depicted in this figure.

Following the final step in the process of product development is the production of the physical prototype with a reduced size model scale 1:20. The proposed methodology includes the production of the final architectural structure through rapid prototyping, laser cutting and engraving techniques. In this way, with the use of laser cutting machines and 3D printers (FDM printing technology), an additional benefit was provided for the understanding of the form, but also for any errors that occurred during the design. The sections A and B (exhibition and green space) were printed, and two physical forms were produced. The equipment for the proposed procedure of 3D printing was an FDM-technology 3D printer. The brand of the equipment is a Cubicon Style and the supported software for the slicing is Cubicreator v3.6+. The 3D models were layered and then printed in detail based on white colored PLA material. PLA is a popular material in 3D printing, enjoyed due to its more environmentally friendly nature and ease in use. The main parameters of the proposed procedure are a) infill percentage (20%), b) layer thickness (0,2mm), c) printing speed (20mm/s) and d) printing temperature (190°C). The parameters apply to both 3D printed models (sections A and B). It is worth emphasizing that the importance of synergy between design and printing-cutting systems, offering easier, faster, and cheaper assembly and construction. Figure 9 presents steps of structure production using 3D printing technology and assembled parts to create the structure.



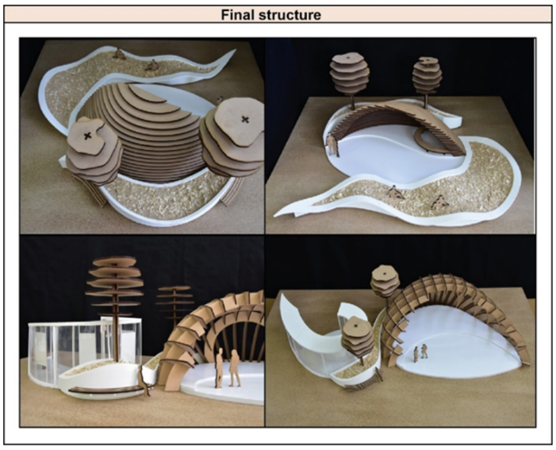
» **Figure 9:** *3D printing and assembly of the one structure*

The other part of the structure is a shell with wooden elements which are designed and exported for laser cutting. Figure 10 presents steps from piece development laser cutting process of elements, assembling of wooden elements and the resulted structure.



» **Figure 10:** *Various steps followed during the production of the structure*

The designer tested the original prototype of his customized design and sense the increased experience of a physical model versus a digital rendered CAD model. The physical prototypes produced using the technologies presented above are arranged together according to 3D virtual model. Figure 11 presents view of the created architecture structure taken from different positions.



» **Figure 11:** *The prototype model of final design approach in different view*

Conclusions

The present paper examines the holistic product design approach from design thinking methodology to product development framework. The research examines the aspect of architectural structures as results from the combination of design language elements (shapes and morphologies) and computational design tools. The main core of the concept was to redefine the creation method of complex structures according to language rules and computational design parameters.

The proposed methodology offers a series of great design and marketing advantages to designers that would be willing to adopt this design procedure: a) ease in the formation of new compositions, b) improved aesthetic perception and c) possibility of different compositions depending on the desired result. This paper combines the use of the parametric design methodologies and sketching styles according to lines, shapes, and structures in ideation stage of product design procedure. The basic reason of this approach is developing innovative and unique architectural structures under the main theme of the designers abstract sketching notes. In addition, through the use of parametric design, design techniques and the new design language, innovative architectural forms emerged. In conclusion, the design and construction of these proposals in public spaces is considered important, giving them a special architectural character, allowing the public to use them during their stay.

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