FORM AND PART THROUGH STANDARD / NON-STANDARD DUALITY

Graduate School of Economics and Social Sciences
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GÖKHAN KINAYOĞLU

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I certify that I have read this thesis and have found that it is fully adequate, in scope and in quality, as a thesis for the degree of Doctor of Philosophy in Interior Architecture and Environmental Design.

Assoc. Prof. Dr. Burcu Şenyapılı Özcan
Supervisor

I certify that I have read this thesis and have found that it is fully adequate, in scope and in quality, as a thesis for the degree of Doctor of Philosophy in Interior Architecture and Environmental Design.

Prof. Dr. Varol Akman
Examining Committee Member

I certify that I have read this thesis and have found that it is fully adequate, in scope and in quality, as a thesis for the degree of Doctor of Philosophy in Interior Architecture and Environmental Design.

Assist. Prof. Dr. Yasemin Afacan
Examining Committee Member

I certify that I have read this thesis and have found that it is fully adequate, in scope and in quality, as a thesis for the degree of Doctor of Philosophy in Interior Architecture and Environmental Design.

Assist. Prof. Dr. A. Derin İnan Çınar
Examining Committee Member

I certify that I have read this thesis and have found that it is fully adequate, in scope and in quality, as a thesis for the degree of Doctor of Philosophy in Interior Architecture and Environmental Design.

Assist. Prof. Dr. Başak Uçar Kırmızıgül
Examining Committee Member

Approval of the Graduate School of Economics and Social Sciences

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Prof. Dr. Halime Demirkan
Director

ABSTRACT

FORM AND PART THROUGH STANDARD / NON-STANDARD

DUALITY

Kınayoğlu, Gökhan

Ph.D. in Interior Architecture and Environmental Design

Supervisor: Assoc. Prof. Dr. Burcu Şenyapılı Özcan

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This thesis formulates its research through a two-fold approach: it introduces a novel algorithm, but first it establishes the relationship model through which the assessment of the algorithm should be made. It discusses the intrinsic relation of “form” and “part” in architecture, through the analysis of concepts “standard” and “non-standard.” The form is the overall shape of an object and part is the numerous constituents of form. “Standard” -which is a central trait for architecture- and “non-standard” -a later introduction to architecture- consisting of various formal alternatives, are included for their important formal and constructional characteristics. All four concepts are studied in their historical contexts and in relation to secondary themes, like tectonics, mass-production, and mass-customization. Simple essential techniques and various geometric formations in architecture are also covered through built examples to further demonstrate the aspects of “standard” and “non-standard,” in terms of “form” and “part.” Based on these four concepts, a quadripartite relation is established. The relationship model formulates a significant interpretation and interrelation of the four concepts, hence creates an analytical framework. Through the findings of the quadripartite relation’s last partition, an algorithm is devised. The algorithm can generate various alternative infrastructure models for surfaces of revolution through several parameters. The findings demonstrate essential advantages in terms of standardization, material use, simplicity and ease of assembly. The algorithm can be altered slightly to adapt to other three partitions.

Keywords: Algorithm, Computer-aided design, Non-standard, Standard, Technique.

ÖZET

STANDART / STANDART-OLMAYAN İKİLEMİ ÜZERİNDEN BÜTÜN VE PARÇA

Kınayoğlu, Gökhan
Doktora, İç Mimarlık ve Çevre Tasarımı Bölümü
Tez Danışmanı: Doç. Dr. Burcu Şenyapılı Özcan

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Bu tez araştırmasını iki yönlü bir yaklaşım ile şekillendirmektedir: yeni bir algoritma önermektedir, fakat önce algoritmanın değerlendirilebilmesi için gereken ilişkisel modelini kurmaktadır. Çalışma, “biçim” ve “parça”nın mimarlıktaki içsel ilişkisini, “standart” ve “standart-olmayan” kavramları üzerinden tartışmaktadır. Biçim bir objenin bütün şeklidir ve parça, biçimin sayısız bileşenleridir. Mimarlık için merkezi bir özellik olan “standart,” ve mimarlığa daha sonradan dahil olmuş, birçok biçimsel alternatiflerden oluşan “standart-olmayan” kavramları sahip oldukları biçimsel ve yapısal niteliklerinden dolayı çalışmaya dahil edilmişlerdir. Dört kavramın hepsi tarihsel bağlamları ve tektonik, seri-üretim, seri-özelleştirme gibi ikincil temalar ile ilişkilendirilerek incelenmiştir. "Standart" ve "standart dışı" kavramlarını "biçim" ve "parça" açısından daha fazla açıklamak için, mimarideki basit ana teknikler ve çeşitli geometrik oluşumlar da, yapılı örnekler aracılığıyla ele alınmıştır. Bunları temel alarak, dört parçalı bir bağıntı kurulmuştur. Bu bağıntı, dört kavramın önemli bir yorumlamasını ve kavramların birbirleriyle ilişkisini formüle etmekte ve bu sayede analitik bir çerçevesini oluşturmaktadır. Dört parçalı bağıntının son bölümünün bulguları üzerinden bir algoritma tasarlanmıştır. Algoritma, çeşitli parametreleri kullanarak dönel yüzeyler için birçok alternatif enfrastrüktür modeli oluşturabilmektedir. Bulgular, standardizasyon, malzeme kullanımı, basitlik ve kurulum kolaylığı açısından önemli avantajlar sunmaktadır. Algoritma, az miktarlarda farklılaştırılarak diğer üç bölüme de benzer şekilde uyarlanabilir.

Anahtar Kelimeler: Algoritma, Bilgisayar-destekli tasarım, Standart, Standart-olmayan, Teknik.

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Always…

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CHAPTER 1

INTRODUCTION

"Architecture starts when you carefully put two bricks together. There it begins."

Mies van der Rohe (1959)

The relation of two minute constituents of a whole may seem like a simple characteristic for any three-dimensional construct. However, it is through countless repetitions of this feature among constituents, the "parts," that make up whole, the "form." This study tries to shed light on the relation of elements among different scales of implementations in architecture by investigating "form" and "part." The smaller quality of "part" when compared to "form" already denotes some qualities for the two. While "part" is the smaller constituent, "form" signifies a totality. This differentiates both fundamentally, but also make the two dependent to each other. A "part" is inevitably the building component of a "form."

For architectural form, besides the "parts," geometry can also be considered as another core component. The increasing potential of geometric constructibility through the introduction of computer-aided design and manufacturing (CAD / CAM) technologies together with the developments in the material industry have made possible for architects to design and build architectural forms with a magnified range of possibilities.

In addition to the expansion of geometric possibilities, CAD / CAM technologies also bring forth an increased concern in terms of economic criterion, which results with the introduction of "rationalization" and "discretization" of freeform geometries. Both concepts are outcomes of "standardization" and have increasing amounts of influence for architecture in CAD / CAM. Although architecture is previously familiarized with "standardization," it expanded its scope with the introduction of the term "non-standard," through the potentials and requirements of newly introduced architectural forms.

Although "standard" and "non-standard" may seem as counterparts, in terms of rationalization and discretization, they both share a common ground of "form" and "part" relation. Therefore, to understand the concepts "standard" and "non-standard," the relation between "form" and "part" is investigated in this study. Both "form" / "part" and "standard" / "non-standard" are studied separately in this study, and it is an attempt to introduce a novel approach to architectural "form" and "part" analysis.

1.1. Research Objectives and Scope of Study

In contemporary architectural experimentations, there is a propensity to standardize “parts” for attaining non-standard “forms.” The uncharted quality of non-standard is still denoted as a significant challenge for architecture and any attempt to resolve undefined geometries is regarded as a valuable exploration. In “Digital Architecture Now,” printed in 2008, numerous approaches in non-standard architectural “forms” are presented (Spiller), leaving aside the implementation processes and focusing only on the generation and visualization of “forms.” However, when projects involved in the three collections of “Fabricate Triennial” - the state of art, showcase conference for universities and architects- (Sheil & Glynn, 2011; Gramazio, Kohler & Lengenberg, 2014; Menges, Sheil, Skavara & Glynn, 2017) are analyzed; one can see the distinct development of architecture in the second decade of the 21st century, through CAD / CAM techniques. The primary attitude of all these projects display transformations from mere formal approaches to efforts to overcome limitations of the “form” by proposing strategies that demonstrate extensive production techniques employing various materials. The dramatic alteration in architecture points out to a highly critical shift from “form” to “part” in architectural design processes.

In architecture, there has always been a need to assemble any “form” through discrete “parts” because of the large scales of buildings. This necessity has given precedence to “parts” in architecture. The formal, functional, scale-wise qualities and requirements of “parts” differ with every project and in this respect, the concept of “standard” has to be redefined for each “form” and “part.” The interrelation of two elements inevitably introduce a “joint,” but joints have not been included into this study. Although they have highly significant qualities within architecture both at the scale of “form” and “parts,” the joints need a more detailed and specially devoted study.

The primary objective of this study is to develop a scheme for understanding the “form” and “part” relationship in architecture through “standardization” and “non-standardization.” The contradictory and complementary nature of the latter two brings forth the possibility of analyzing “form” and “part” in an extensive manner. The study also covers the formal characteristics of the concepts besides their historical and theoretical contexts.

The analysis is realized through a quadripartite relation, generated by the permutation of the concepts “form” and “part,” together with “standard” and “non-standard,” creating “standard form – standard part,” “standard form – non-standard part,” “non-standard form – standard part” and “non-standard form – non-standard part.” The four conditions of the quadripartite relation create diverse qualities in architectural terms with each partition having distinctive existences. The analysis of “forms” and “parts” present a valuable knowledge about architecture and the way it is designed and constructed.

The secondary objective is to develop a unique discretization scheme by utilizing the findings acquired from the quadripartite relation’s analyses. The secondary objective is implemented through a model, which is devised by the author. The model is utilized by adopting sectioning technique for surface structures to increase material efficiency and standardization, and it is specifically designed for surfaces of revolution infrastructures to support the ideas developed throughout the thesis.

1.2. Structure of Thesis

After the introduction, the second chapter starts with the definition of terms, "form" and "part." It is followed by further analysis of "form," by tracing the concept's historical background. Apart from being a visual concept, "form" has been investigated among different readings all tied to architecture. It is through this understanding the following sub-chapter is formed, "the generation of part." The strong connections between the "form" to architecture, brings forth the "part" concept as the generator of "form," hence the tectonic dependence of "part" and "form." Topology is included in the study as an important concept, and it is for this reason that both "form" and "part" is dealt in a topological manner, instead of a case-specific geometrical approach. This enabled the analyses to have a much broader quality.

Platonic solids are studied to form a common base for further geometric considerations to strengthen the topological stance of the thesis. It is then followed by a group of more complex geometries, surfaces of revolution, ruled surfaces and freeform surfaces. The increasing complexity of the four subchapters illustrates the geometric qualities they govern in a much clear and distinct way. The given examples demonstrate the formation of geometric constituents of the architectural examples, the “form” and the “part.” The examples have not been limited with specific periods of architecture, but instead examples from different periods ranging from antiquity to contemporary architecture are presented, because of the concepts’ anachronistic qualities.

The third chapter mainly covers two important terms for architecture, “standard” and “non-standard.” The “standard” is investigated in detail as the main factor for the accomplishment of modern architecture in the 20th century. Mass-production is also investigated as a participatory actor for the concept “standard” and “standardization.” Their implementations as the proof-of-concepts are included to exemplify the means of interpretation in the mid-20th century. “Non-standard,” as presenting vast potentials in “form,” is also investigated, with its several implementations. Both “standard” and “non-standard” are supported by the concepts “rationalization” and “discretization.” As a means for generating “parts” from “forms,” they are explained in detail by discussing their potentials through different types. This part is followed by demonstrating the techniques used –i.e., contouring, sectioning, tiling, and forming– in the surface generation and manufacturing through the concepts of “form” and “part.” The chapter concludes with the analysis of the factors that are vital in the generation of forms in computer-aided design and manufacturing (CAD / CAM). Although the titles denote the opposite except for the last sub-section, computer-aided design is the underlying theme of this chapter. Both terms standard and non-standard are also investigated via CAD tools and concepts.

Succeeding the explanation of the fundamental terms “part,” “form,” “standard” and “non-standard,” the fourth chapter introduces a quadripartite relation, formed through the multiple relations of the terms of the second and third chapter. Both “form” and “part” are analyzed in terms of ‘standard and ‘non-standard.’ Each variety of the two groups are analyzed regarding formal, economic, tectonic and computational criterions. This provides the basis for evaluating these four different variations, while also comparing each type of formation to each other. All four types of existence are exemplified both through built architectural examples and unbuilt geometric relations. The chapter concludes with the overall assessment of the differing interrelations of the two sets of terms.

Built upon the criteria proposed in the previous chapter, the fifth chapter introduces the model as a demonstration tool for the concepts aforementioned in the thesis. Besides exemplifying the explained concepts, the suggested model tries to produce elucidations to the problems of the “form” and “part” relation. By defining the parameters like material, scale, economy, and function; the devised model is explained in detail. The model deals with the surface structures of surfaces of revolution. Two variations are manufactured and assembled for demonstrating the possible material existences of the model and the parameters of the proposed model are also studied extensively in the following subchapter through numerous variations.

CHAPTER 2

FORM AND PART

"…for we think we know a thing only when we have grasped its first causes and principles and have traced back to its elements."

Aristotle (Phys. I.1, 184a12-14, trans. Waterfield)

A three-dimensional construct, whether it be a nanometer scale engineering marvel or a kilometer-high skyscraper, would be a combination of numerous constituting elements. By joining those constituents, an assembled construct is attained. The construct's complexity is dependent on the degree of variations in its constituting elements and their relation to the whole. Any three-dimensional construct would be fit to give as an example, yet a simpler, maybe the simplest, one would be a jigsaw puzzle. A puzzle consists of numerous pieces, making a single whole, with the pieces' correct set of interrelations. While the pieces are the constituting elements, the finished puzzle is a three-dimensional construct. Although this 3d construct is perceived as a single whole when the puzzle is complete, one would still be able to identify every piece of the puzzle.

In any three-dimensional construct, while the size of both the construct and the constituting elements may vary, there is a hierarchical scalar relation in between the two. In scalar terms, the constituting elements would always be smaller than the whole, and they would build up larger wholes by coming together. The number of constituting elements may vary, but this would not affect the scalar comparative relation of the two. The construct can also be made from a single forming element, making the size of the whole and the element equal.

An assembly can be divided into numerous constituents and continued with the additional division of the constituents. If the disintegration of the components would be repeated, in the end, one would attain mono-material constructs. Otherwise, it signifies the possibility of further identification of lower levels of constructs and analyses regarding constituent and whole relation. Therefore, a three-dimensional construct can be made from constituents, which have also been formed from further components, making all constituents separate wholes. This chain of formation can lead to much more complex relations, but still preserving the hierarchy in all levels of associations of the two. However, it should be noted that the degree of differentiation remains in the physical limits of materials, neglecting the chemical qualities they have.

An architectural project consists of several diverse systems, i.e., static, mechanical, electric, etc. We can say that is made up of those separate systems, but we cannot denote those systems as singular entities. These systems consist of highly complex diverse sets of mechanisms with multiple entities building up larger wholes in various hierarchic relations. While an architecture undergraduate can express an architectural project as an arrangement of spaces with specific functions, a contractor would denote the same project as an integration of several engineering assemblies. A mechanical engineer would interpret the exact same project as a combination of numerous mechanical systems. This variability of interpretation of the same concept by different subjects signifies the possibility of diverse understandings. However, all the readings above consist of some constituting elements and a three-dimensional construct at the end. This diversification of subjects clarifies the notion of a hierarchy of construct's and elements' relation.

Within this perception, this study introduces an analytical approach to architectural projects by investigating the forms of the constructs and the constituents of design in various scales. Within the context of this study, the elements that make up the larger whole are denoted as the "parts" and the larger whole, the three-dimensional construct, as the "form." It is a conscious choice to use the term "form" instead of "whole," for the latter would still signify the properties of the "part," whereas the former indicates a whole new set of qualities. Both "form" and "part" is analyzed in a geometrical approach. Although a "form" may consist of some diverse "parts" regarding material, function or form, various levels of abstractions are still possible. Through an abstract interpretation of the overall "form," it can be considered as a single geometry.

Considering an architectural project as a single geometry signifies a deduction of many groups of constructs, leaving aside further possible analyses. However, this type of reasoning allows a concise conclusion about the "form" of the analysis. In the cases of this study, the "form" has been thought on both scalar bounds; as the whole project and as a single constituent. The scalar variation allows an inductive reasoning of the findings.

2.1. The Concept of Form

Aristotle had widely studied the idea of form as early as the fourth century BC (Aristotle, Phys. I.2, trans. Waterfield). His approach mainly covers the aspects, constituents, and qualities of form. Although Aristotle's approach is more of an ontological and philosophical one, it is beneficial to refer to his analysis. Aristotle's concept of form mainly deals with the form's constituents to reach up to an overall understanding of form and tries to discern the logical components of the whole to grasp the "overall message" (Aristotle, Phys. I.1). While Aristotle had attempted to define the logical elements of form, this study tries to disintegrate the bodily components of a "form."

Within the field of arts, "form" is considered as one of the main building blocks, together with line, shape, value, space, color, and texture (Crane, 1900). In its broadest and simplest terms, a form is the overall shape of a thing (Langer, 1957). Usually, while "shape" denotes a two-dimensional geometry, the term "form" denotes three-dimensional properties. All three-dimensional objects, regardless of their size or complexity, have a form. In architectural terms, form is closely related to the concept of space (Jirousek, Textiles, & Apparel, 1995). An architectural form would and should imply a spatial quality and configuration. Any interrelation of two identities, the "parts," brings forth a combination of the two, producing a new order with a novel “form,” whether it has a useful function or not (Aristotle, Phys. I.2, 185b5-18).

Aristoteles talks about a human and a human statue by noting the differences in between the two and concludes that although they are both shaped the same, they cannot be considered as equal entities (Phys. II.2, 193a12). However, for this study, a human being and a statue are equal in terms of “form,” and this study deals with the form of both, together with the constituents of it. In other words, the function is not considered as one of the determinants for the evaluation of forms, unless function has been utilized by the designer as a determinant for the most basic constituent of “form,” the “part.” This study tries to formulate an analytical method to understand the qualities of the building blocks of a whole within the framework of the formal characteristics of the totality itself.

In one of the first treatises on architecture, “Ten Books on Architecture,” Marcus Vitruvius Pollio (c. 90 - c. 20 BC) talks about a broad variety of topics that range from town planning to details of pavements and overall conceptions of geometry (Vitruvius, 2016). Here also specifies the exact details for all his descriptions through materials or details, as if they are culinary recipes. However, “form” is not a criterion to consider for Vitruvius. Although Vitruvius talks about the formal attributes of capitals of the period in a geometrical and descriptive sense, there is an instructive stance throughout, an inevitable consequence of the relation between form and technique. Unless the constructive method of a particular “form” is not known, it cannot be built. “form” is a resultant factor of the construction technique.

One of the most significant and critical principles on “form” has been propagated by Louis Sullivan in 1896. His conception of “Form follows function” has affected and continues to affect architecture since then (Sullivan, 1896, p. 408). It denotes the interrelation of form with the function, limiting the form only to the outcomes of the notion of function. However, one cannot consider function as the sole determinant of form. Function indeed denotes a formal typology that is dependent on itself, but it would not be enough to consider it as the single utmost criteria. Therefore, form owes its existence to certain other factors, such as technique, material, economy, and aesthetics.

2.2. Generation of Part

Aristotle, in his seminal *Physics*, also talks about the relation of the elements and the whole they make up (Phys. I.4, 187b13). In order to assemble a large whole, it is essential to have discrete parts. The aim and need for reaching to a larger-scale entity make the “part” an indispensable constituent of “form.” Through this approach, together with the “form” that is said to be designed, the designer also creates the “part,” even before the “form.” This notion creates a dependency in-between “form” and “part,” defining all the attributes of the “form.” In this respect, the material, color, texture, and size of its constituents, together with the ease of manufacturing and economy of a “form” are all dependent on “part.”

While for a masonry wall, bricks would be the “parts”; for a structure clad with steel, the steel plates would be. It can be seen that “part” is considered as the simplest repeating constituent of the design; but another approach is also possible, in which the “part” is considered as an intermediary element making up the “form.” The term piece is not used in this study, but instead “part” is chosen. Piece denotes a single entity that may lead to an upper degree of totality and the same is valid for the “part,” but they are differentiated by the “part’s” possible existence of a larger construct. A “part” may consist of several other “parts” and it is not the case for a piece. A piece denotes the simplest constituent of a whole, whereas a “part” also has the potential to signify an intermediary component of a “form.” Therefore, any piece will also be a “part,” but not vice versa, making the piece a subset of “part.” The approach of this study does not necessarily decompose a “form” to its most basic “parts,” hence the pieces, but takes an analysis specific stance. By breaking the decomposition process at an intermediary stage, a new level of analysis becomes possible.

In the example of Winery of Gantenbein by Fabio Gramazio and Matthias Koehler (2008) the structure is constructed from thousands of brick elements, each positioned and oriented individually by robotic arms. At first glance, the bricks can be considered as the “parts” and the façade as the “form.” It should also be noted that each brick element can also be seen as a “form” by itself. However, if scrutinized, it would be seen that there exist intermediary constituents of the façade: the rectangular frames creating intermediary “tiers of assemblies” (Kieran & Timberlake, 2003, p. 19). While the façade still being the final “form,” the frames also become intermediary “forms” built by the bricks. The frames would then be considered as the secondary “parts” of the design and the bricks be counted as primary. Here, the first and second ordering of “parts” is a result of the hierarchical relations and sequence of formation for each group of elements. This approach explicitly demonstrates a different degree of abstractions for “form” and “part.”

Figure 1. Winery of Gantenbein in Fläsch, Switzerland (Gramazio & Kohler, 2008, p. 100).

Although it has been said that the constituents, namely “parts,” can be disintegrated until they are composed of a single material, it is not the only criterion to define the limits of “parts.” It is the way a “part’s” constituents are arranged, in relation to each other, namely their physical relationships that are being analyzed in this study. With the introduction of computer-aided design (CAD) and computer-aided manufacturing (CAM) techniques, a “part” can be manufactured by infinitely many number of constituents, each designed and fabricated separately. Although the production process of a rapid-prototyped object would be composed of a single material, it still can govern a part wise formation. Then the prototyped objects would be “parts,” in which every one of them is made up from many “parts” and they would assemble the “form.” This makes up the “form,” an assembly of multilevel “part” and “part” relations.

For the mono-material constructs, as there does not exist a “form” to “part” relation, the “form” and “part” relationship is also altered. A contemporary example in this context would be an object manufactured by rapid-prototyping. As the fabricated product would be composed of a single material, it cannot be stated that a “form” and “part” relation exists like in an ordinary construct. On the contrary, the concepts “form” and “part” are fused into each other, and there does not exist a “part” apart from the overall “form” and vice versa.

Although a three-dimensional form cast from concrete would be considered as similar to the given an example above, a higher level of abstraction will present an entirely different point of perspective for analysis. Any concrete form would be a single three-dimensional entity with a single “part,” but to cast it, a formwork construction is needed. Consequently, the formwork would be composed of more than one discrete element, which transforms the concept of “part” to a new level. It is now a constituent of the “form” not as an integral counterpart but as an essential component for the pre-formation phase. Hence, the concept of “part” does not have to be limited only with the end result, but instead, it can also include the production procedure, entailing the whole lifecycle of the “part.”

Within the context of this study “part” is considered to be the most central quality a “form” houses. Although at first, it is the overall “form” of a structure that attracts attention, through a more comprehensive perception and analysis, one would be aware of the constituents that make up the whole, and it is the relation in between those "parts" that materialize the "form." The "parts" may be at any scale, maintaining the scalar hierarchy in respect to "form." The definition of a "part" may be an outcome of several factors. While the designer's intentions can be the most central, it may also be the scalar limitations of materials or manufacturing techniques that bring forth the necessity of introducing the concept of "part" and this also adds the necessity to interrelate each "part" with its neighboring "parts." To connect the "parts" a joint is needed, and the joints would create the interrelation of "parts" with each other.

2.3. Tectonic Dependence of Form and Part

Tectonics, etymologically Greek, from *tekton* meaning carpenter or builder, is an architectural topic dealing with how two distinct elements come together (Frampton, 1995). Starting from the 19th century with the definitions by Karl Bötticher as 'complete system binding all parts of the Greek temple' and by Gottfried Semper as "lightweight, linear components," tectonics can be considered concisely as the poetics of construction (Frampton, 1995). Tectonics has been defined as the "art of joinings" by Adolf Heinrich Borbein, in 1982 (as cited in Frampton, 1995). Borbein has included joinings at all scales, ranging from objects to artworks, together with building parts to this definition. Although the term indicates an artistic stance towards the joinings, it is merely a technical one.

In a tectonic analysis, the joining of two hierarchically equal parts that are vastly repeated throughout a design is taken into consideration. Joining two discrete elements would create a new entity in some higher hierarchical scale, and tectonics focuses on the relation of the initial two, but not of the hierarchically upper one, the whole, with the initial two's, "parts." In hierarchical terms, "part" is the main constituent of the overall "form," yet it can be said that there exists a different and particular type of tectonic dependence between the two. While a tectonic relation signifies two hierarchically equivalent elements are creating a larger whole, the tectonic relationship of "form" and "part" denotes a dependence. The tectonic dependence criterion of the "form" to "part" represents a unidirectional link in between the two, making the "form" tectonically dependent to "part." The formal, material or technical aspects of a "part" directly affects the corresponding qualities of "form," hence the dependency of "form" to "part."

In tectonics, instead of the size and dimensions of elements, relations among them are investigated, and it is the fundamental aspect of tectonics. Therefore, the methodology of tectonics can be considered as a qualitative and topological stance instead of a quantitative one. Even the joining of two timber elements denotes certain aspects for tectonics. How the elements are brought together, the final form of the joining, the geometrical characteristics of both the "parts" and the assembly are all unique norms for tectonics. All the aspects mentioned denote distinct qualities, but none of them indicates scalar qualities.

2.4. Topology as a Tool for Inspecting the Formal Aspects of Parts

The concept of topology is included into the study to investigate the geometric qualities of “form” and “part” beyond the scalar limitations of the studied examples. Topology is a mathematical term, and it is used in this study for its close relation with geometry (Choquet, 1966). Topology is the science dealing with the geometric structure of shapes, instead of their size, shape or curvature (Carter, 1995). In topology, any variation of a geometry attained through actions like deforming, twisting and stretching is identical to each other but tearing or gluing creates a topologically different geometry (Firby & Gardiner, 1991).

Like topology, typology also deals with the shared formal qualities among examples. Typology creates groupings under some predetermined concepts like function, material or cultural values. However, topology is solely interested in the geometric qualities of forms without any added value. Therefore, topology attains a higher level of abstract and geometrical analysis, whereas typology often comprises additional aspects. The absence of such points in topology allows the analysis to have a more geometric stance, allowing to focus on the form and shape of designs. Similar geometric approaches have been taken in typology (Caniggia & Maffei, 2001; Krier, 1992; Onat, 1991), but there was always at least one coalescent factor besides geometry, diminishing the analyses’ formal effects. A formal and topological analysis of “parts” together with the overall “form” brings forth possibilities of evaluating architectural projects denoting a geometric approach to design.

In topology, the most basic example given to demonstrate the qualities topology offers is the teacup attained from a torus. By stretching and deforming a torus, one can end up with a teacup geometry (Figure 2), but it is topologically impossible to end up with a teacup from a sphere, cylinder or cone unless the geometry is torn up to create a hole in it. Two forms with identical topologic properties are called homeomorphic. In the given example, torus and teacup are homeomorphic geometries. A homeomorphism is derived from Greek words *homoios* and *morphē*, meaning “similar” and “form” respectively and it is a subdomain of topology, focusing on the morphological qualities of geometries (Firby & Gardiner, 1991). An instance of a homeomorphic entity would be entirely different in terms its dimensions but still topologically identical with the rest of its variations and counterparts (Kolarevic, 2003).

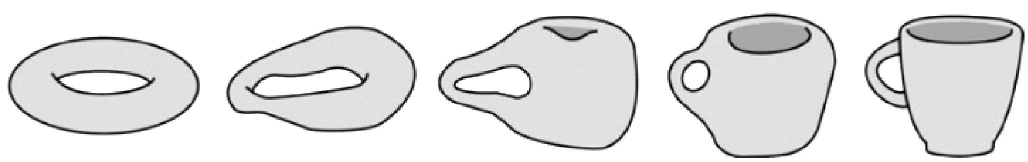


Figure 2. Torus to teacup deformation (Lynn, 1999, p. 22).

“Landesgartenschau Exhibition Hall,” designed at the Institute for Computational Design, Stuttgart, in 2014, is a plywood structure with a single space. Topologically the form of the structure is an elongated sphere, sliced from both sides to create entrances and openings. The outer surface is panelised by planar hexagonal plywood elements, and there is a total of 243 unique panels, which form a lightweight curvilinear blob-like form. There are minute dimensional differentiations among panels, and they are homeomorphic. Hence every part is equal in topological terms.

Figure 3. Landesgartenschau Exhibition Hall in Gmünd, Germany (Menges, Schwinn, & Krieg, 2016, p. 113).

For this study, criterions like a number of faces, edges, and vertices of the geometries are considered as topological properties. In other words, intrinsic geometric and topological properties of the forms have been considered as the primary concern, leaving aside scalar quantities, reaching to a homeomorphic level of analysis. As the design process has shifted mainly from designing forms to designing relations (A. Kilian, 2006), the topological approach has become a vital element in analyzing and comprehending the operations and outcomes of design, preventing one to fall into the limitations of aesthetic and formal judgments for single instances of design elements.

While a “part” can be considered as a topological, homeomorphic entity, a “form” can also be considered likewise. This allows the consideration of both in a more generic manner, leading to the interpretation of the examples given throughout the thesis in a broader sense. In this study, the concept of homeomorphism has been used as a methodological analysis tool for the “form.” When a “form” is designed for the manufacturing phase, its constituent “parts” —if there are any— are also designed and determined. A variation in the “form” would only differentiate the `parts` in a topological manner. Through variation, some parts’ dimensions may change, but “parts” would be still homeomorphic. Any alterations in the “form” would not necessitate to fundamentally alter the “part” as long as the topological qualities of the relations in between “parts” are not differentiated. On the contrary, any change, whether minute or dramatic, in one of the intrinsic qualities of a “part” unequivocally influences the utmost scale of the “form.” The material, size, cost, and a number of the “parts” can be considered as several factors in this chain of effects. Therefore, “part” is the primary determinant of the “form,” hence the proposed saying “form follows part.”

2.5. Geometric Formations in Architecture

Although architectural instances have varied dramatically throughout the ages in terms of geometry, the core relation of “form” and “part” has remained as the most significant formal property architecture governs and both “form” and “part” need deeper investigations to grasp their relations and geometrical qualities. The following four subchapters demonstrate different types of geometries used in design in a homeomorphic manner, characterized by their differing types of geometric formations. Beginning with the simple geometric elements, which form the essential constituents of architecture, surfaces of revolution and ruled surfaces are also included as initial geometric, together with the formal explorations of freeform surfaces.

2.5.1. Simple Geometric Elements

In *Towards a New Architecture*, Le Corbusier describes the ancient Egyptian, Greek, and Roman architecture through five noble forms; cylinder, pyramid, cube, prism and sphere (2013). His approach was certainly a homeomorphic and topological one as Corbusier omits the scalar qualities of the elements employed when describing the examples of the Classic Era. Branko Kolarevic also refers to Le Corbusier's sketch to point out the significance of those geometric elements with the geometric "primitives" used in digital CAD software (Le Corbusier, 1931 as cited in Kolarevic, 2005) (Figure 4). The constant quality of geometric elements for more than 2000 years present the significance of geometry and its topological stance in architecture.

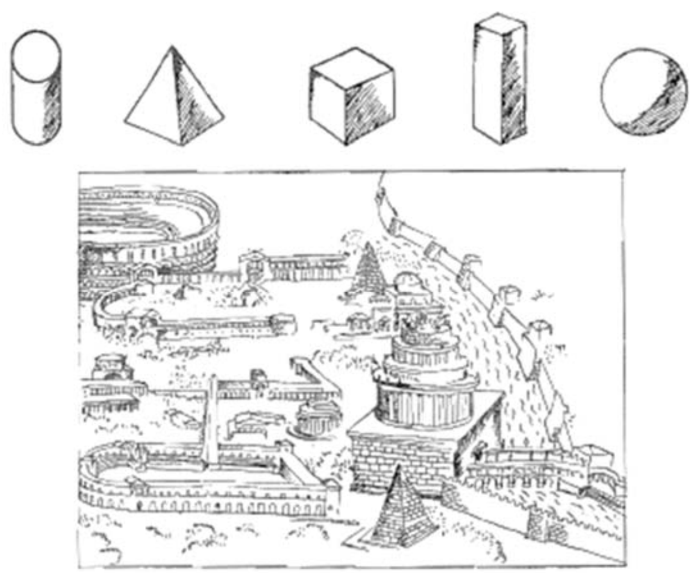


Figure 4. Geometric primitives (Le Corbusier, 1931: 159).

Through "transformative design," one can attain a shape on any scale from those five elements. By stretching, deforming or other topological operations, hence keeping the intrinsic formal qualities constant, countless forms can be created (Ching, 1996). The transformation process of a geometry allows the generation of endless alternative forms. Additive transformation allows new additions to the initial shape (Ching, 1996) and alters the topological qualities of a shape. It may also be a combination of parts created through transformative design. There also exists subtractive transformation, in which the designer removes parts from an initial primitive geometry to end up with a more complex form.

It is through the transformation and combination of cubes that have created the most examples of modern architecture. It is for sure that there exist numerous other factors, which have affected the causality for the selection of the cube as the initial point (Frampton, 1995), but in geometrical terms, the end results can be classified as products of transformative and additive design. As additive transformation alters the topological qualities of a geometry, it can be through those types of alterations to attain geometries beyond topological limitations. The problem of creating a teacup from a non-torus shape, like a cube, can be overcome through additive or subtractive design approaches by connecting several of those elements to each other to create a closed chain-like form or tearing up the geometry and attaining an orthogonal torus shape (Firby & Gardiner, 1991).

As all those simple geometric elements are closed surfaces, they are also considered as solids or masses (Corbusier, 2013). On the contrary, in contemporary architecture, with the advancements in mathematics and geometry, the solid based interpretation of design has transformed into a surface based one (Pottmann, Eigensatz, Vaxman, & Wallne, 2015). This shift from solids and masses to surfaces has dramatically evolved the examples of architecture. Within the context of this change, following subchapters exemplify the geometric qualities of different types of surfaces commonly used in architecture.

2.5.2. Surfaces of Revolution

Surfaces of revolution present a vast degree of possibilities, because of their relatively complex formations, when compared with orthogonal geometries. Surfaces of revolution have always been an integral part of architecture despite their curvilinear forms. The sphere, the cylinder, and the cone can be considered as subsets of surfaces of revolution. Any dome with a circular-plan can be denoted as an implementation of surfaces of revolution. The constant curvature of a surface of revolution has been the key criterion for making it a constructible form. Either by creating the cross-section and revolving it around the center or by building successive circular plans on top of each other, a surface of revolution can be constructed with relative ease. While a simple cross-section for a surface of revolution would generate a considerably simple formation, a complex one would end up with a highly intricate surface geometry.

Geometrically, a surface of revolution can be generated by revolving a cross-section curve around an axis (Pottmann, 2007). Depending on the characteristics of the cross-section, straight or curvilinear, a surface of revolution can either be single or double-curved respectively. By having a vertical axis of revolution, if the cross-section is a straight line, the end result would be a cylinder, and if it is slanted, a truncated conical form would be attained. The curvilinear quality of the cross-sections presents various alternatives of double-curved surfaces, and even a spherical form can be generated by using a semicircle as the cross-section. A surface of revolution would have a circular-plan layout as long as the axis of revolution is vertical. If the axis is horizontal, the plans of the surface would have diverse possibilities that range from a rectangle to curvilinear outlines.

Domes have played a central role in architecture throughout the history, and they can be denoted as typical instances of surfaces of revolution. As they are structurally stable forms, they had been implemented in many materials, scales, and functions. Although dome-like shelters are dated back as early as 400,000 years ago (Pottmann, 2007), one of the most significant examples of domes is the Pantheon in Rome, Italy and it was designed by Apollodorus of Damascus in 116 AC (Figure 5). It is one of the most dominant buildings in the history of architecture. Despite its historically-laden qualities, for the scope of this thesis, a geometrical analysis is made. To define Pantheon geometrically, noble forms including a triangular prism, *tympanum*, raised on 20 cylindrical columns defining the *portico*, *the rotunda* as a cylinder and the *dome* as a hemisphere with an opening on top, *the oculus* may be employed (MacDonald, 2002). The hemispherical shape of the dome is a typical example of a surface of revolution with an arc as its cross-section. Although the "parts" of Pantheon cannot be spotted with ease, as it has an unreinforced concrete structure, the interior coffered ceiling pattern of the dome is designated with a quadrilateral subdivision that is repeated throughout. Therefore, although the quadrilaterals are not constructive elements of the dome, they can be indicated as "parts" geometrically. There are 5 rows of quadrilaterals inside the dome and each quadrilateral is repeated 28 times. It is certain that the unreinforced concrete dome cannot be denoted as a surface, geometrical properties of a surface of revolution have been used to its extent with its geometry and the quadrilaterals of Pantheon's dome. There are much more examples of surfaces of revolution in great structures throughout the history of architecture with similar qualities to Pantheon.

Figure 5. *Pantheon* interior view (Marder & Jones, 2015, p. 18).

One of the first examples of a dome built in the 20th century was the *Glashaus,* designed by Bruno Taut in 1914. *Glashaus* was a pavilion at the Cologne Deutscher Werkbund 1914 (Nielsen, 2015) (Figure 6). The structure's dome was a crude surface of revolution because of its quadrangular panels all around, but the repeating panels at every level depict typical characteristics of a surface of revolution (Weston, 2004). The concrete frames had housed 14 triangular and 98 quadrilateral colored glass panels, and there were 7 types of “parts,” each repeated 14 times in the structure. The low number of variations was a result of the dome’s geometry, and the same was valid for the timber elements of the formwork (Nielsen, 2015). *Glashaus* was demolished at the end of the exhibition.

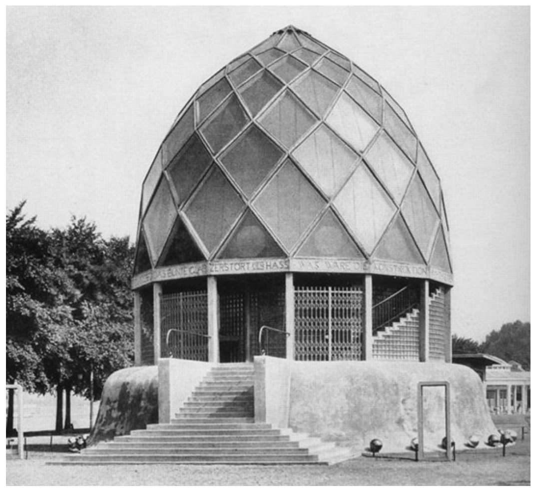


Figure 6. *Glashaus* in Cologne, Germany (Nielsen, 2015, p. 2).

Besides the domes, surfaces of revolutions were also implemented in circular-planned buildings and structures. Although a circular shape in the plan does not necessarily denote a surface of revolution, the verticality of the peripheral elements or a constant cross-section throughout the does so. One of the most significant implementations is the Solomon R. Guggenheim Museum in New York, dated 1939, designed by Frank Lloyd Wright. The circular formation in the building is actually a continuous spiral throughout all the levels with a slightly slanted vertical exterior surface. A similar condition is also present in the interior of the structure by the introduction of a circular atrium, and the spiraling ramp connects all levels inside. Formed by the combination of varying circular surfaces of revolution throughout the stories and an orthogonal configuration, Frank Lloyd Wright implemented surfaces of revolution in his design at their fullest extents together with the interior circular shaped atrium (Pfeiffer, 1995).

Vladimir Shukhov was a highly significant Russian engineer, and he has utilized surfaces of revolution in his numerous towers at the end of the 19th century. By implementing his own patented technique, Shukhov has constructed more than 200 towers with heights ranging from 37 meters to 130 meters (Beckh, 2015). Structurally, Shukhov's towers were all catenary frames, but the geometry they governed was surfaces of revolutions because of their circular-plans. Due to being catenary frames, all the towers had a standard geometric formation of hyperboloid form. In his towers, Shukhov had utilized numerous vertically slanted linear elements in two opposing directions, arrayed in a polar fashion. The particular configuration of the elements created a highly stable structural organization, and Shukhov's towers are also denoted as the predecessor of contemporary diagrid systems for the geometric qualities they govern (Ritchie, 2012).

Pierre Luigi Nervi's and Buckminster Fuller's numerous structures should also be noted as outstanding examples of surfaces of revolution. Although Fuller's technique is specialized for geodesic domes and patented under the same subject, both Nervi and Fuller devised unique methods for attaining surfaces of revolution. Fuller has mainly focused on spherical steel structures (Figure 7), and Nervi implemented concrete shells to their fullest extent via curvilinear formations that are not only limited to surfaces of revolution (Nervi, 1956) (Figure 8).

Figure 7. US Pavilion at Expo ’67, Montreal, Canada (Pawley & Fuller, 1990, p. 167).

Figure 8. Palazzetto dello Sport in Rome, Italy (Charleson, 2014, p. 19).

In 2005, Foster and Partners designed an extraordinary tower, 30 St. Mary Axe that is differentiated from its contemporaries both by its circular-plan and cross-section (Figure 9). The cross-section of 30 St. Mary Axe is formed from the combination of several concave arcs, and the resultant form of the tower is a double-curved surface (Boake, 2014). The curvature of the cross-section has enabled Foster and Partners to attain a public plaza at the ground and various advantages in terms of aerodynamics, structure and material use (Foster & Partners, 2008). There are other towers in the shape of a surface of revolution with similar approaches, such as Tornado Tower (Figure 10) and Canton Tower (Figure 11). While the Tornado Tower is designed by CICO Consulting Architects and Engineers, which is in Doha, Qatar; Canton Tower is designed by IBA, in Guangzhou, China and they are both built in 2008. Both towers' cross-sections are convex arcs, hence double-curved surfaces similar to 30 St. Mary Axe.

Figure 9. 30 St. Mary Axe Tower in London, UK (Foster & Partners, 2008, p. 273).

Figure 10. Tornado Tower in Doha, Qatar (Boake, 2014, p. 71).

Figure 11. Canton Tower in Guangzhou, China (Boake, 2014, p. 10).

Cylindrical buildings can also be considered as a type for surfaces of revolution in architecture, and maybe they are the most common. A constant plan repeated throughout the stories, which is a highly typical situation for residential and office blocks, together with a circular formation will inevitably create a surface of revolution, the cylinder.

2.5.3. Ruled Surfaces

Other formal experimentations have been carried out in architecture prior to the introduction of CAD technologies. Instead of arbitrary forms, geometrically well-defined forms were preferred because of their ease of methods of construction. Ruled surfaces, in that sense, are powerful tools for creating various types of curvilinear geometry, also providing the necessary means to construct. The formation process of a ruled surface is simple. A ruled surface can be created by extruding a straight line along a curve in three-dimensional space, regardless of the formal qualities of the curve. Most of the ruled surfaces are developable, which also denotes the possibility of unrolling the ruled surface onto a plane without any stretching, deformation or tearing of the surface. The surface can be constructed out of this planar sheet element with bending. Whether a ruled surface is developable or not; as the generator of ruled surfaces are straight lines, among the cross-sections taken from any point on the surface, there would be at least one cross-section that generates a straight line (Shelden, 2002). In other words, it can be said that any ruled surface is formed from infinitely many parallel straight lines, the rules that differ in rotation in space. It should also be noted that in ruled surfaces, the rules do not intersect each other, i.e., every cross-section is parallel to the rest, in terms of surface geometry. It is this property of ruled surfaces that makes them perfectly suitable for building curvilinear surfaces. Ruled surfaces served as a great tool for overcoming the construction problems in the realization of curved surfaces prior to the introduction of computers.

Although creating ruled surfaces is not the only possible method for attaining curvilinear surfaces, it has been the most used option among other curvilinear geometries. The main reason behind this choice is the ease ruled surfaces offer in the formwork construction. The transition of ruled surfaces from conceptual design to physical existence can be through a number of different ways. A developable ruled surface can be built from sheet materials; like metal, timber, plastic or paper. Non-developable surfaces cannot be made from sheet materials, but they can be constructed from point-like elements, such as bricks, linear elements like successive beams, or monocoque structures. Those techniques can also be used for formworks of ruled surfaces, followed by the casting of a plastic material like concrete.

The straight lines composing ruled surfaces have enabled architects to build desired surfaces with comparable ease in the 20th century (Fallavollita & Salvatore, 2012). Eladio Dieste, an Uruguayan engineer and architect, has extensively explored the possibilities of ruled surfaces by utilizing masonry construction system. Back in 1960, in his “Church of Jesus Christ the Worker” in Atlantida, Uruguay, Dieste employed ruled surfaces, both on the building’s facades and the roof. The non-developable curvilinear ruled surfaces were built by bricks, hence the “parts.” By locating the geometrical construction points of the ruled surface in physical space through the structural framework and positioning each brick element accordingly, the accuracy of the surface assembly was achieved (A. Kilian, 2006). The regular pattern of the sinusoidal wave on top of the walls provides an increased bearing for the ceiling’s barrel vaults and increased slenderness for the walls thus the structural firmness, while also creating the curvilinear effect both on the outside and inside of the building (Figure 12).

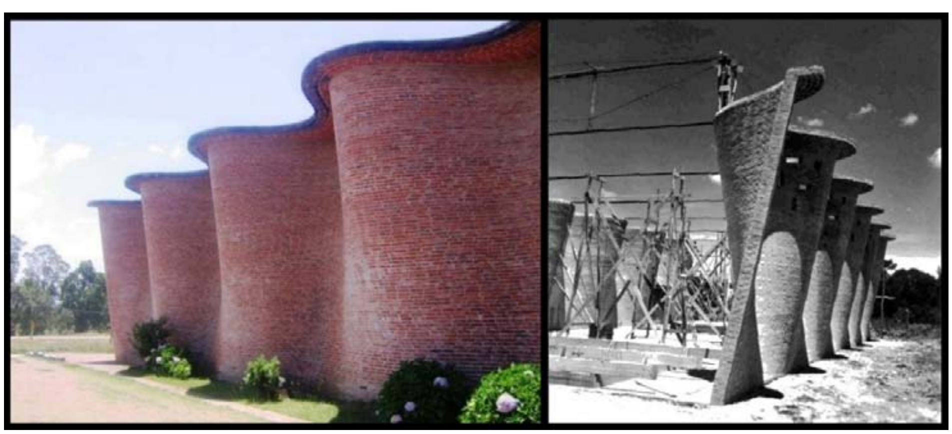


Figure 12. Church of Jesus Christ the Worker in Atlantida, Dieste (Anderson & Dieste, 2004, p. 56).

Still created by moving a straight line in space, also double-curved ruled surfaces can be obtained. A particular occurrence of double-curved ruled surfaces is the hyperboloid, which is one of the geometrically most complex ruled surfaces. A rectangular surface can be converted into a hyperboloid, a special kind of a ruled surface, by lifting one of its vertices perpendicularly (Iskhakov & Ribakov, 2015). Unlike single curved ruled surfaces, hyperboloid has linear cross-sections parallel to all sides of the rectangle in both directions, creating a double-curved surface. The contradictory curvilinearity created by bi-directional straight lines also offers a structural stiffness and quality when built as a monocoque structure (Pedreschi, 2008).

Felix Candela, an important figure of modern architecture, has devised methods for constructing hyperboloid structures out of concrete. For any ruled surface can be formed out of linear elements, building the formwork of the surface out of a number of timber parts positioned side by side is also possible. Regardless of the form, any ruled surface can be constructed by this method. However, this feature is not enough for a ruled surface to be structurally stable when built. Furthermore, Candela has generated a unique structure out of eight hyperboloid ruled surfaces, located radially. By intersecting eight parts of the structure, a unique shell is attained, still maintaining the structural characteristics of a single hyperboloid surface. The structural capability of the surface has allowed an excessive thinness in the concrete shell. The continuous curvature of the surface causes the transformation of the forces into the ground without any discontinuation allowing

Candela to decrease the thickness of the structure as little as 4cm (Chilton & Isler, 2000) (Figure 13).

Figure 13. An exemplary hyperboloid surface under construction by Candela (Pedreschi, 2008, p. 16).

Santiago Calatrava also benefits from ruled surfaces, by using straight elements in his designs. Ranging in terms of scale from a garage door to an airport roof structure, ruled surfaces can be traced in Calatrava's many projects. Because of the mathematical quality lying beyond the creation of the ruled surface, the surface gains structural firmness, in addition to its formal quality. The operable shades of Milwaukee Art Museum, by Santiago Calatrava, display a recent example of ruled surfaces (Figure 14). Each linear element of the shade can be rotated according to the direction of the sun rays, creating an endless ruled surface variation throughout the year. An inoperable example of ruled surface implementation by Calatrava is the Bodegas, a winery for the Ysios Company. Calatrava has formed an undevelopable ruled surface for the roof surface of the building from sequential beams. The linear cross-sections can easily be seen from interior spaces as well as the building's periphery.

Figure 14. Operable shades of Milwaukee Art Museum (Schulze, 2001, p. 20).

Figure 15. Ysios Winery in Laguardia, Spain (Hartje, Perrier, & Kliczkowski, 2004, p. 43).

Besides in architectural practices, the ruled surfaces are also popular in academic researches. A graduate program offered in ETH Zurich, by Fabio Gramazio and Matthias Kohler since 2006, is one of the most significant examples. The team tries to investigate the architectonics and constructive potentials of contemporary techniques and geometries by exploring the digital fabrication technologies and material limitations. Several projects have been implemented covering a broad range of materials and fabrication techniques ranging from laser cutters to robotic manufacturing and installation (Gramazio & Kohler, 2008). Among their projects, an example of ruled surfaces is the Sequential Wall Project, realized in 2008. The composition of numerous wooden slats in varying lengths, each cut to the dimension by computer-numerically controlled machinery, has resulted in seven adjacent ruled surfaces. Although the project does not govern any functional qualities, it offers an architectonic trial by adopting digital fabrication techniques. These kinds of autonomous experiments serve as grounds for architectural practice to develop.

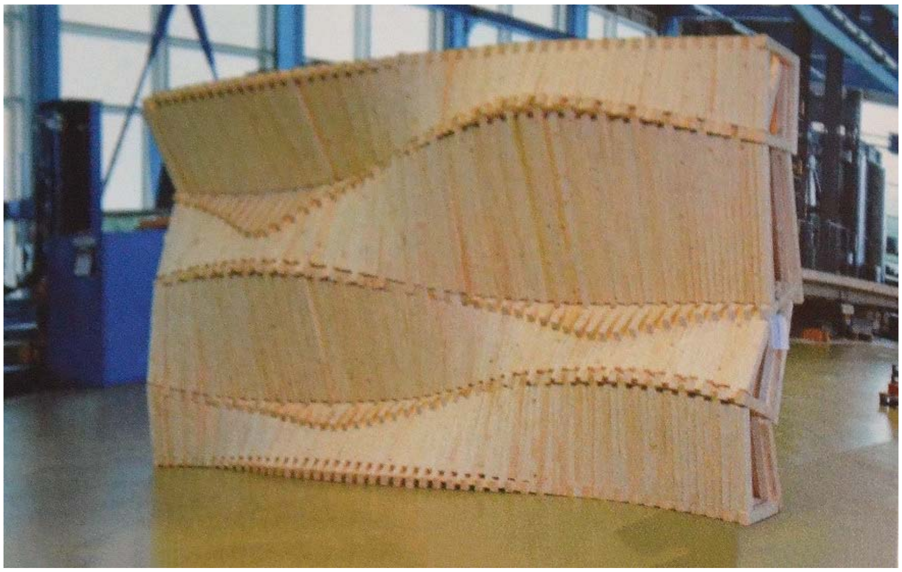


Figure 16. Sequential Wall (Gramazio & Kohler, 2008, p. 70).

2.5.4. Freeform Surfaces

A form that cannot be described via simple geometric elements can be regarded as a freeform surface. Any deviation from noble geometry would create a relatively complicated process of realization due to the modified geometry's departure from the simple definition of a simple geometric form. Topologically, the modified cube would still be considered as a cube, but the realization phase of it would be highly dissimilar from an unmodified one. An unmodified cube has a constant connection in its 8 corners, but even a small translation of a corner would differentiate 3 edges and their respective connection details. Therefore, even a little deviation from a noble form creates a more complicated process of realization.

Any simple or modified form designed for architectural purposes is dependent upon several criteria like the performance of materials, scope of construction techniques, economic concerns and geometric description of the desired form. A shortcoming on one of these will result in highly increased difficulties throughout the building process or even the cancellation or failure of construction. It was not until the introduction of computers that the geometric descriptions advanced. However, there were still some attempts in geometrical and formal terms prior to computers.

One of the most notable formal efforts in architecture in the 20th century may be traced in Antoni Gaudi's complete collection of works. Although Gaudi lived prior to the introduction of computers in the first half of 20th century, between 1852 and 1926, the design of *La Sagrada Familia* was highly sophisticated because of its scale and geometry. Gaudi has worked in the church for more than 43 years and had died prior to its completion (Fischer, Herr, Burry, & Frazer, 2003). Mark Burry has started working on the design and realization process of the church in 1989. He utilized CAD / CAM techniques through transforming aeronautical software since the architectural software of the time were not sufficient to solve complex geometric configurations. Burry acknowledges Gaudi's efforts and success in geometry (Fitzpatrick, 2011) and he has developed innovative geometric solutions to Gaudi's attempts. The geometrical studies and the church's construction phase is still unfinished because of its highly complex geometry. Both Gaudi's and Burry's geometries include hyperboloids, helicoids, and surfaces of revolution. Burry notes that Gaudi had worked through models instead of drawings for his design's complex geometric formations (Burry, 1993). The preference of models is born for the necessity of testing the three-dimensionality of freeform surfaces, and prior to CAD / CAM, it was a universal need for any free-form surface.

Figure 17. *La Sagrada Familia* in Barcelona, Spain (Kliczkowski, 2004, p. 58).

Among other non-orthogonal geometric experiments and projects in the 20th century are Erich Mendelsohn's Einstein Tower (1921) and *Notre Dame du Haut* (1955) by Le Corbusier (Figure 19). Both Mendelsohn and Corbusier had utilized freeform concrete surfaces and highly complex geometries in their designs. The freeform qualities of both projects were achieved by numerous, discrete timber formwork elements, the "parts." The differentiation among "parts" has created the problem of precision of construction as all timber elements needed to be measured, cut and fixed in place separately. It is stated that both designs lacked successful construction phases ending up with forms not exactly as they intended, due to the forms' complex geometries and limited construction techniques of the time (Corbusier & Petit, 1995; Hentschel, 1997).

Figure 18. Einstein Tower in Potsdam, Germany (Weston, 2004, p. 44).

Figure 19. *Notre Dame du Haut* in Ronchamp, France (Crippa & Francoise, 2015, p. 11).

With the introduction of CAD / CAM techniques to architecture in mid-1990's, the formal limits of design and the possibility of precise manufacturing and implementations have varied dramatically. One leading figure displaying new advances is Frank Gehry, with Guggenheim Bilbao Museum (**Error! Reference source not found.**). The museum consists of various surfaces with convoluted geometries and intricate, non-orthogonal shapes of "parts." The museum consists of a specialized steel structure to form the unique curvilinear shape of the building and is clad with more than 33000 distinct curvilinear panels (Kolarevic, 2003). Therefore, the need for precision was utmost for all the elements beginning from the design phase to manufacturing and assembly. Gehry and Partners have implemented a special software, CATIA, to overcome the unique requirements of the process. CATIA is a highly developed and condense software that was specially designed for aerospace industry, and Gehry has adopted it for architectural purposes.

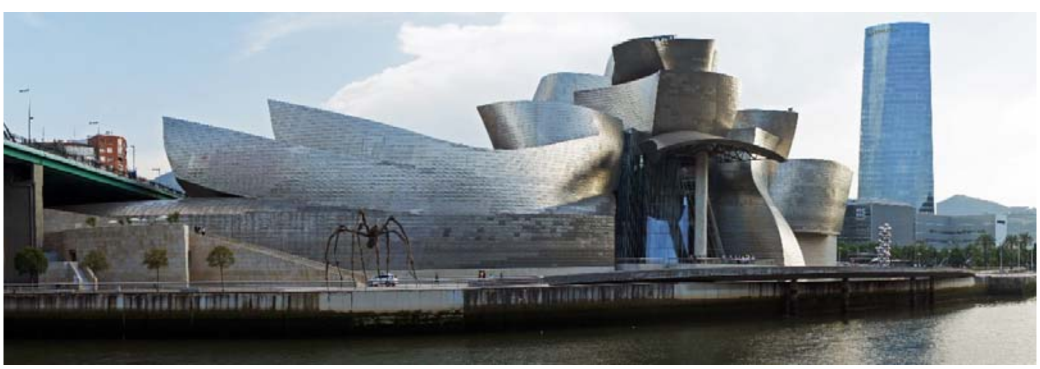


Figure 20. Guggenheim Museum in Bilbao, Spain (Ortiz, 2012).

Gehry has widely utilized Bezier and B-spline surfaces in Guggenheim Bilbao. Bezier and B-spline surfaces are defined and represented through several subdivision control points that do not necessarily lay on the surface itself but act upon the geometry by pulling the surface towards itself, as attraction points (Figure 21). The amount of a control point's power is defined by the degree of the surface, whereas the degree defines the number of control points that are effective on a particular portion of the surface. Therefore, a first-degree Bezier or B-spline surface will be a faceted geometry with edges on it and the control points will lie on the surface and a second or third-degree surface will be more curvilinear. Any B-spline surface can be transformed into a Bezier surface through manipulating the B-spline surface's parameters. Both Bezier and B-spline surfaces have an enormous range of geometric possibilities, but they demand sophisticated mathematical operations to be generated, worked on and manufactured.

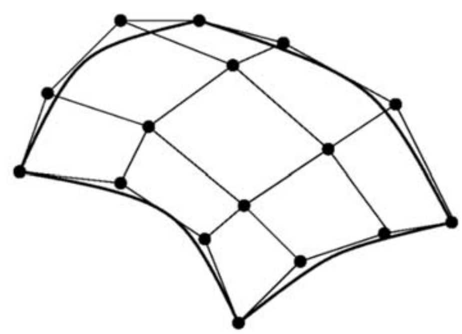


Figure 21. An example of a 2nd-degree Bezier surface with control points (Segarsa, Mahesh, Beck, Frey, & Tsui, 2008, p. 3802).

The definition of surfaces through mathematical equations and CAD have also led to the alteration of fabrication processes in a fundamental way, because of the demanding geometrical qualities of such surfaces. In CAD processes, when the computer model of the project is completed, it is considered as ready to be manufactured and assembled in-situ. The process is actuated by sending the data from the architectural office to manufacturing plants without any intermediary actors, and this is called as File-to-Factory chain (Kolarevic, 2003). The process is highly advantageous in overcoming the possibility of failure in the transition of data from one medium to another; such as design offices to the contractor, contractor to fabrication center or fabrication center to the construction site and assembly.

CHAPTER 3

THE CONCEPTS STANDARD AND NON-STANDARD IN ARCHITECTURAL GEOMETRY

"*If you think of standardization as the best that you know today, but which is to be improved tomorrow; you get somewhere.*"

Henry Ford (1926, p. 80)

There has always been an effort to produce an identical of a previously created thing, a second instance. Since ancient times, whether it be a small utensil or a protective shelter for the family; mankind had to repeat the production procedure of things to attain copies and there inevitably occurred differences among them. The action of copying does not have to rely solely on formal attributes. While producing another ax for chopping trees only depends on the functional aspects, the production of a clone of a vase depends more on the form of the item. For an object that functions on its own, differentiations among copies –whether minute or large, do not matter so much as long as the object functions correctly, but once two identical copies have to interact with each other, specifications of items have to be taken into consideration; such as objects' shapes, dimensions, densities and material specifications, etc.

Development of machines has radically altered the production techniques since a machine can repeatedly perform a single task with perfection in a speedy manner. The repetitive quality of the machines allows them to quickly create the exact same thing infinitely many times, allowing to have identical copies of any object. This ability to produce exact copies of things have brought forth the idea of "standardization."

Following the concept of standard, there also occurred its successive counterpart: non-standard. Although it has been based primarily on formal criteria, the idea of non-standard has developed to comprise a much larger agenda including the formation processes, aesthetics, and standardization (Mennan, 2008). This chapter focuses on the concepts of standard and non-standard through geometrical characteristics together with their historical backgrounds and their associations with mass-production and mass-customization. The concepts of standard and non-standard are also regarded as having potentials for architecture, and they are investigated from a topological standpoint to cultivate them further. Additionally, the chapter discusses production techniques introduced by technological developments like sectioning, contouring, tiling, and forming. Although these techniques seem to be discrete form-wise approaches in architecture, since they were made possible by the developments in CAD / CAM technologies, they shall be considered as intrinsic methods in architectural design related to both “form” and “part.”

3.1. The Concept of Standard and Standardization

Architecture follows a parallel development with industrial progressions. It may also be said that architecture is the showcase of the construction industry through built examples, like bridges, factories, skyscrapers and other structures. In addition to the way they are constructed; the strength, cost, implementation speed and precision of the structures are also proofs for the relation of construction industry and architecture. Within the industrial production process, there is the need to attain some constants to have a compliance throughout all the elements of the industry and this results in the concept of standardization.

As any architectural work is composed of many “parts” and those “parts” are required to be manufactured in numerous amounts, standardization has been a crucial concept for architecture since the 20th century. The need to produce buildings through economic and fast production processes has made the idea of standardization a common criterion for both industry and architecture. Apart from architecture, standardization developed in numerous industries in a parallel fashion in the 20th century. It is directly related to industrial developments because the central actors in standardization are the machines. The Second Industrial Revolution and consequently introduction of the concept of mass production have acted as the most primary constituents of the development of standardization in all industries.

3.2. Mass Production

The beginning of the First Industrial Revolution is dated around mid-18th century with the inventions of the steam engine, development of chemical processes, new iron refining methods and augmentation of machines in the production processes (Deane, 1979). It directly affected textile industry by mechanized hand labor and inventing methods for manufacturing cotton, and that was followed by several other developments in electrics, mechanics, chemistry, and strengthening of the iron and steel, which led to the Second Industrial Revolution in the 20th century (Gras, 1969). Many branches of industry are still under the effect of Second Industrial Revolution. Although a single invention cannot be related to its beginning, as there were numerous inventions in that era like electric light, telephone, refrigerator, and airplanes; the most common significance is in the implementation of mass production.

Mass production was developed in 1913 by Henri Ford, for the manufacture of cars in a serial fashion, completely altering the automotive industry at immediacy and all industries henceforth. Prior to mass production, workers in a factory walked from one item to another and repeated a number of different procedures at every assembly in the plant. Henry Ford had removed the movement of workers through the factory but instead moved the parts by conveyor belts through assembly lines limiting the variety of actions to a single task and deeply revolutionized the manufacturing process. The movement of assemblies with constant speed through the front of workers has also eased and increased the rate of production (Batchelor, 1994). The term “mass” in mass production signifies both the people using the products as a noun and the products manufactured *en masse* –by mass, as an adjective (Hounshell, 1985).

After the Second Industrial Revolution, beginning of the Third Industrial Revolution is claimed increasingly with the invention of internet, digitalization of manufacturing, advanced robotics and development of artificial intelligence technologies (Rifkin, 2011) and while it is being pointed out that it has already arrived, and industry is under its influences, some mark recent future for its augmentation, like Thomas Fisher, who mentions mass-customization as the milestone for the Third Industrial Revolution (2015).

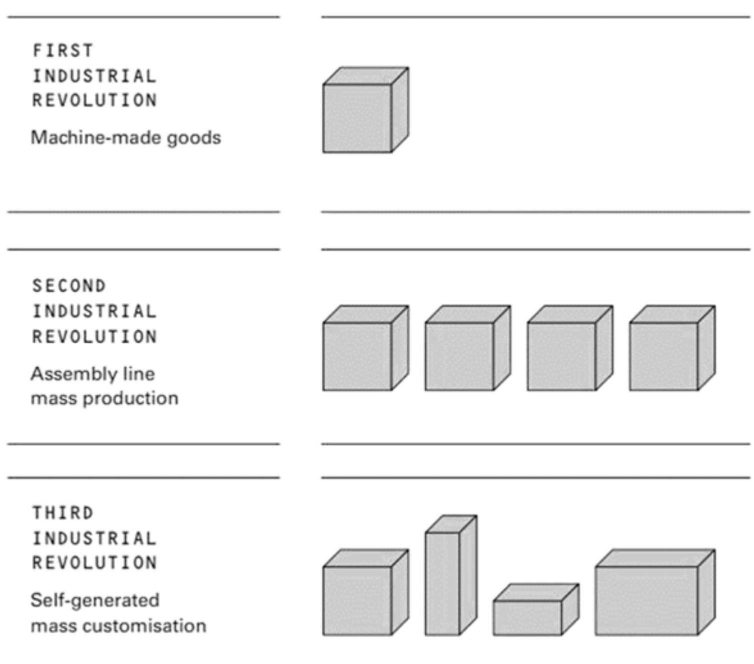


Figure 22. The figurative depiction of industrial revolutions (Fisher, 2015, p. 42).

3.3. Implementations of Standardization in Modern Architecture

Within architecture, often there is the tendency to standardize elements of design at all scales for rendering the manufacturing, assembly, and construction processes easier and for reducing the costs. Like any other industry, standardization in architecture takes place when an element is repeatedly utilized without being changed throughout. This constituent does not necessarily have to be the smallest component. Unlike other industries, standardization in architecture describes a wider scope of implementation. It is not limited to the elements within a project but also possible through a project's numerous repetitions at different sites. Therefore, instead of universal standards of architecture, standards and the concept of standardization for each project have to be redefined depending on the qualities of “form” and “part.”

Although there have been several influential architects in the context of standardization, like Frank Lloyd Wright, Ludwig Mies van der Rohe, Alvar Aalto and Walter Gropius; Le Corbusier had played a vital role in the adaptation of standardization into architecture. His admiration for the fast and economic productions of automobile industry resulted in the ambition for both standardization and its derivative, mass housing in architecture. In his seminal book “Towards a New Architecture,” Le Corbusier had pointed to the importance of standardization for architecture together with the concept of mass housing and has included a chapter on it with sketches, plans, and ideas for numerous housing schemes (2013). He tried to achieve a comprehensive operation of industrial concepts within architecture through precast elements, standardized parts, repetitive structural systems and generic forms by minimizing in-situ constructions and maximizing the number of production processes in factories (E. R. Ford, 1996). Additionally, in his short article entitled "Mass-Produced Buildings" written in 1924, Le Corbusier mentions the importance of standardization and mass production for architecture, together with their economic consequences in a precise manner (p. 134). He tried to utilize the concepts of standardization and mass production in architecture throughout his works as well.

As the direct interpretation of his unique approach to attain generic forms, Le Corbusier's most influential project was *Maison Dom-ino* –combination of *domus*, Italian for "house," and "innovation" (Watkin, 2005) (Figure 23). The project was highly original for its time by having no form, but instead, a system of formation. Composed of only three rectangular slabs, six columns with footings and a staircase, the proposal did not have any façade, but it was a generic construction system scheme for residential projects. Le Corbusier had developed the system in 1914 and employed it in many of his projects. It should be noted that the *Maison Dom-ino* system was not limited to only two stories and six columns. It enabled the customization of designs through generic formation by changing a number of stories or columns and by changing the façades. An outstanding quality *Maison Dom-ino* offered was the common ground for a typical, standardized, residential construction enabling even prefabricated construction. While it can be used with its initial formation for a single dwelling, it can also be extended into a mass housing complex via multiplying the base unit in two axes, as in "*Maison Citrohan"* (**Error! Reference source not found.**) and "*Unité d'Habitation"* (Figure 48). The degree of standardization achieved through *Maison Dom-ino* can be considered as a quality for architecture in terms of the infrastructure.

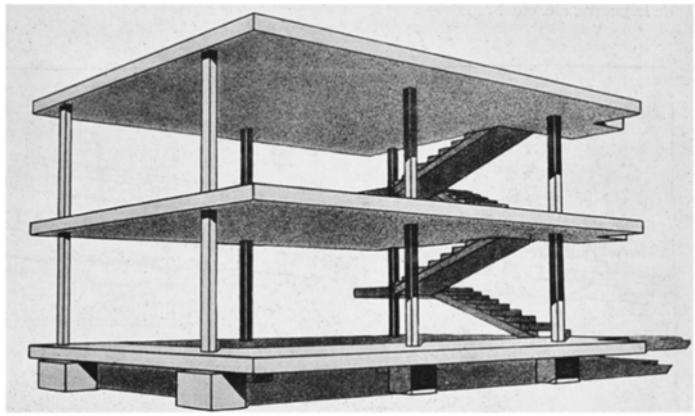


Figure 23. ***Maison Dom-ino*** **(Corbusier, 2013, p. 234).**

The first instance of standardization in architecture is dated back to 1920, by Le Corbusier, for a typical housing scheme. Corbusier tried to implement Ford's assembly line concept in architecture by using standard elements, minimizing the connection details and attaining simplified assembly procedures. As a display for his appreciation of cars and their manufacturing processes, Le Corbusier had even named *Maison Citrohan* after the famous automotive company Citroën (Colquhoun, 2002). The prototype had developed from 1920 to 1927 with five versions, and its last alternative was built in 1927 in Stuttgart, Germany. *Maison Citrohan* has actually been designed for families as a generic solution applicable to different sites and conditions. It was regarded by Le Corbusier as an economic proposal for the post-war period for the masses, and he described it as efficient as a machine (Baker, 1996) It consists of simple geometric elements, and the whole design creates a rectangular prism. The pure quality of forms of all constituents had enabled most of the "parts" to be precast and standardized. If the "parts" could not be manufactured via prefabricated methods, they were cast in place through industrially produced formworks (Legault, 1997). The implementation of *Maison Dom-ino* can be traced in the building through its generic and standardized "form." Corbusier has also defined *Maison Citrohan* as a prototype for "mass production villa" and a "machine for living" (Corbusier, 2013, p. 240) (Figure 24).

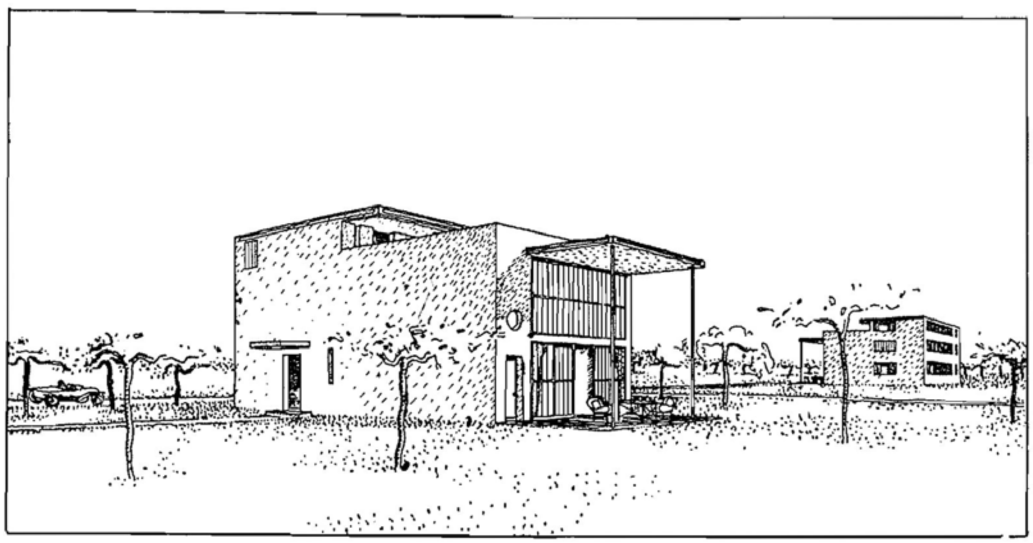


Figure 24. *Maison Citrohan* as a mass-produced house (Corbusier, 2013, p. 240).

A highly differentiated formal approach to mass-produced housing was endeavored by a very significant architect and inventor, Buckminster Fuller with his "Dymaxion House" –Dymaxion as a combination of adjectives *dynamic* and *maximum,* and a chemical term *ion*. Similar to Le Corbusier, Buckminster Fuller was also obsessed with automobiles and aircraft, and his fascination has led to an industrial solution to the post-war epoch residential crisis. "Dymaxion House" has initially been created as a prototype in 1927 (E. R. Ford, 1990) and it had continued to be developed until its implementation in Wichita, Kansas, 1945. Governing a cylindrical formation, "Dymaxion House" had a central mast, holding a dome on top and was sheathed with corrugated steel circumference (Ward, 1985). Although it remained as a prototype with only a few implementations, “Dymaxion House” demonstrates the extents of the possibility of mass-production techniques in architecture (Pawley & Fuller, 1990).

Figure 25. Dymaxion House (Fuller & Ward, 1984, p. 114).

One more significant contribution of Le Corbusier for standardization was “*The Modulor*” in 1943 (Corbusier, 1977). Created by the anthropometric dimensions of the human body, Le Corbusier presented various measurements with respect to bodily proportions, in order to standardize floor heights, column thicknesses, dimensions of interiors and even furniture. Le Corbusier used *“The Modulor”* to generate both the interior dimensions and the total formation processes of several projects, such as “*Unité d'Habitation”* in Marseille, “Church of *Sainte Marie de La Tourette”* in Lyon, France and “Carpenter Center for the Visual Arts” in Cambridge, Massachusetts. Le Corbusier’s efforts on “*The Modulor”* and standardization focused on generic qualities of design instead of discrete instances. Therefore, it can easily be said that Le Corbusier had produced parametric algorithms capable of generating unique projects.

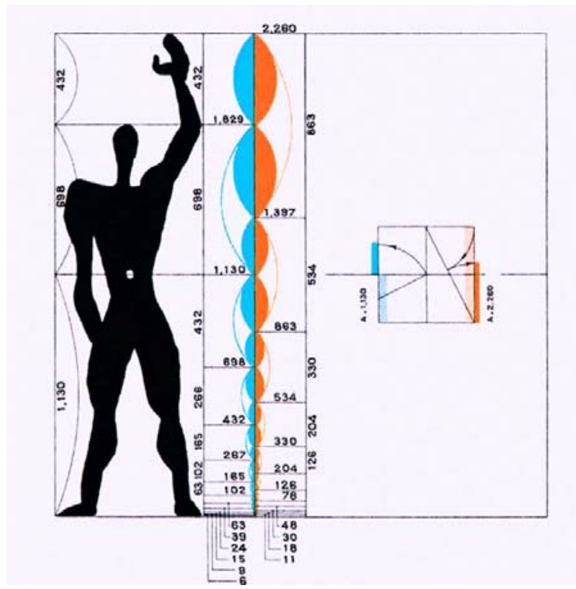


Figure 26. Diagram of Le Corbusier's "*The Modulor*" (colored by the author) (Gargiani, Corbusier, & Rosellini, 2011, p. 164).

Another central actor for the implementation of standardization and mass production in architecture was the "Bauhaus School of Design" in Weimar, which had been active between 1919 and 1933. It was established by Walter Gropius, who is also the architect of the Bauhaus's second building in Dessau in 1926 (Baumann, 2007). Bauhaus was a response to the post-war situation of arts and architecture, aiming to correlate architecture with the industry. The products of Walter Gropius and Bauhaus covered a broad range of areas in addition to architecture, such as kitchenware, chess sets and children's toys (Schuldenfrei, 2013). Bauhaus's primary intention was to integrate arts and industry by teaching its students the mass production techniques and industrial processes through hands-on experience. The courses and integrated workshops included carpentry, glass, pottery, metal, weaving, stage design, and painting (Bayer, Gropius, Gropius, & Newhall, 1938).

Modern Architecture has been shaped around the concept of standardization. The orthogonal “form” had been an unavoidable outcome of the aim of achieving a standardized quality in design and construction processes. Leaving aside subjective interferences of the architect into design through curvilinear forms, which also lead to an ill-defined course of construction for the undeveloped means of the time. The choice for orthogonal geometries and standardization in Modern Architecture has also introduced a distinct configuration of “form” composed of only “parts.” The “parts” can be clearly identified in most of the works of Modern Architecture through discrete, repeating, geometrical shapes. The “parts” signified in this context can either be slabs, columns, walls, openings or staircases; each of which can be denoted as topological equivalents of planar, rectangular, circular or prismatic forms.

A later implementation of standardization is “Habitat 67” in Montreal, Canada, designed by Moshe Safdie. It is a highly intricate version of *Unité d’Habitation*. Instead of unidirectional arrayed units with a single corridor at every story, “Habitat 67” governs combinations of prefabricated concrete rectangular prisms in varying numbers with discretized circulatory elements. Although the planned complex had more than 900 units, only 158 apartments from 354 units were constructed, with each apartment being a combination of up to eight units (Gössel & Leuthauser, 2012). If each unit is regarded as a “part,” there are 158 different “forms,” creating the intermediary “forms” and they end up with a single organic “form” from standardized units.

Figure 27. Habitat ’67 in Montreal, Canada (Cotter, 2016, p. 14).

Pier Luigi Nervi, on the other hand, is a pioneer for employing standardization in industrial, architectural structures in the mid-20th century. Nervi has commonly utilized standardization in his projects through formwork elements and modules implemented in his designs. Although the differentiations in “form” from their orthogonal counterparts had severely complicated the construction process, Nervi had overcome the complex formal issues through geometric standardizations (Huxtable & Nervi, 2011). Hangar for Italian Air Forces in Orvieto, Italy, is one of his most unconventional projects, because of its nonorthogonal formation in a rectangular plan and Nervi had utilized a standardized formwork throughout the structure, also leading to structural advantages. Standardization of the scaffolding elements had enormously speeded-up and decreased the cost of construction (Nervi, 1956).

Figure 28. Hangar for Italian Air Force in Orvieto, Italy (da Sousa Cruz, 2013, p. 15).

Standardization continues to play a central role in architecture because of its advantages in economic terms, ease of manufacturing, means of construction, and an increased rate of compliance of "parts" to each other. Although standardization has been denoted at the level of "parts," it can also be superseded to "form," in which standardization takes place by repeating a complete set of "parts" in varying scales, materials, contexts, and functions.

3.4. The Concept of Non-standard

The term "non-standard" was introduced in 1966 by mathematician Abraham Robinson, through infinitely small numbers, infinitesimals, and incredibly great numbers (Robinson, 1966). Apart from mathematics, the term "non-standard" has started to be used in architecture from the beginning of the 21st century, following an exhibition *Architectures Non Standard*, in Pompidou Center, Paris, curated by Frederic Migayrou and Zeynep Mennan (2003). The exhibition housed 12 design offices; Asymptote, DECOi, DR-D, Greg Lynn FORM, kol/mac, Kovac, NOX, Objectile, ONL, R&Sie, Servo and UN Studio, all of which are considered as precedents of non-standard architecture.

A non-standard form can be defined as an experimental result of an innovative process achieved through digital technologies. Such forms display the potential of the CAD/CAM technologies in the design and manufacturing processes. Mario Carpo defines non-standard as the series of forms that are composed of minute changes between each element, in which instead of the forms themselves, small differences create the whole (2005). He concludes that the non-standard production is the mass-production of non-identical parts, hence the direct opposition to the "standard" (2005). The introduction of algorithms and their implementation in CAD/CAM techniques have allowed even a single algorithm to create an enormously large set of non-standard family of forms (Terzidis, 2006). Each element of the family turns out to be different from one another, but any member can be easily identified in a family of forms, and it still carries out the common genetic codes that build up the family (Carpo, 2011). It is this property of the non-standard that it can also be described through information workflow. For non-standard projects, the processing of the data required for production is redefined for each individual case, making the realization process a non-standard one (Williams, Stehling, Scheurer, & Gramazio, 2011). The capability of manufacturing variations in an economical, precise and fast manner was one of the most crucial problems for non-standardization to be overcome until the end of the 20th century.

Prior to technological developments, a design consisting of numerous alternatives with small differentiations could have been conceived; but the production of those variations was not plausible neither timely nor economically. Unlike mass production, mass customization allows manufacturing a series of diverse items with speed close to mass production technique, together with economic advantages. In this context, mass customization is a step further of mass production, in which the end-products are varied from each other in small amounts that do not completely differentiate the products, but enough for the specialization of each product (Carpo, 2011). The concept of mass customization was first mentioned by Stanley M. Davis in his book *Future Perfect* (1987). Mass-customization could not become an integral component of industrial production due to the technological possibilities of 1987, but the anticipation of Davis was highly innovative. Mass customization has been achieved in apparels, food industry, and industrial design objects, prior to the actual incorporation in design and architecture. This has not been possible until the introduction of computer-aided design (CAD) and manufacturing (CAM) techniques.

Together with the computer-aided manufacturing (CAM) techniques, non-standard forms have started to get produced with improved speed, cost, and precision. The minute differentiations and details of any "form" could be computed and executed in the manufacturing processes, depending on the capabilities of the manufacturing machine. The possibility of varying an item at the speed of mass production techniques with reasonably close costs has presented huge potentials for designers. A proper CNC machine can manufacture 1000 identical objects approximately at equal amount of time, material and cost with manufacturing 1000 unique objects

(Kolarevic, 2003). Although Mario Carpo criticizes mass customization for the lack of necessity for differentiation as long as the function of the items does not change (Carpo, 2011), once the focus is shifted to mass customization of “parts” in an architectural project, the differentiation of parts’ shapes inevitably brings forth the necessity to customize each “part.” It is through this type of variation among “parts” that enables the construction of non-standard “forms” in an economical manner.

3.5. Implementations of Non-standardization in Architecture

A non-standard form is dependent on two aspects: its design and its implementation. While the former has been achieved through computers and software at the end the 20th century, the technologies for the latter matured much later. The asynchronistic quality among the two aspects can be followed in non-standard projects’ differentiations in ten years. Among the 12 participants’ projects exhibited in “*Architectures Non-Standard”* (Migayrou & Mennan, 2003) in 2003, most offices focused on “form,” by achieving non-standard geometries, leaving aside the considerations required for the manufacture and the assembly of the designed projects. Within ten years, the focus of attention for non-standard projects has shifted, leaving the “form” and strictly emphasizing the aspect of “how?” (Figure 29). From 2007 and on, Gramazio Kohler Architects have devised numerous projects dealing with the technique instead of “form” and even denoting formless proposals. In their façade design for the headquarters of Keller AG Ziegeleien in Pfungen, Switzerland, Gramazio Kohler has utilized robots for the positioning and orienting of each brick, enabling any “form” to be constructed.

Figure 29. Twisting brick façade of Keller AG Headquarter in Pfungen, Switzerland (Naboni & Paoletti, 2014, p. 85).

In 2003, Bernard Cache introduced an interface for the design of customizable coffee tables, named *Tables Projectives,* and an integrated manufacturing system using planar timber boards, in which the users could customize the dimensions and the shape of their tables, and instantly manufacture, pack and get the desired table they wanted (Carpo, 2004) (Figure 30). The proposal is considered to be the first implementation of mass customization in the design industry. The tables were different from each other in terms of geometry but topologically equal. At the time, the proposal did not draw the desired attention from the customers, but it is considered as a milestone for mass customization in architecture. *Tables Projectives* was more focused on the customization of the design process, because of its utilization of conventional CNC techniques of the time. However, the possibility of differentiating instances of a model demonstrated an important aspect of architecture. It is questionable if the geometry of *Tables Projective* displays a non-standard form, but the non-standard quality of the formation process with its mass-customization qualities evidently presents a non-standard one.

Figure 30. Three alternatives of *Tables Projectives* (Carpo, 2004, p. 55).

The development of mass customization has revolutionized and would continue to revolutionize the industry. However, for architecture until the second decade of 21st century, as in the case of *Tables Projective*, mass customization has taken place at the scale of “parts.” Mass customization on the scale of “form,” attaining groups of implemented design variations, would be a more radical breakthrough. In this context, it can be said that Le Corbusier’s approach in *Maison Dom-ino* as early as 1914, has also been an early attempt to achieve mass customization on the scale of “form.” In a broader sense, the attempt was to establish a common structural foundation for any design. Therefore, *Maison Dom-ino* was an exceptional instance for both mass-production and mass-customization at the beginning of the 20th century. While any orthogonal concrete frame system may carry out properties of *Maison Dom-ino* as in a mass-production system, their façades may display traces of mass-customization. Many architects, even perhaps unconsciously, have repeatedly customized the system of *Maison Dom-ino*, for its highly generic configuration.

There has always been a direct dependency between methods of production and products of architecture. William J. Mitchell states that the relation of designs and the finished products rely on the fact that “architects tend to draw what they can build, and build what they can draw” (2001, p. 354). Consequently, progressions in both CAD / CAM have dramatically altered the extents of what architecture can be. Like CAD, CAM techniques in architecture has also started to be developed from mid-1990’s on (Dunn, 2012) and Frank O. Gehry commonly adopted the techniques in his several projects. Guggenheim Bilbao Museum, 1997, (**Error! Reference source not found.**), Experience Music Project, 2000 (Figure 32) and Walt Disney Concert Hall, 2003, (Figure 31) have all required immense amounts of computation and labor to be rationalized, optimized and manufactured (Lynn et al., 2013) to the unconventional forms of the projects.

Figure 31. Walt Disney Concert Hall in Los Angeles, USA (Kolarevic, 2003, p. 111).

Figure 32. Experience Music Project in Seattle, USA (Januszkiewicz, 2016, p. 498).

3.6. Fabrication of Standard and Non-standard Geometries

There are various manufacturing techniques used for architectural purposes in varying scales. The most common and the earliest of all are the 2 or 3-axis CNC cutters. The “axes” in a CNC machine are the possible directions it can perform the defined action, i.e., cutting, milling, routing, etc. and while the initial two axes are basically X and Y directions in an orthogonal orientation, the third axis is introduced as the depth wise movement, the Z direction (Iwamoto, 2013). The 2-axis machines are suitable for cutting planar materials with a wide variety from paper to glass and steel, depending on the properties of the machine’s cutter. In addition to the possibilities offered by 2-axis machines, a 3-axis CNC machine has the capability of carving and milling, and it can produce relief-like forms from 3D blocks by subtractive fabrication techniques.

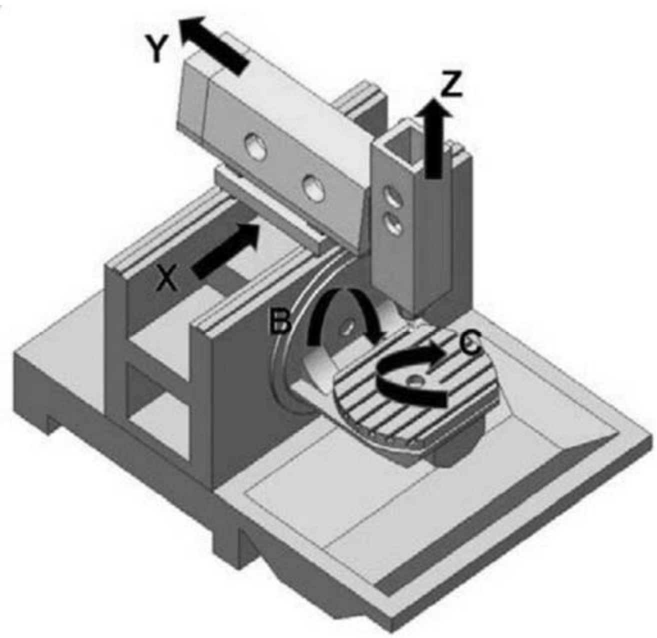


Figure 33. A five axes CNC machine diagram (Bologaa, Breaza, Racza, & M., 2016, p. 185).

Besides 2 and 3-axis CNC machines, there are other devices with further possibilities. Any added axis to a CNC machine introduces new maneuvers, hence new sets of “forms” to be manufactured. The additional 4^{th} and 5^{th} axes, B and C axes, rotate the table where the cut material is positioned, presenting new directions of cutting and milling. Moreover, the introduction of the 6^{th} axis substantially shifts the way a machine performs, together with its capabilities. A 6 or 7-axis CNC machines are also called “robot-arms,” because from a fixed point of operation they can freely move around like a human arm. The last axis introduced in a 7-axis “robot-arm” operates through the rotations of the stool. Besides the mentioned 7-axis, no additional axes are needed and introduced, because the maneuvers presented by other axes would only repeat previous axes’ already attained qualities.

Figure 34. A 6-axis CNC robot arm (Naboni & Paoletti, 2014, p. 72).

The “Robotic Wood Tectonics” project is an experimental implementation of timber beams, manufactured via a 6-axis robot-arm (Yuan & Chai, 2017). The assembly consists of 16 individual beams, which are composed of laminated wooden layers. Each rib is shaped by the robotic arm from all its sides according to the curvature continuity of the final surface, together with the milling of the required slits to attain the intersecting-parts quality. Although the form of the implemented assembly is highly curvilinear, the procedure is, in fact, a formless one; as following the same sequence of steps, one can attain any “form.” The approach is important because Yuan and Chai show the possibility of assembling a number of beams in a perpendicular fashion; while the number of beams, form of the structure, or depth and width of beams are not taken into account.

Figure 35. Robotic Wood Tectonics Project (Yuan & Chai, 2017, p. 45).

Another significant manufacturing technique is the rapid-prototyping (RP), which is an additive manufacturing method (Knaack, Strauss, & Bilow, 2010). There are various types of RP machines, but most of them follow a common simple logic: creating a 3D object by casting successive thin layers from a powdered or a plastic material. RP machines were limited to small-scale constructs, mainly intended to attain prototypes, as the name indicates through materials like polymers, ceramics, metals and even concrete. Although RP was initiated as a machine suitable for small-scale constructs, by combining a large-scale robot with concrete, RP has overcome the dimensional limitation. A larger scale in-situ RP machine can manufacture houses in a serial fashion with highly reduced costs when compared to ordinary construction processes with discrete parts and workers (Khoshnevis, 2004) (Figure 36). Such operations may be the key approaches in attaining mass-customized "forms" in architecture, for the complexity of "forms" does not differentiate the construction process accomplished via RP.

Figure 36. Partial rapid-prototyped house construction detail (Reinhardt, Saunders, & Burry, 2016, p. 96).

The recedence of dimensional and shape-wise qualities can be considered as the primary advantageous outcomes of CAM techniques. A CAM device can produce any geometry in any dimension, remaining within formal and dimensional specifications. As long as the geometry to be manufactured remains within the machine’s limitations, the shape of the geometry is not a criterion and any additional degree of axis definition allows manufacturing of further geometries, together with the ones remaining within the scope of machines with lesser degrees of axes. Except for the last example of large-scale RP machine, a CNC machine cannot manufacture a building and this results in the shift of interest from “form” to “part” and the “parts” means of assembly. This has also led to the introduction of concepts like “discretization” and “rationalization,” the former for generating the “parts” and the latter for organizing the whole family of “parts” suitable for the criteria of manufacturing.

Discretization is the transformation of a continuous body into distinct “parts.” For the vast range of scale in architectural design, discretization is an essential component of the architectural production. Particularly for freeform buildings, a higher degree of discretization is required because of their differentiating geometries. Discretization brings forth the feasibility of the construction together with the possibility of lowering costs of building part manufacturing (Stavric, Wiltsche, & Freissling, 2010). Additionally, there are studies, aiming for the production of the building as a whole in-situ through large scale “printers” without any need for additional discretization processes (Knaack et al., 2010; H. Schimek, Wiltsche, Manahl, & Pfaller, 2013). Although “printers” are capable of creating any non-standard form, currently, they are trying to imitate the formal language of standardized production techniques, i.e., buildings “printed” through rapid-manufacturing technology that has a “standardized” look when completed. However, it should be noted that the possibility of producing non-standard forms does not necessarily obsolesce the existing means of discretization and standardization, but instead, both approaches will coexist for their particular advantages and hindrances.

Rationalization is the successive step of discretization. As discretization solely represents separating the overall form into discrete parts, a process for rationalization is needed to systematize the “parts” depending on various criteria, like the type and dimensional limitations of CAM machine used, or the material used for manufacturing. Although there is the possibility of customizing each part during the design and fabrication processes, and time and labor required for such non-standard “parts” and “forms” have been profoundly lessened; the cost and time needed for the fabrication processes are still beyond the desired levels

(Scheurer, 2010). Therefore, in addition to the discretization methods, rationalization becomes a crucial phase of the design process. It has been observed that studies regarding discretization and rationalization made in recent years have mainly focused on panelization of freeform surfaces for discretization, and rationalization of those panels (Cabrinha, 2005; A. Kilian, 2003; Manahl, Stavric, & Wiltsche, 2010; Postle, 2012; H. Schimek & Meisel, 2010). The relation of the two with "form" displays a unique arrangement. While the process of discretization does not have an effect on the "form" and it only functions as a generator of "parts," the rationalization process inevitably alters the discretized "parts" and hence affects the "form." As the rationalization process requires specific arrangements for "form" and "part", a generalized group of actions cannot be presented. On the contrary, each discretization technique has unique qualities regardless of the "form" it is applied to. The discretization techniques covered in this chapter are the simplest ones, yet they are capable of creating highly curvilinear and non-standard "forms," and they have been implemented in architecture even before the introduction of CAD / CAM techniques.

However, the factors included in this subchapter are mostly introduced by CAD / CAM technologies, which affect the quality of manufacturing processes. Although architecture has been presented with a new library of "forms" with CAD / CAM, architects still have to consider the factors related to "parts," as they are the principal constituents of any "form." Regardless of whichever technique is used, there are several typical criteria to be followed in computer-aided generation and manufacturing of "forms."

Prior to production, the “parts” have to be rationalized for some conditions. As long as discretization is applied to a “form,” there would be “parts” generated, and the most important criterion is ensuring the curvature continuity of the final, to be assembled surface. As a natural consequence of the discretization process, a “form” is represented by another cluster of “parts” and this may end up with the weakening of the surface continuity. Therefore, adjustment of “parts” may be necessary. If needed, the “form” has to be altered according to curvature criteria or the “parts” can be modified manually according to the desired effect on the final surface.

Since there are various techniques for the production of “parts,” the most critical question becomes which technique to adopt in the manufacturing process. With the developed technologies of CAM machines, a “part” or “form” can be manufactured via most of the machines. A 7-axis robot arm can perform as a 2-axis cutter or a 3-axis milling machine, but it would be illogical and irrational to lessen the capabilities of a machine. Therefore, selecting an appropriate device is the most crucial decision and it would ultimately define the quality of the manufacturing process, produced “parts,” and the final “form.”

If the “form” is going to be assembled through discrete “parts,” and the “parts” are going to be manufactured in a 2-axis machine, the most important factor is the planarity of discretized “parts.” It should be checked carefully because the lack of planarity will deform the final “form” together with some problems that occur during the assembly. Following the assurance of planarity, “parts” have to be nested into sheets with predetermined dimensions. A successful nesting process directly affects the material efficiency and decreases time and energy required for manufacturing.

Although for most of the presented techniques, standardization does not have a substantial effect, it is sometimes still an important criterion to consider. As long as the final “form” is suitable to adopt standardization, even partially, it would cause some advantages in the manufacturing process, besides the simplification benefits in the assembly process. All aforementioned criteria are related to the increased material use efficiency, with reduced time and energy, and improved formal curvature quality of the constructed surface, together with a problem-free manufacturing and assembly process.

3.6.1. Contouring and Sectioning

The first and the simplest techniques used for discretization are the sectioning and contouring techniques. Although similar in logic in terms of their implementation of numerous successive sections in a “form,” the two techniques are differentiated from each other by the way sections are produced and the way material is used. While sectioning utilizes two-dimensional planar materials to create sections, contouring uses three-dimensional forms and carving successive contours on an object (Dunn, 2012). Because both techniques are subtractive processes, they are regarded as inefficient in terms of material use (Iwamoto, 2013).

Contouring technique imitates a sculptor by its need for having a solid block material. Unlike a sculptor, who carves away a block in a random order, contouring removes unnecessary material starting from the top level and going down, reaching to the desired three-dimensional object at the end. The fineness of the milling tip determines the height of each level together with the resolution and the precision of the final product, and the total time required for the process. Contouring technique requires at least 3-axis CNC milling machines, because of the need for milling. It should be noted that, as long as the parallel quality of the contours of the object remains, they do not have to be parallel to the ground. Vertical or radial parallel contours also fulfill the requirements of contouring.

The topography models carved from a single block can be resembled to the early examples of architectural relief-like models and the parallel contours can be seen on the model (Figure 37). Although the end result is completely identical to a conventional topography model, in which numerous layers are produced and joined through sectioning, the creation process for contouring is highly different. Instead of cutting each section separately, the topography model is carved from a monobloc material. While building a terrain model out of contouring is not considered as an example of sectioning, joining the sections together for creating a single mass generates a case of both sectioning and contouring.

Figure 37. A topography model made by contouring (Dunn, 2012, p. 138).

Due to the way contouring technique is applied, the scale of the manufactured objects is limited with the dimensions of CNC machines. An early example of automated contouring technique is a timber desk, name “mTABLE,” by Gramazio & Kohler, manufactured by a simple 3-axis CNC milling machine(Gramazio & Kohler, 2008). Being the first part of a series of user customized daily items, “mTABLE” could be specialized by users interacting with the interface accessible via a cell phone. In terms of contouring, Figure 38 shows the effects of the varying heights of levels on the formal qualities of the product, ranging from discrete vertical sides to a continuous smooth surface. Contouring is the simplest technique because it can be connoted as an automatized version of a simple model-making technique in architecture.

Figure 38. mTABLE (Gramazio & Kohler, 2008, p. 15).

Sectioning, on the other hand, is an enhanced version of contouring, in which there still are successive contours, but the contours do not form a singular monobloc object. The intervals of the sections are not manufactured but instead, are connected via additional elements and are left void. Sectioning technique was an invention of ship industry since the Middle Ages and it is still being used, together with the aircraft industry, to form the curvilinear forms of both (Eyres & Bruce, 2012). In the shipping industry, following the construction of the infrastructure of the ship hull, it is covered by linear timber elements are positioned and bent on the hull to achieve a watertight “form.” The same procedure is applied in the aircraft industry, planar metal sheets replacing linear timber elements in this case.

At the scale of architectural implementations, sectioning technique is mainly a method for attaining surface structures and is studied extensively in the literature (Bollinger, Grohmann, & Tessmann, 2010; Griffith, 2006; Pottmann, 2011; Schwartzburg & Puly, 2011; Sowa, 2004). The technique involves the creation of cross-sections of the aimed surface in singular or varying directions. The planar quality of the cross-sections lead to the production of single-curved ribs. These ribs can be manufactured with equal ease to double-curved ones and a sectioning assembly has the capacity of augmenting structural properties of the surface, due to their rib-like quality (Bechthold, 2008). By connecting the parts to each other through various methods – interlocking, mounting, laminating – the final surface structure can be attained in an easy and economical manner. Le Corbusier had also utilized the same technique in *Notre Dame du Haut* to simplify and solve the construction process of the complex roof form (Figure 39). A more contemporary example, “Robotic Wood Tectonics” project is also a typical implementation of sectioning (Figure 35).

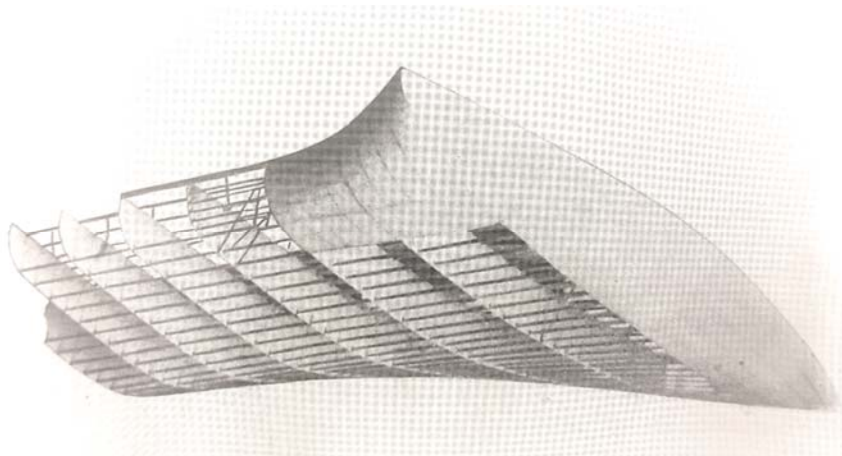


Figure 39. *Notre Dame du Haut'*s roof construction detail (Ford, 1996, p. 190).

Although sectioning may imply smaller scale constructs, it is being widely used in large scale architectural projects. Sectioning technique is mainly limited to the dimensions of manufacturing techniques and materials, therefore attaining a “part”-wise construction leads to overcoming the scale related limitations. In “Yokohama International Port Terminal Project,” dated 1995, a similar stance has been taken by Foreign Office Architects (FOA). By implementing the sectioning technique, numerous cross-sections of the amorphous terminal building were calculated and FOA managed to build the desired form through discrete formwork elements (Figure 40).

Figure 40. Yokohama International Port Terminal in Yokohama, Japan

(Groenendijk & Vollaard, 2009, p. 140).

Metropol Parasol project is a timber structure located in Seville, Spain, designed by Jürgen Mayer in 2010, which displays a successful implementation of the sectioning technique in urban scale (Figure 41). The structure has a span of 150 meters by 74 meters with 28 meters height and is composed of over 3400 elements, created by 180 cross-sections (Koppitz, Quinn, Schmid, & Thurik, 2011). Sections that run through the structure are located in a bi-directional orthogonal pattern, creating a grid-like structure when viewed in the plan. As Mayer states, the final “form” of the structure resembles six mushrooms merged at the top and has a highly curvilinear quality. An orthographic projection of rib directions onto a surface is a deductive process omitting the formal qualities and specific formal requirements of the surface. In other words, because of the top-down process of rationalization through orthogonal sectioning, the contrasting characteristics of the overall “form” and the sections create problematic points of implementation, like the points with high curvature.

Figure 41. Metropol Parasol in Seville, Spain (Koppitz et al., 2011, p. 249).

3.6.2. Folding

Unlike sectioning and contouring, the folding technique is realized through a maneuver and it uses an operation to attain the desired shape instead of creating a new form. As its name denotes, folding is achieved by pleating a planar piece through two or more creases, and folding a piece of sheet material brings in structural integrity in the direction of folding (Dunn, 2012). As folding implies planar materials, CNC laser-cutters are commonly used for attaining folding patterns by etching the materials besides cutting.

Besides sectioning, Yokohama Port International Terminal has also utilized the folding technique in its structural organization and interior formation. By adopting folding technique into concrete beams, larger spans could be crossed and the folds also exposed in the cladding elements. The folding technique can be seen in the interiors throughout the Terminal's longitudinal section (Figure 42). Both cladding panels and concrete beams have produced a highly intricate geometry by a multi-layered folding process, which could be calculated by CAD / CAM techniques.

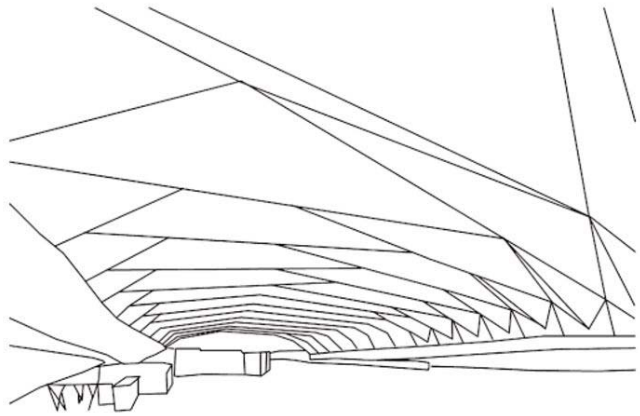


Figure 42. Yokohama International Port Terminal Interior (Hurol, 2015, p. 231).

A more monolithic approach to folding technique can be seen in UN Studio's *Theatre Agora* building, in which the formation process includes a folding approach to the overall "form." The building is constructed in 2007 at Lelystad, the Netherlands, with a steel structural frame construction and numerous standardized steel plates on its façades. Although the "parts" are not affected by the set of folding operations shaping the overall "form" of the building; the "form" has been entirely developed by folding. The folding operations have created various geometric encounters creating complex formations, but CAD / CAM techniques allowed the computation of surfaces and the "parts" in a rational and precise manner (van Berkel & Bos, 2008).

Figure 43. ***Theatre Agora*** **in Lelystad, the Netherlands (Groenendijk & Vollaard, 2009, p. 66).**

3.6.3. Tiling

Tiling can be considered as the oldest among mentioned techniques in architecture. The tile has been an integral constituent of constructions since antiquity for its vast range of possibilities and the constructed “form’s” structural integrity (Frampton, 1995). As long as the tile used in tiling technique is an ordinary rectangular prism and laid off in a regular pattern, the technique is highly simple, but it gets more complicated once the tiles are positioned in varying orientations and also when the tiles are produced in a customized manner. Henceforth, in addition to the overall “form” designed, “parts” also have to be both designed and manufactured and this presents an incredibly excessive range of possibilities (Iwamoto, 2013).

As noted in Chapter 2, both Pantheon (Figure 5) and “Church of Jesus Christ the Worker” (Figure 12) are extraordinary instances of tiling prior to CAD / CAM techniques, and both buildings have accomplished noteworthy tasks in realizing nonorthogonal “forms” through tiling. While Apollodorus had produced sets of standardized tiles for each row of the dome in Pantheon, Dieste had utilized standard tiles and achieved the complex geometry by varying the orientations of the bricks in his design.

A more contemporary implementation of tiling technique is applied in Horten Law Firm's Headquarters Building in Copenhagen, Denmark, designed by 3XN. The façade of the building is composed of numerous non-standard travertine tiles, creating a relief-like formation on the façade. Both manufacturing of the tiles and their installation required a precise process because of the diverse shapes and orientations of the tiles.

Figure 44. Horten Headquarters Building in Copenhagen, Denmark (Brownell, 2013, p. 33).

3.6.4. Forming

Forming is a more complicated and intricate technique when compared with the first three techniques, for it initially requires a preliminary "form," namely a formwork, to cause a secondary element to be formed. Although the forming technique has been used in architecture since the invention of plastic materials like plaster, concrete or plastics; it has been developed by the possibilities offered by the CAD / CAM (Iwamoto, 2013). In the forming technique, the abandonment of planar materials definitely presents a vast array of options. However, the process is critically dependent on the formal characteristics of the formwork and even the material that is going to be used in the final assembly befalls secondary.

An exemplary project implementing forming technique is the BMW Bubble Pavilion constructed for the International Motor Show 1999 in Frankfurt, designed by ABB Architects and Bernhard Franken (ABB Architects & Franken, 2008). Bernhard Franken describes the “form” as the fusion of two water drops, computed by using an animation software. The non-standard “form” has also necessitated the use of forming technique in the surface “parts.” “BMW Bubble” uses sectioning technique for creating the steel structural elements inside the acrylics-glass panels. The structure consists of 40 customized steel ribs at total and 350 unique double-curved acrylics-glass panels. While the ribs were manufactured from sheet steel, the production of cladding elements was a highly meticulous process. Each panel required a CNC milled timber block produced via contouring technique for its formwork and planar acrylic-glass was thermoformed to mold into the required shape (Figure 46). In the industry, those types of formworks are produced mainly for mass production purposes, but their utilization for the manufacturing of a single item increases the total cost of the construction process. Therefore, forming technique is not a preferable option for unique non-standard forms that are going to be implemented only once.

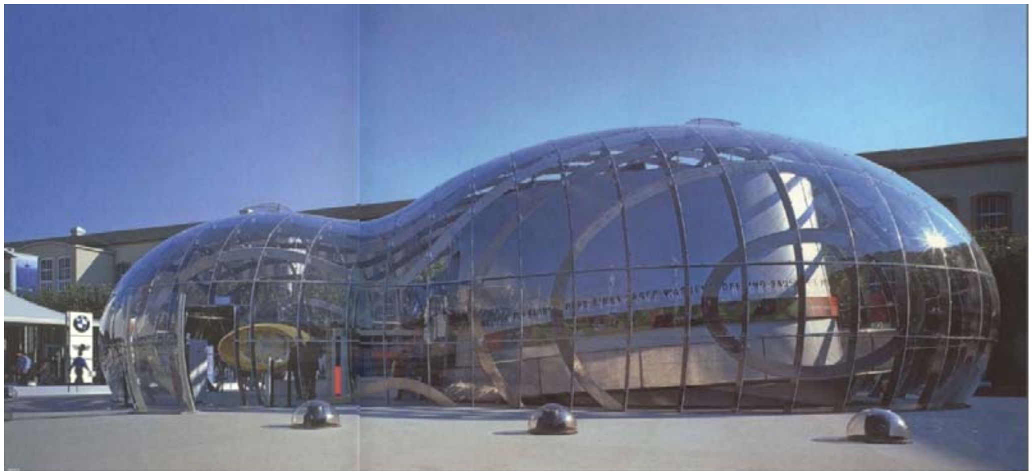


Figure 45. BMW Bubble in Frankfurt, Germany (ABB Architects & Franken, 2008, pp. 40-41).

Figure 46. Forming of acrylic-glass elements (Dunn, 2012, p. 152).

CHAPTER 4

FORM AND PART THROUGH STANDARD / NON-STANDARD: THE QUADRIPARTITE RELATION

"...what is the ground on which we are able to establish validity of this classification with complete certainty?"

Michel Foucault (2002, p. xxi)

A quadripartite relation has been proposed to analyze architectural works at any scale, by assessing the projects in a topological manner. The division investigates the constituents of design: the "parts," together with its totality: the "form," in terms of "standard" and "non-standard," the two most dominant qualities of industrial production of contemporary technologies. This approach generates a quadripartite relation, and it can classify any design, in one of those four groups.

Through the variations of "form" and "part" via "standard" and "non-standard," there occur four different interrelations in-between. The dual interaction of the two concepts creates a quadripartite relation; *standard form through standard parts* (1), *standard form through non-standard parts* (3), *non-standard form through standard* *parts* (4) and *non-standard form through non-standard parts* (2) (Figure 47). The groups are generated through the permutation of two criteria. However, the numbering and succession of these in the following subchapters are organized in chronological order, but this does not guarantee consecutive existence of each. Within the analysis, a case-specific stance is taken. There are some general outlines in the investigation of “form” and “part” for their denotation of either “standard” or “non-standard,” and it is through induction instead of a top-down definition for each quarter.

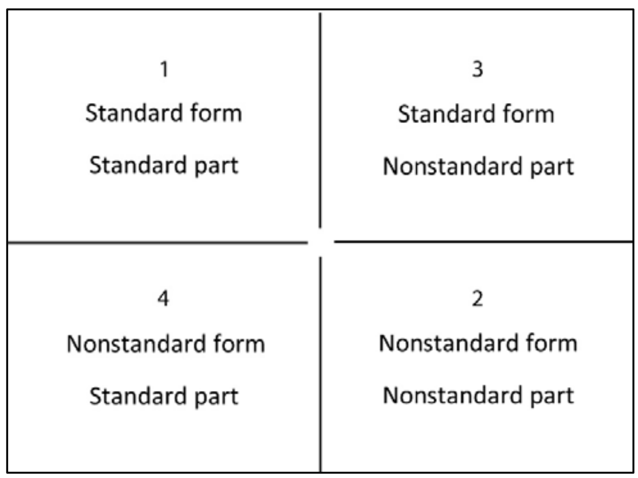


Figure 47. Quadripartite relation (Image created by the author).

The division considers standard formations of “part” as primary, for the advantages achieved in terms of economy, material use, ease of manufacturing, and assembly simplicity. On the other hand, for the “form,” non-standard has been prioritized and regarded as its typical understanding in architecture, through the unconventional shapes of designs.

The repeating quality of the “part” is the most central requirement. For the analyses, project specific positions are taken for the identification of “parts.” In a project, a “part” would be an element that is repeated many times in the construct. The repeated entity, hence the “part,” can either be a single brick, a glazing element, a slab, a whole story or even an entire building. The scale of the “parts” is not a criterion, but their formal properties have more integral roles within the analysis. Consequently, “form” is considered as the assemblage of “parts.” Contrary to the “parts,” “form” is considered as a construct’s geometric attributes at utmost scale. If there exist some intermediary “forms” compiled from “parts,” then they also signify “parts” at totality, which are going to build up the final “form.”

By analyzing the formal qualities of “parts,” their similarities and differentiations throughout, “standard” and “non-standard” conditions are obtained. If an element is repeated with a fixed form, it is considered as “standard.” On the contrary, if it is repeated throughout the project with the same function, but has minor or major changes throughout its instances, then they are denoted as “non-standard.” Therefore, depending on the formal characteristics of the final assembly, such a project will be classified under second or third groups in the quadripartite relation.

For the analysis, the concept of “standard” does not necessarily impose orthogonality. As CAD / CAM techniques have nullified the significance of form, in “parts,” standardization can also be attained via repeated curvilinear forms. Therefore, there does not exist a shape-wise approach in the proposed analysis, but rather a holistic consideration of “parts” that describes the degree of standardization. For the “form,” besides geometrical qualities, its level of geometrical complexity defines it is being standard or non-standard. A “form” is considered as standard if it is possible to be constructed without the assistance of CAD / CAM techniques, and if it ends up as a simple geometric formation or as a combination of several simple geometries. Whether orthogonal or not, a standard form may also include curvilinear geometries.

As an exceptional case for the analysis, if there is a single “part” in a “form” creating a monocoque structure, which can be produced via a rapid-prototyping machine, there occurs an equivalence of “form” and “part.” Then, the structure cannot be assigned to one of the classifications presented by the quadripartite relation, because of the lack of repeating the quality of the “part.” However, a classification is still desired, depending on the formal characteristics of the project, such a structure should belong either to the first or the second group, as “form” will also govern the “part.” However, such a classification would not represent any meaningful connotation as neither “part” nor “form” have standard or non-standard characteristics.

4.1. Standard Form – Standard Part

The first and the simplest partition of the proposed relation is the combination of standard form and standard part. The sample examined cases for this group commonly have repeating “parts,” whether as surface geometries or façade elements, creating a standard “form” at the total. The “form” can be perceived as a simple topological entity, like a prism, cylinder or a sphere. Although both the “form” and the “parts” are “standard,” the sample cases are not simple, ordinary constructs. On the contrary, they display highly complicated construction processes for the times in which they were built. The first sample case is *Unite d'Habitation* by Le Corbusier, and the second is the Sydney Opera House by Jøn Utzon.

Built in 1956 by Le Corbusier, *Unité d'Habitation* is a twelve-story high, concrete, mass-housing complex with 337 apartments, located in Marseille, France. Composed of a generic structural frame, section wise L-shaped units –the "parts"– are stacked as "bottles in a wine-rack" (Bergdoll, 2008, p. 98) on top and on the side of each other. The units are connected via central T-shaped corridors at every two or three stories. The only differentiation in the units' directions is at one end of the block, creating the T-shape of the corridor. Le Corbusier had also decomposed each unit into its components. The majority of the elements inside the units are constructed with precast elements through minute "parts," creating intermediary "standard" "forms." The differentiations among units are the entrance being either on an upper or lower story. Still for both cases, the entrance story is half-width, and the other story spans to both sides of the building with balconies. While the final "form" of the "parts" is a combination of two rectangular prisms with L-shapes, the "form" of *Unité d'Habitation* is a simple rectangular prism, making both "part" and "form" "standard."

Figure 48. *Unité d'Habitation* in Marseille, France (Gargiani et al., 2011, p. 192).

Another significant example for *standard form – standard part* is the Sydney Opera House by Jøn Utzon, which was a winning entry in an international design competition in 1957. The building was completed in 1973. It may seem controversial to classify such a building under standard form, but the analysis only evaluates "forms" through "parts," and the degree of standardization of both "parts" and "form" connotes the first group. The original design proposal for the building consisted of ten curvilinear shells, which were later transformed into spherical forms with a constant radius of 75 meters (Nutt, 2013). The project is categorized under standard form, because of these repeated spherical domes. The preference of a spherical shape with constant curvature was an outcome of several factors; besides decreasing the level of complexity of the construction process and considering economic criteria, the aim was to standardize "parts," both for eased manufacturing and assembly processes (Murray, 2003). The spherical forms of the vaults have enabled an enormous degree of standardization, together with their highly increased structural integrity. The “form” has transformed into a more regular one through the standardization of “parts” implemented into the construction (Figure 49). In the design and construction processes of Sydney Opera House, engineers had utilized computers to solve the highly complex calculations as early as 1960’s (Drew, 1995), which was more of a computer-aided engineering instead of CAD or CAM. As an inevitable result of the “form” of Sydney Opera House, despite its high degree of standardization, the total costs for the project have ended up 15-fold of the initial estimations (Watson, 2013). Although the impact of the building is highly unconventional, the project is denoted as a *standard form – standard part* within the analysis, because of its repeated spherical “forms” and their numerous standardized modules.

Figure 49. Sydney Opera House and a construction detail (Watson, 2013, p. 89).

For this category of the relation, the negligence of CAD / CAM and prementioned techniques was not a prior decision, but instead, it has been unavoidable. The introduction of CAD / CAM techniques has profoundly affected the formal possibilities that can be attained in architecture, completely altering the final products. Therefore, to further demonstrate the characteristics of the partition, both examples are chosen from pre-CAD / CAM period.

4.2. Non-standard Form – Non-standard Part

The second group in the analysis is *non-standard form – non-standard part*, as the exact opposite of *standard form – standard part*. The instances of this group have been the first implementations of CAD / CAM techniques. The early presence of rationalization with its immature qualities and the limited three-dimensional capabilities of the software along with the potential of manufacturing technologies have prevented architects to standardize neither the “forms” nor the “parts” in early projects.

Frank Gehry, the forerunner for the implementation of CAD / CAM techniques into architecture has achieved “non-standard” qualities on both “form” and “part.” As the first sample, Frank Gehry’s *Nationale Nederlanden* Building may be analyzed.

What Gehry has managed is a noteworthy achievement. Even though the industry was not yet utilizing CAD / CAM techniques, his attempts via CATIA have resulted in unconventional projects as early as mid-1990’s. *Nationale Nederlanden* Building; built in 1996, was one of the earliest projects of Gehry through CAD / CAM techniques. The building is a freeform structure, consisting of two primary “forms,” each with slanted, curvilinear facades. The structure on the left in Figure 50 is a transparent block, composed of the combination of two conical “forms” and cladded with uniquely shaped glass panels mounted on steel ribs. The glass elements were generated via a process of discretization and it can be considered as a product of tiling technique. On the contrary, the block on the right with its connected prism is an opaque structure with numerous standardized rectangular openings. There is a high need for accuracy to construct both structures and this was achieved by CAD / CAM techniques. The overall building is a free form non-standard structure, together with its non-standard glass panels. The openings and the planar façade are standardized, but the degree of standardization at the scale of the building is minute.

Figure 50. *Nationale Nederlanden* Building in Nové Město, Czechia (Bruggen, 1998, p. 118).

In one of Gehry's later projects, New York by Gehry, he has designed a 76 story-high residential skyscraper with a unique "form." The tower has a T-shaped plan and all façades, except one, are differentiated from each other with their curvilinear "forms." The curvilinear quality of the façades is attained via the sides of slabs and vertical opaque elements (Figure 51). Gehry has implemented sectioning technique at a large scale, by utilizing each story plate, hence the "part," as a section of the final non-standard “form.” All stories of the building have unique shapes, generating in-between non-standard “forms” and they are clad with discrete steel panels. In addition to the story plate “parts,” the project consists of 10500 unalike non-standard panels for story claddings, which did not involve a rationalization process. Contrary to the large number of unique panels, the final costs of the tower have ended up nearly equal to an orthogonal “standard” tower due to the potentials of the advanced software (Gehry, 2010).

Figure 51. New York by Gehry ("New York by Gehry rental gallery and model units now open amid high demand for luxury rentals," 2011, p. 129).

The Heydar Aliyev Center (2013), in Baku, designed by Zaha Hadid, is one of the most significant implementations of non-standard architecture with its roof’s ribbon-like geometry (Kara & Bosia, 2017) (Figure 52). The design is a combination of various curvilinear surfaces creating a fluid “form.” The construction process needed complex CAD software and CAM techniques to overcome difficulties of double-curved surfaces. The main structure of the building is built from reinforced concrete, and there are 16150 unique curvilinear skin panels (Winterstetter et al., 2015). Forming technique is widely used for the manufacturing diverse “parts.” The non-standard quality of both “form” and “part” created difficulties in both manufacturing and assembly processes (Januszkiewicz, 2016). The construction process for Heydar Aliyev Center required an increased amount of precision, to attain the continuous curvilinear quality of the final “form.”

Figure 52. Heydar Aliyev Center in Baku, Azerbaijan (Winterstetter et al., 2015, p. 65)

The combination of *non-standard form and non-standard part* creates a vast array of possibilities in geometric terms. As long as they are possible to be implemented, employment of double-curved geometries ultimately differentiates the formal qualities offered by CAD / CAM technologies. Both Gehry and Hadid design the “forms” of their projects via freehand drawings, which are later transformed, rationalized and discretized in CAD medium. Like Gehry and Hadid, regardless of the method used to generate novel geometries, architects governing non-standard forms, utilize freeform surfaces and try to overcome the difficulties faced in the manufacturing phases. The design and construction of a non-standard “form” could be considered as a challenge for the initial periods of CAD / CAM techniques, but currently the CAD / CAM techniques are far more advanced.

4.3. Standard Form – Non-standard Part

The third category in the quadripartite relation is *standard form – non-standard part*, and this kind of approach to a design solution is highly challenging in terms of design, manufacturing, and construction. Key features of the projects in this group are having numerous unique smaller parts constituting a much larger, single whole, hence the standard quality of the "form." The end result turns out to be analogical to a puzzle, in which each piece is differentiated with its unique position and makes up a totality. This category has highly similar properties with the previous one, because of the typical non-standard quality of "part." As long as architects decide to govern non-standard forms in their designs, the choice of reaching a standard or non-standard form does not differentiate the design and manufacturing processes dramatically.

Two sample cases are discussed in this category: the first being an early instance of standard form – non-standard part, Toyo Ito and Cecil Balmond's Serpentine Gallery Pavilion, which was assembled in 2002; and the second Beijing National Aquatics Center, built in 2008, by PTW Architects and ARUP. The significance of both designs lies in the complexity they govern in their design and construction processes. Although both examples have implemented rectangular prisms as their "forms," the way they were built encompasses a highly complex set of procedures, in terms of material use and detailing.

Serpentine Gallery Pavilion was constructed in Hyde Park in 2002 as a temporary structure and later demounted. However, the pavilion is widely acknowledged for its form, tectonics, and means of implementation. Although CAD / CAM techniques were not as developed then, the standard, orthogonal form of the structure has enabled its realization. The architects defined each “part” from four individual elevations and a single roof-plan. The surfaces of the pavilion were segmented into various subdivisions through angular, straight lines forming different types of polygons (Pottmann, Eigensatz, Vaxman, & Wallne, 2015). Tiling technique is utilized for the creation of facades, but instead of a repeating “tile,” a non-standard version is preferred. The planar quality of parts highly eased the manufacturing process, but the design and formation of the prism, as the final “form,” has followed a process akin to conventional ones, for having relatively less number of “parts.”

Figure 53. Serpentine Gallery 2002 in London, UK (Pottmann, Eigensatz, Vaxman, & Wallner, 2015, p. 160).

Beijing National Aquatics Center is constructed in 2008 and designed by PTW Architects with civil engineering services by ARUP. The project is a rectangular prism, composed of numerous units. PTW Architects has used the formation scheme of intersecting soap bubbles to design the outer skin of the prism (Burry & Burry, 2012). To construct the different curvilinear units of the prism, the architects have determined to use a unique tensile polymer material (Burridge, 2015), which reduced the complexity and the cost of the bubbles' manufacturing process, leaving only the need to construct the outer steel skeleton. The steel skeleton consists of more than 22000 elements, with different connection angles, hence also differentiating the connection details (Carfrae, 2006). Like Serpentine Pavilion, tiling technique is used in the construction. Although there are numerous different items, there still has been an effort to standardize the "parts," obtained through a pattern on the façades, but the degree of standardization is so minute that the "parts" are still regarded as non-standard. Also, within Beijing National Aquatics Center's neighboring site lies Herzog and de Meuron's famous Beijing National Stadium, and it is also composed of numerous non-standard ribs, generated via sectioning technique in a non-parallel fashion. The sections create a single standard form. Both structures are similar in terms of their relations in "form" and "part."

Figure 54. National Aquatics Center in Beijing, China (Whitelaw, 2010, p. 157).

The relation of *standard form and non-standard part* has a huge possibility of diverse formations. Although the form is limited with standard geometries, the way it can be decomposed into smaller constituents brings the possibility of differentiating each "form." It can also be seen in the above mentioned two examples. Although both share a simple rectangular prism "form," they do not even resemble each other at any aspect. This type of formation transforms the "form" into a secondary quality for the design and prioritizes "parts" through their varying geometries.

4.4. Non-standard Form – Standard Part

The final category of the quadripartite relation can be considered as the most current one, present in the tendencies in CAD / CAM implemented designs of contemporary architecture. Architects have started to be able to generate non-standard forms using standardized "parts," with the help of innovative uses of materials and geometry. One of the primary causes for preferring standard parts to devise non-standard forms is the increased possibilities in manufacturing and assembly procedures.

A generic type of discretization for getting standardized “parts” can be made by decomposing a “form” into its smallest constituents and achieving a pixel-like standardized quality in the “parts.” This also limits the form to a generic geometry like a prism or a sphere and the pixelation of a “form” inevitably creates incredibly large numbers of “parts” to build up the desired geometry. However, the automatized techniques can overcome highly complex combinations containing an extremely large number of elements. As, a CAM machine can complete a defined task repeatedly with equal perfection, quantity does not have significance for machines. By increasing the resolution of a “form,” hence increasing the number of “parts,” any “form” can be constructed with precision. The concept of precision plays a central role in these types of constructs; as the position, orientation and connection of the units define the final quality of the built “form.”

One of the first executions of discretization through “pixels” was accomplished by Fabio Gramazio and Matthias Kohler at the Winery of Gantenbein, in 2006 (Figure 1). The project consists of 72 rectangular frames, with each frame assembled from approximately 270 bricks with a total of 20,000 (Gramazio & Kohler, 2008). It is apparent that tiling technique is the formative operation for the panels. However, the vast number of bricks did not present a difficulty; on the contrary, it has resulted with high-resolution representations of curvilinear surfaces on the panels. The task was an achievement of six-axis robot arms and an automatized assembly process. The final products of the manufacturing have huge potentials to be universalized for the construction of any “form.” For Winery of Gantenbein, the production process and outcomes can be criticized as being solely relief-like surfaces, instead of having structural qualities. Nevertheless, it still has highly significant merits in terms of utilizing standard parts and reaching non-standard forms.

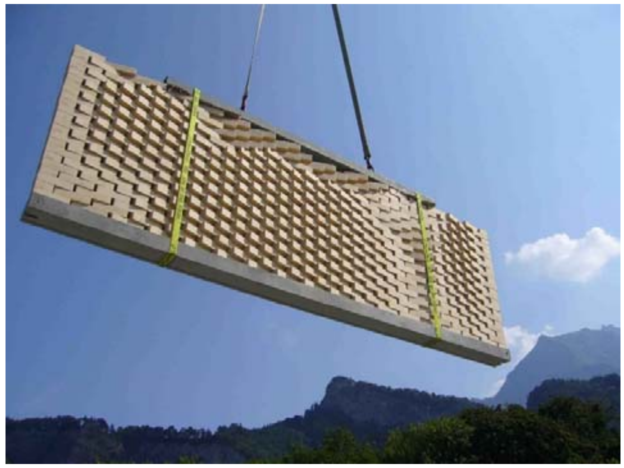


Figure 55. A panel of Winery of Gantenbein (Gramazio & Kohler, 2008, p. 98).

Later efforts for *non-standard form – standard part* have focused also on structural criteria of surfaces. The ongoing research at "Block Research Group," at ETH Zurich by Prof. Dr. Philippe Block devises techniques for surfaces performing structurally via curvilinear non-standard forms. The research implements vaults as its source of "forms," because of their intrinsic structural qualities by using tiling technique (L. Davis, Rippmann, Pawlofsky, & Block, 2012). The construction of the vaults is realized by arraying standard brick elements on falseworks, which are later dismantled. The diverse 3D orientations of blocks enable to construct a continuous curvilinear surface. Although research at ETH currently focuses only on non-standard "forms," the devised techniques can easily be simplified for regular planar surfaces. Therefore, the construction of standard forms can be considered as a subset of the implemented technique.

Figure 56. Vault prototype at ETH Zurich (L. Davis et al., 2012, p. 46).

Scale-wise extreme approaches to “part” display vital qualities of contemporary architecture; “form” is no more considered as an integral element of architecture, but instead, a secondary constituent, attained through “parts.” Through various techniques, architects have reached to a quality of formless designs, where they can realize any “form” without any change in the complexity of assembly, the required time for manufacturing or total costs.

Although a generic type of discretization other than reaching up to the smallest unit size cannot be addressed, there exist possible alternative approaches to discretization. Geometrically dependent alternative discretization techniques display highly advantageous results when compared with their conventional counterparts. While a generic discretization for a geometry may end up with numerous variations of “parts”; a geometrically dependent discretization can minimize the differentiations among “parts” and end up with a standardized solution. Regardless of the complexity of the geometry, it is asserted that there exist some intermediary scales of discretization, in which the “parts” have standardized qualities.

4.5. Assessment of Quadripartite Relation

The quadripartite relation demonstrates unique features of different variations of “form” and “part” in architecture. The analyses of samples date back to 1956 but, they can be extended to any period of architecture following the same methods of analysis. A limited number of works are included to quadripartite relation, but selected exemplary works have potentials to cover the aspects of each partition. Through the analysis, it has been shown that there is an evident tendency towards non-standard geometries in architecture beginning from the last decade of the 20th century, both in “form” and “part.” In addition to the propensity of architecture, the possibilities presented by CAD / CAM have considerably proliferated the attempts and implementations. The motivation for such an approach is significantly apparent for architects: the desire to overcome problematic states of “form” through established design and manufacturing techniques.

Architecture is now able to produce any form with ease with the help of contemporary CAD / CAM techniques. While CAM machines have highly developed and intensified within the last 30 years, the CAD processes are not completely automatized yet. Therefore, for some circumstances, they remain insufficient and additional actions are needed for discretization and rationalization processes manually.

CHAPTER 5

THE PROPOSED MODEL FOR NON-STANDARD FORM AND STANDARD PART

"Today, when architects calculate and exercise their thoughts, everything turns into algorithms!"

(Rocker, 2006, p18)

The significance of the combination of *non-standard form and standard part* for architecture is shown in the previous chapter via quadripartite relation. As a symbolic execution of the findings, a model implementing such relation is devised. The model introduces an algorithm that generates the surface structure parts of surfaces of revolutions. The main reason for the implementation of the algorithm on surfaces of revolution is that they are the simplest among other complex geometries but they also govern highly intricate non-standard geometries attained with complex cross-sections. In this study, while the algorithm is applied in two small-scale constructs, possible adaptations to larger scales will bring forth the model's further advantages.

In architecture, the definition of a surface infrastructure connotes highly critical information for the implementation's subsequent steps. Besides being the core component of an assembly, the infrastructure is the definitive constituent both for "form" and "part." While it presents the overall plastic quality of a "form," it also designates the "parts" that are going to be used on its outer surface.

Surfaces of revolution have a wide range of application possibilities in architecture for their relatively complex geometries (Steadman, 2015). The proposed model aims to present a geometrical variation for the development of infrastructures of surfaces of revolution beyond the geometric limitations of orthogonal configurations. The non-orthogonal quality of the proposed technique presents various advantages in terms of material use, standardization and assembly ease.

While a cylinder is a simple Platonic solid; a surface of revolution generated by an intricate curve creates a highly complex geometry. The implementation of the model overcomes the complexities offered by such a geometry and enables the production of the elements via simple, planar materials. Sectioning technique is used for the generation of the infrastructure and the discretization generated by the model is advantageous in terms of standardization, manufacturing, material use and assembly procedure. The devised model needs simple information about the surface, like the cross-section, number of parts and piece properties; and produces the shop drawings of the required elements for the assembly.

5.1. The Algorithm

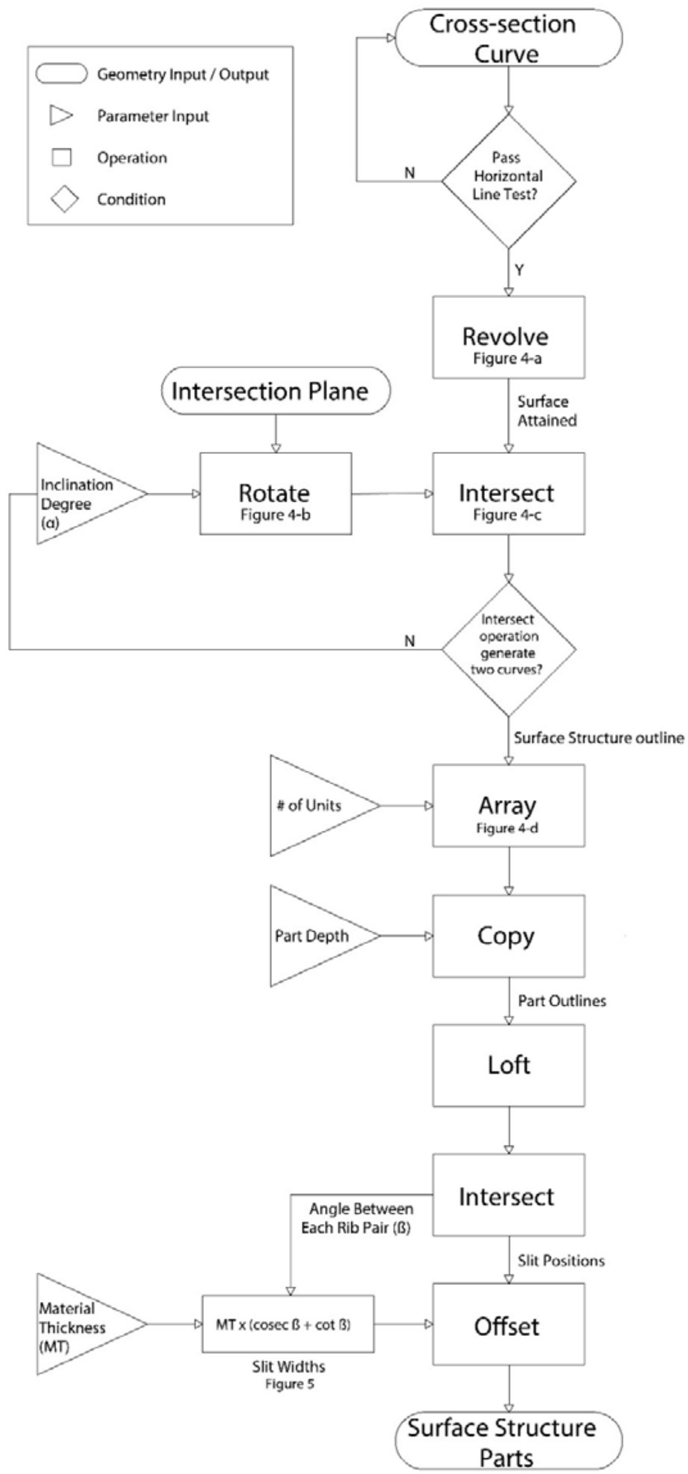


Figure 57. Flowchart of the algorithm (Image created by the author).

The algorithm is created in Grasshopper (www.grasshopper3d.com), which is a plug-in for Rhinoceros and the software has powerful parametric capabilities in generating variations through parameters. The flowchart of the algorithm is presented in Figure 57 and the screenshot of the Grasshopper code can be found in Appendix A. The algorithm can be implemented in any medium following the flowchart procedure as it is a generic geometric formation. The inputs are cross-section curve, number of ribs, inclination angle, the thickness of the material used and width of pieces. The input data are used to compute the ribbed structure of the revolved surface.

The algorithm begins with a cross-section curve, *c*, for the formation of the final surface of the structure (Figure 58A). Although *c* has to be disclosed and planar, it can be linear, curvilinear, continuous or even broken. There is only a single criterion that should be checked for the suitability of *c,* and that is the horizontal line test. While the horizontal line test is used for determining the characteristics of the functions in mathematics, here it is used for identifying the suitability of *c* for the algorithm (Figure 59).

In mathematics, horizontal line test reviews a function for the number of intersection points with all horizontal rays, parallel to the x-axis. The function succeeds if the rays either intersect the function's graph only once or do not intersect at all (Stewart, 2012). Similarly, within the context of this procedure, *c* is checked for the number of intersection points with rays perpendicular to the revolution axis, *y-axis*. The cross-section curve should be revised until it passes the horizontal line test. Following the horizontal line test, *c* is revolved around *y-axis* to form the outer surface of the structure. (Figure 58B).

In order to create the rib sections of the structure, the surface is intersected with an inclined *XY plane*, in which "the inclination angle" will determine the angle of the system's pieces (α) (Figure 58C). The intersection process produces a rib section curve on both sides of the surface (Figure 58D). Both intersection curves are then arrayed around the *y-axis* with the desired "*number of ribs"* creating the outline of the structure (Figure 58E). Although the section curves are mirror images of each other, for practical reasons, each group of arrayed section curves produces the inner and outer ribs consecutively. By offsetting the intersection curves towards the center, *y-axis*, rib sections form the rib outlines.

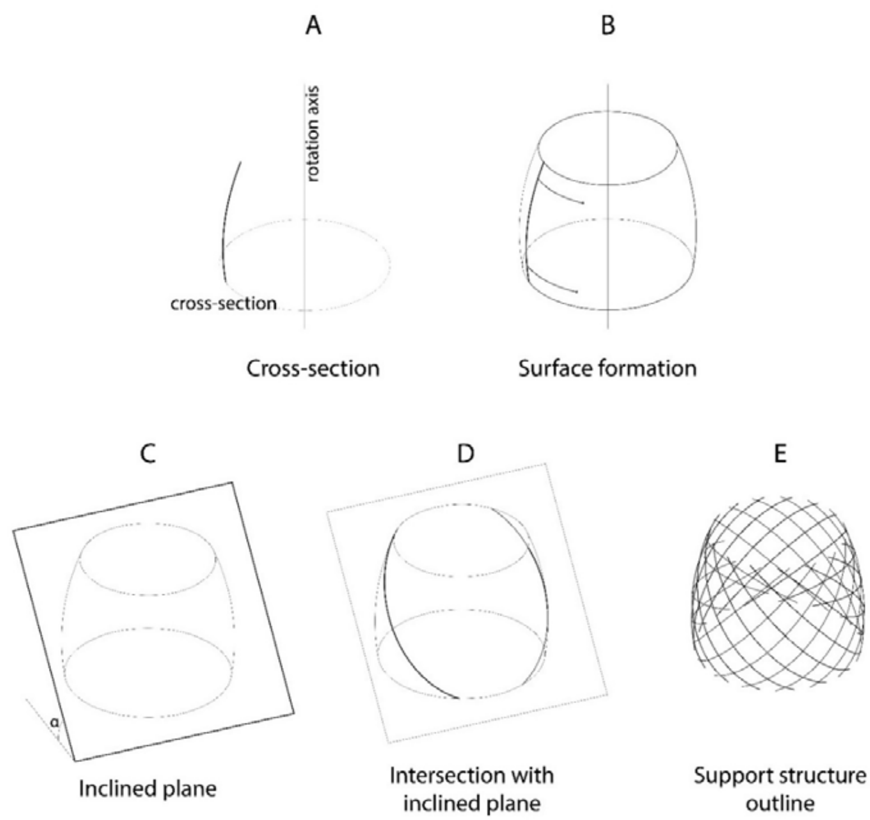


Figure 58. Formation process (Image created by the author).

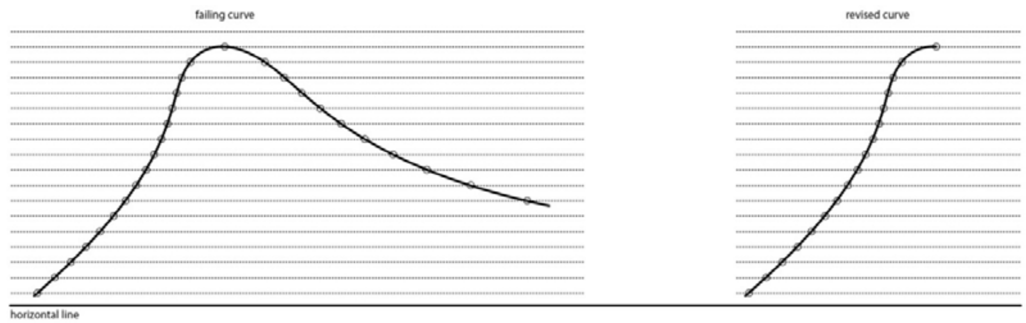


Figure 59. Horizontal Line Test (Image created by the author).

If the assembly is manufactured via two-axis CNC cutters, the slit sections would have vertical sections. The slit widths differ according to the thickness of the material and the varying intersection angles (ß) (Figure 60). The width of slits are found by a simple mathematical formula. Slit depth (SD) is equal to half of the piece depth (PD), but it can be differentiated as long as it keeps the intersection quality of the pieces. The slit widths (SW) are calculated with the following equation:

SW= Material thickness * (cosec ß + cot ß) where SD = PD / 2.

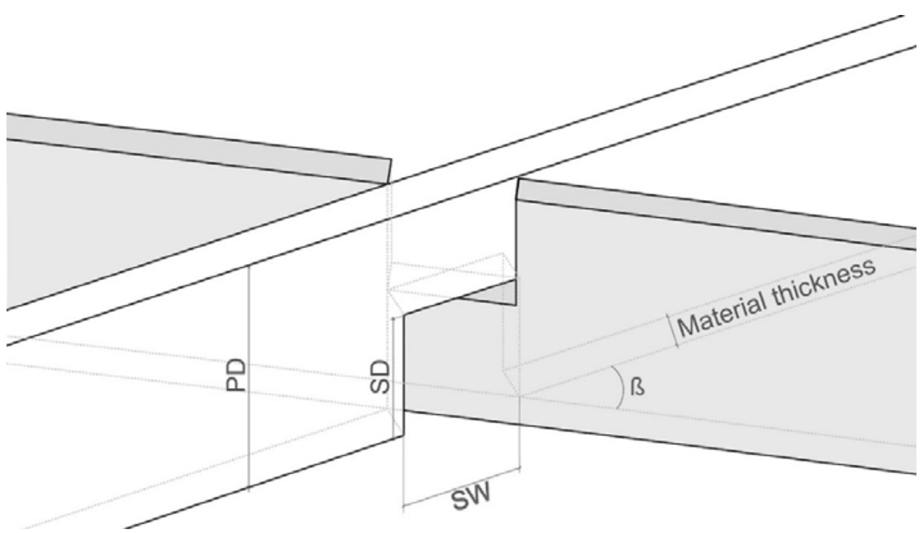


Figure 60. Slit formation detail (Image created by the author).

5.2. Implementation and Assessment

Two implementations are realized to demonstrate the potentials of the model. For the first one, a small-scale construct from cardboard is made, solely to show the interlocking quality. Additionally, a second implementation has also been carried out with the subdivision process to overcome the dimensional limitations of the CNC technology.

In the first implementation, for the cross-section, a concave arc with a radius of 750mm is used. It has a height and diameter of 540mm, and 28 pieces are manufactured from 2 mm thick cardboard by a 2-axis CNC laser cutter (Figure 61A). The assembly sequence of the structure follows a relatively straightforward procedure. The assembly process requires the consideration of some pieces as “primary ribs.” These pieces help the stabilization of the structure during the erection phase, but they do not differ in functional or formal terms in the final construct. Assembly of equally distanced three inner and outer rib pairs is enough for the preliminary stabilization of the structure allowing the addition of remaining pieces (Figure 61B). The assembly process of internal and external parts is defined by the connection of conjugate slits, i.e., first to first, second to second, etc. Because of the opposing and varying direction of slits, the assembly process should be done in a mixed sequence of inner and outer pieces. With every rib assembled, the structure gets more stable, increasing the overall interlocking of the parts (Figure 61C). Approximately, the placement of half of the pieces is enough for the stabilization, and the assembly of the last rib fully interlocks the structure (Figure 61D). A highly important criterion to be considered in the unsubdivided assembly sequence is the need for the elasticity of the material to attain the mounting of pieces, due to slits' varying directions. If the material used is not elastic, it would become impossible to intersect the pieces, as the directions of slits vary.

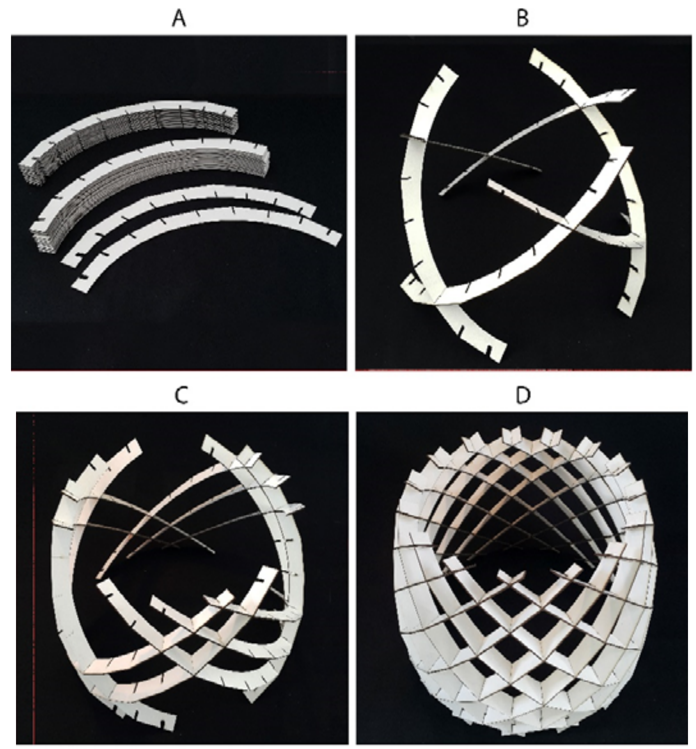


Figure 61. Assembly process (Image created by the author).

For the second implementation (Figure 62), a surface of revolution, generated by a convex arc with 1400mm radius is constructed. The diameter of the structure is 1150mm with the height of 1100mm, and it is manufactured from Medium-Density Fiberboard (MDF), 4mm thick. However, the model can be implemented with any planar material, and thickness. The size and number of elements can also be varied. For the assembly, a total of 28 ribs are used, and each rib is subdivided into 5 segments. The ribs were manufactured by a 2-axis milling machine from 6 MDF boards with dimensions 700 * 1000 * 4 mm. The assembly consists of 140 pieces, 5 for each rib. Additional mounting fixtures were required for reconnecting subdivisions. For attaining the stability of the construct, a pair of bolts and steel filler plate connections, with dimensions 15mm * 60mm * 1mm were used for each connection, with a total number of 224 (Figure 63).

Despite the excessive number of pieces of the structure, it has an extremely simple mounting procedure. There are only two types of pieces: inner and outer. The connection of coupled slits, which have the same counts, the primary elements are assembled. As in the case of the second assembly, fragmentation of ribs denotes an ordered assembly sequence beginning from the base and continuing with the mounting of successive elements, connected by filler plates.

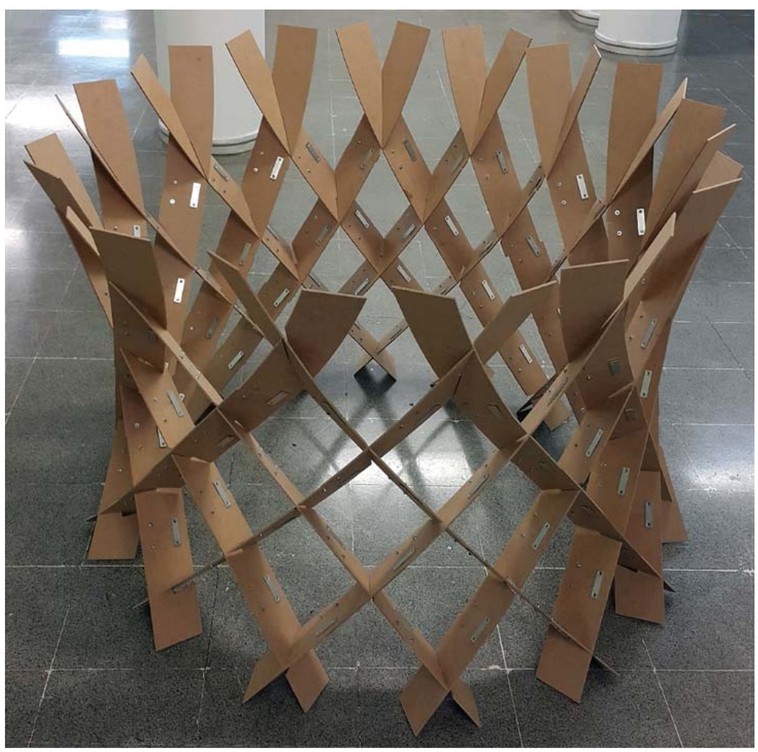


Figure 62. Assembled structure (Image created by the author).

Figure 63. Pieces' intersection and filler plate connection detail (Image created by the author).

To lessen the dimensions of the pieces, they can be divided from intermediary points in any number. It has been shown in the second assembly, butt connection technique is capable of performing required stability of the construct. There occurred only 4.3% differentiation between the digital model and the physical construct, with the radius of digital model being 575mm and the physical assembly's being 600mm. The necessity of an increased level of precision may also be obtained by fixing the construct with a foundation.

5.3. Variations

To further demonstrate the potentials of the model, several examples are shown via various parameters. As the number of possible variations builds up exponentially with the differentiation of the cross-section and parameters, only a limited number of examples are included. However, an ideal set of variables or the algorithm to operate has not been presented for this purpose. Instead, randomized variables are used. And it has been found that with any set of variables the model produces acceptable qualities in terms of planarity, nesting, material use and standardization.

In each figure from Figure 64 to 69, only a single parameter has been varied, and the rest of parameters have been kept constant for displaying the influence of parameter in a more distinct way. Six following figures present variations in cross-section, revolution radius, the inclination angle of the intersection plane, number of pieces, thickness and depth. For each variation, two exemplary pieces of the structure, one inner and one outer, are shown for demonstrating their nesting capability.

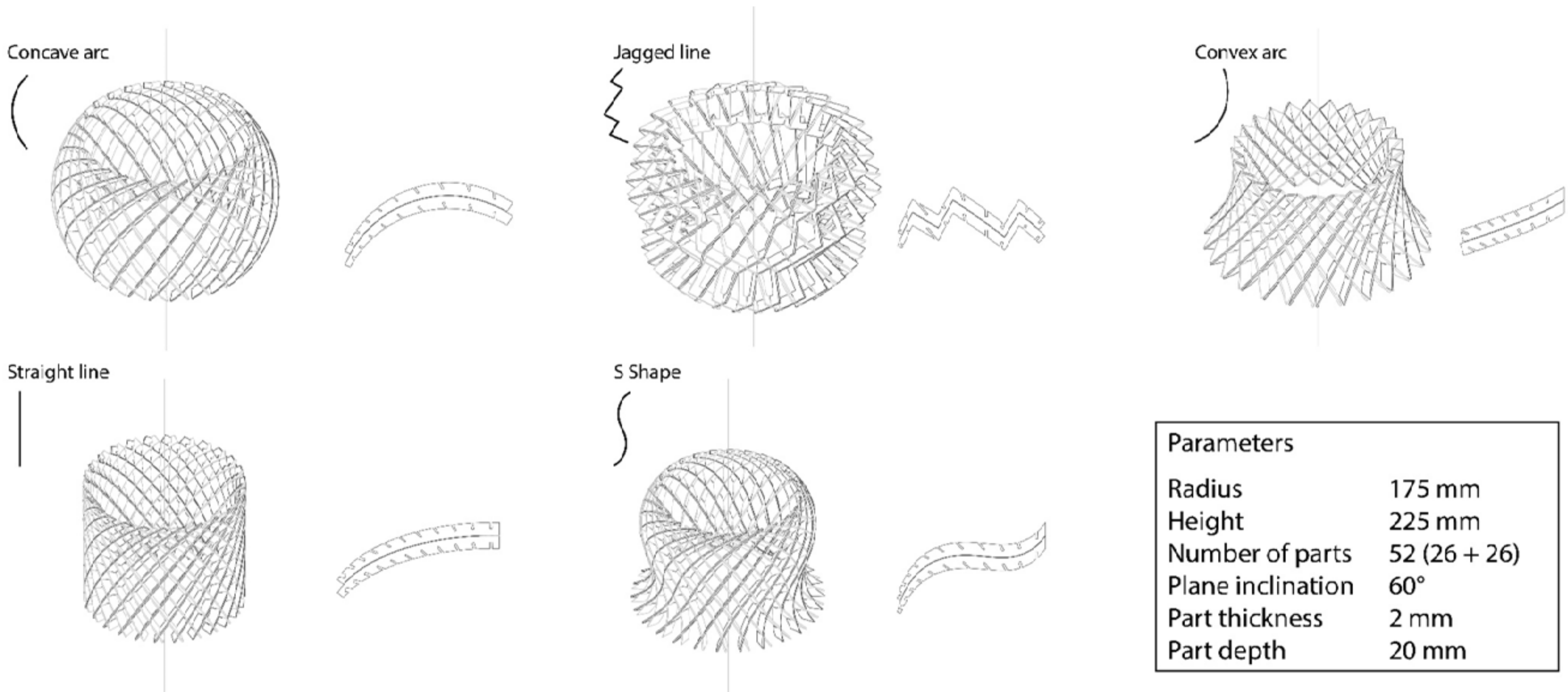
Five different alternatives are computed with varying cross-sections (Figure 64Figure). The cross-sections include a concave arc, a jagged line, a convex arc, a straight line and an S-shape. The cross-sections were chosen for showing the possibility of the implementation of the model through different curvilinear qualities, i.e., straight/curved, single / double curved, positive/negative curvatures. In these cross sections, only the pieces' shapes change.

Number of pieces controls the density of the surface structure (**Error! Not a valid bookmark self-reference.**). It also affects the stability of the structure, for the interlocking quality is attained with the intersection of pieces. The number of pieces is substantially related to material usage efficiency. Although the pieces can be nested side by side without any material loss, manufacturing from a rectangular material would waste a considerable amount at the beginning and the end of the nesting pattern.

The revolution radius is the distance of the revolution axis to the centroid of the cross-section curve, and it affects the frequency of the members in the surface structure. If the revolution radius is increased by keeping the number of pieces, the structure gets loose both in structural and visual terms. The number of slits on each piece is lessened from 9 to 3 by a change in the radius from 175mm to 440mm with rest of the parameters being kept constant (Figure 66). The loosening in terms of structure is a direct outcome of the decrease in the number of slits and intersections. Therefore, parallel to the increase in the radius of the structure, there should also be an increase in the number of pieces.

The inclination angle of the intersection plane is related to how upright the pieces would be in the structure (Figure 67). Due to geometrical limitations of the model, intersection process has to generate two discrete curves, and this constrains the inclination angle to a limited range of values. As the inclination angle determines the angle of the pieces, it mainly affects the number of intersections each piece has and the total interlocking quality of the structure. It also affects how narrow the slits would be.

Although piece thickness and depth variations differentiate the structure visually, they mainly affect the width and depth of the slits (Figure 64) (Figure). While the thickness of the material changes the width of the slits, the depth of the pieces alters the thickness of the final pieces, keeping the width of the constant.



Parameters	
Radius	175 mm
Height	225 mm
Number of parts	52 (26 + 26)
Plane inclination	60°
Part thickness	2 mm
Part depth	20 mm

Figure 64. Variations in cross-section (Image created by the author).

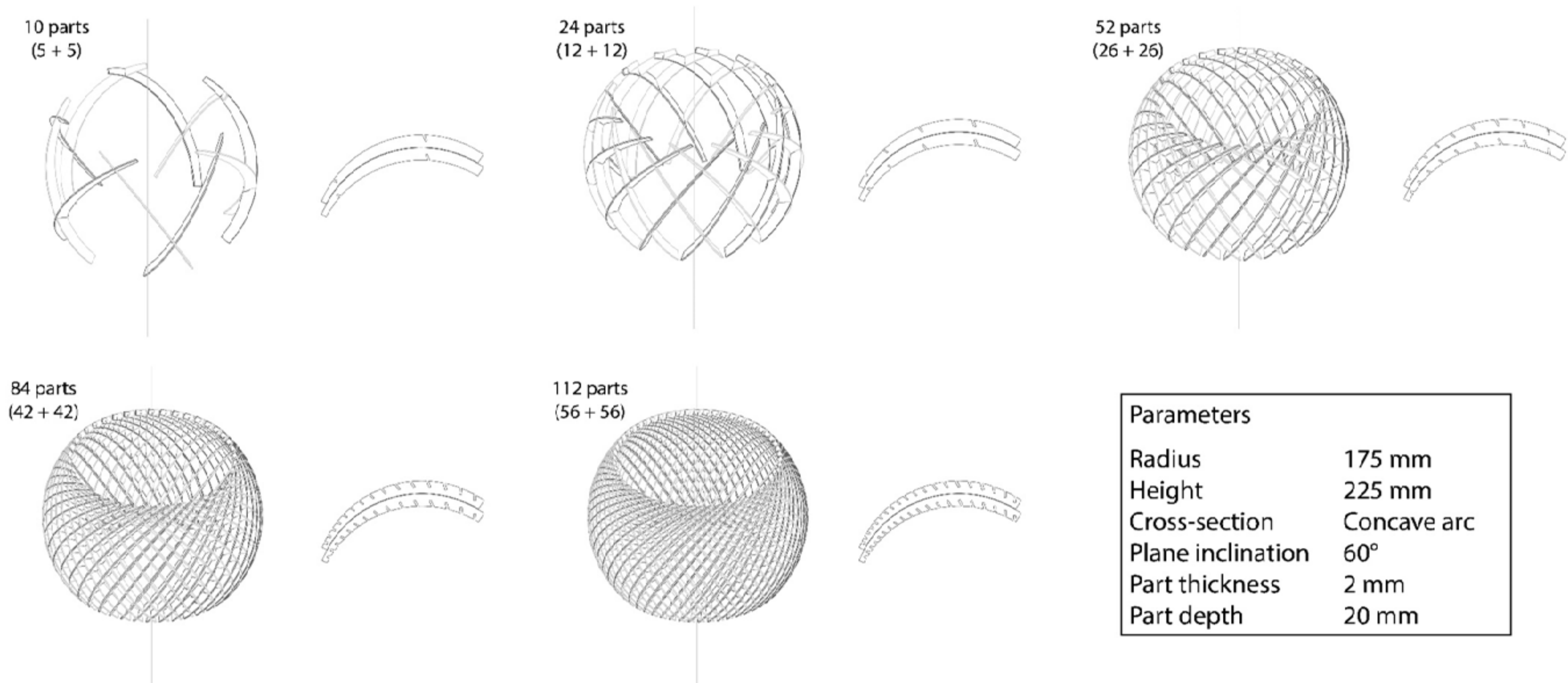


Figure 65. Variations in number of pieces (Image created by the author).

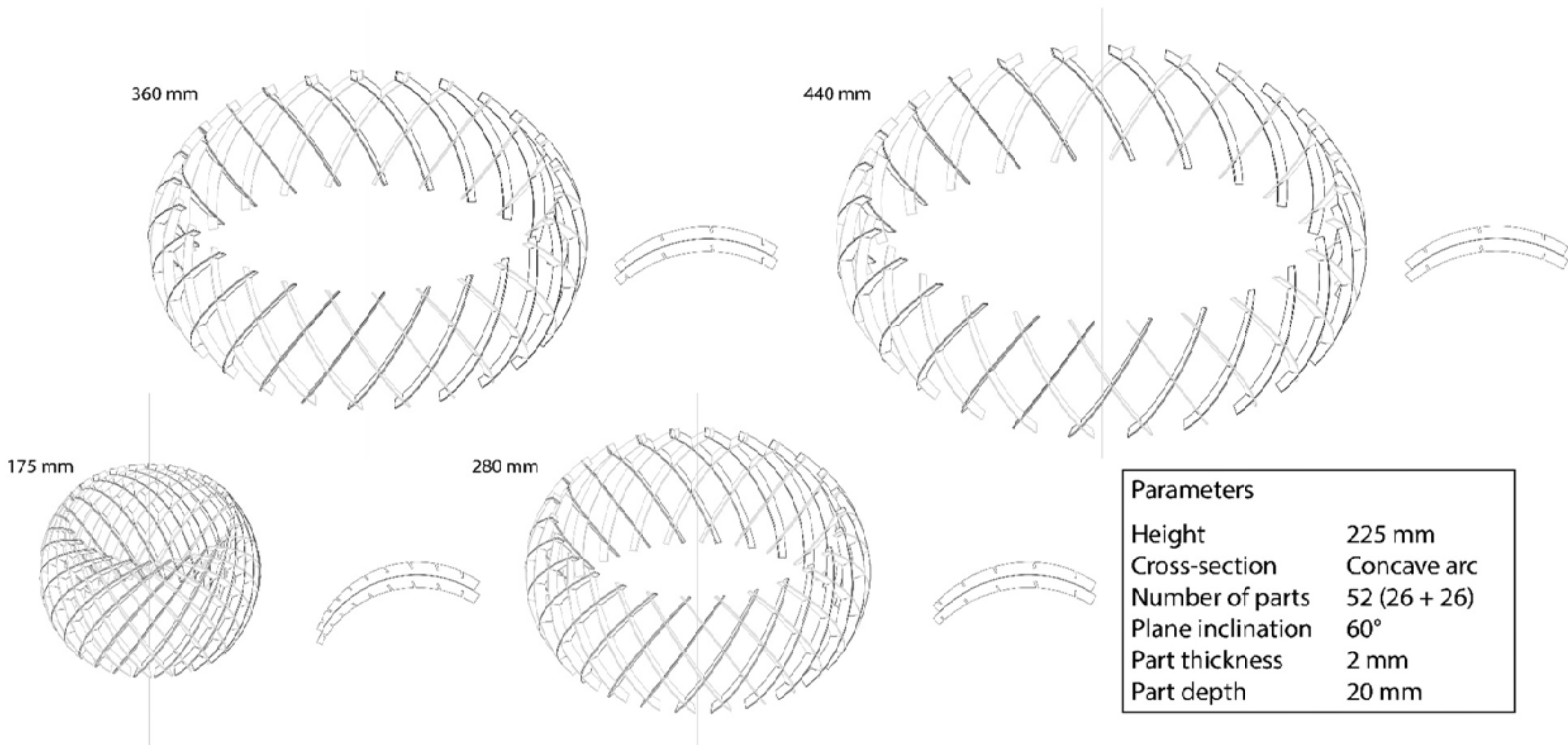
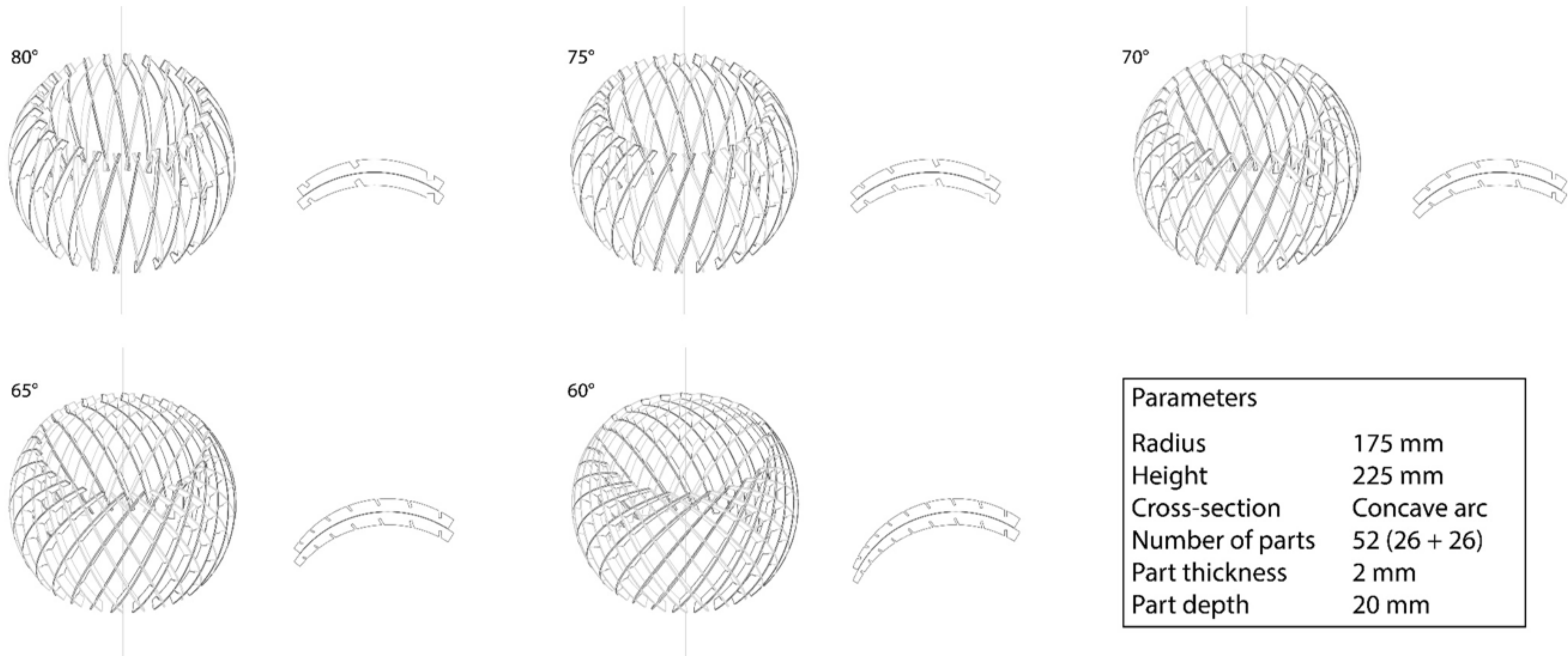
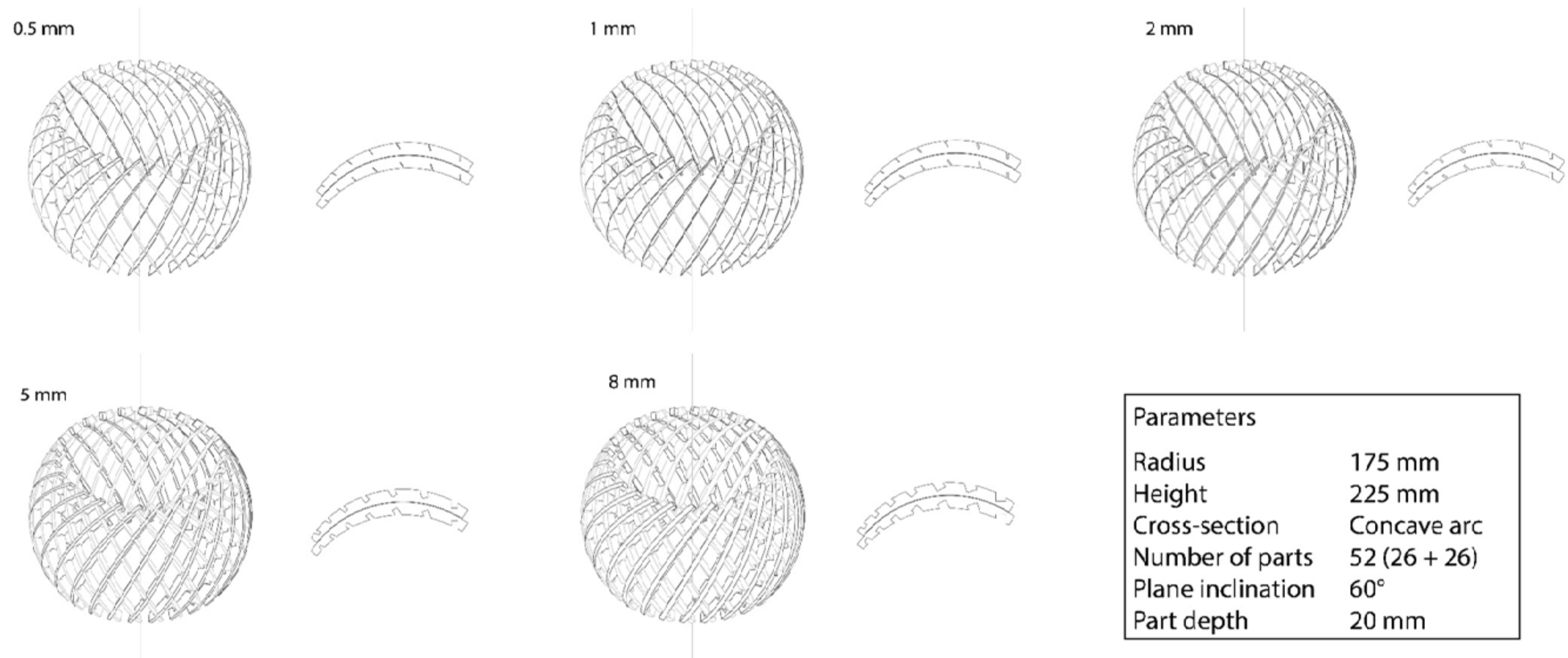


Figure 66. Variations in revolution radius (Image created by the author).



Parameters	
Radius	175 mm
Height	225 mm
Cross-section	Concave arc
Number of parts	52 (26 + 26)
Part thickness	2 mm
Part depth	20 mm

Figure 67. Variations in inclination angle of pieces (Image created by the author).



Parameters	
Radius	175 mm
Height	225 mm
Cross-section	Concave arc
Number of parts	52 (26 + 26)
Plane inclination	60°
Part depth	20 mm

Figure 64. Variations in piece thickness (Image created by the author).

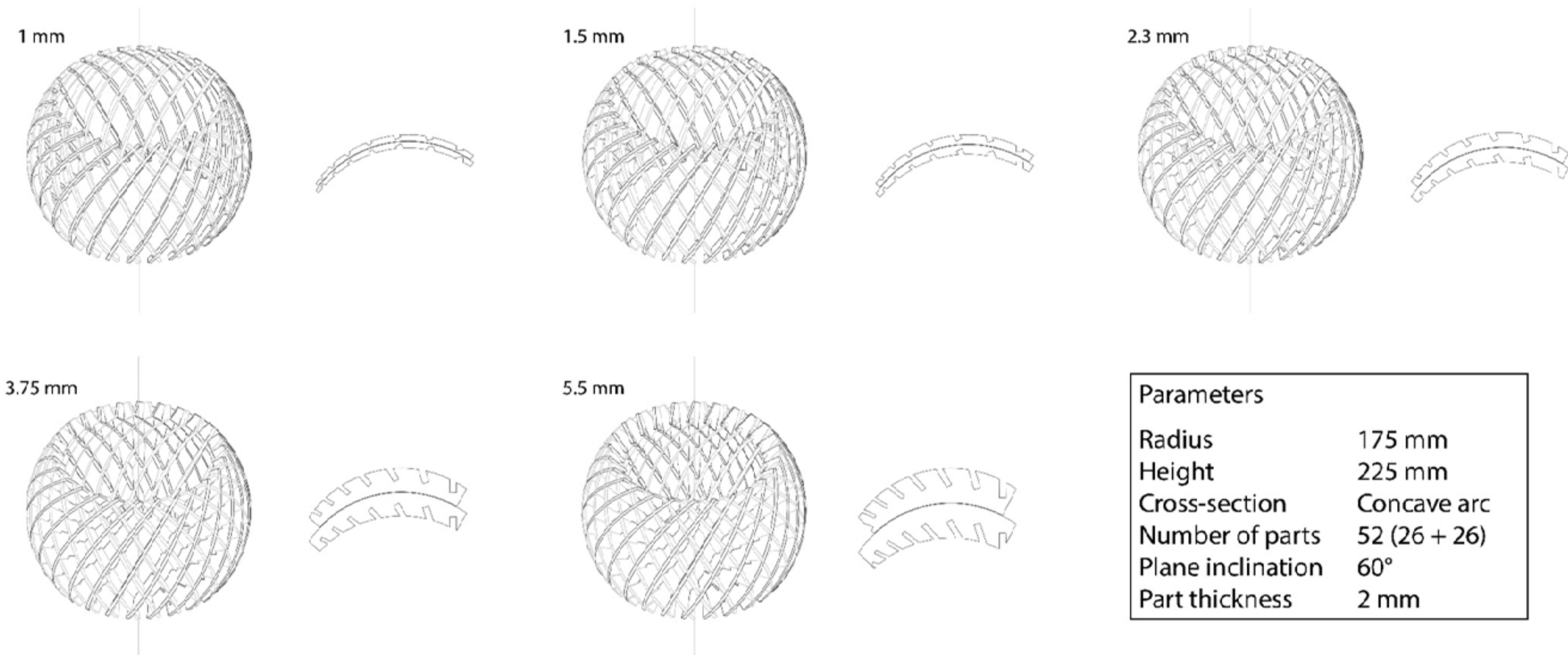


Figure 69. Variations in piece depth (Image created by the author).

5.4. Discussions

The devised technique has numerous advantages. First, the possibility of assembling a complex three-dimensional form using standardized planar materials is highly advantageous. This presents a vast choice of alternatives among CAM techniques and materials. The planarity of pieces enables to use simple CNC manufacturing techniques, like laser cutters, routers or water jets, together with the possibility of implementing generic sheet materials for the production. Moreover, the standardization of parts also eases the assembly process.

Although the use of simple manufacturing techniques is highly beneficial, it also brings forth some negative qualities to the pieces. All edges of a piece produced via 2-axis CNC techniques certainly become vertical and this ends up with improper connections of pieces, because of their various angles of joinings. The verticality of the edges of pieces also disrupt the formal continuity of the outer surface. It is for this reason, depending on the desired characteristics of the final construct, verticality of edges may also become a disadvantage. The intention to attain a continuous outer surface would necessitate using a 6-axis robot arm, to have varying curvilinear edge formations of pieces. This would also allow to have varying angles in the pieces' inner sides, creating a smooth surface inside the infrastructure. The more intricate geometries of pieces' edges also lead to a more integrated connection and interlocking quality of the technique. An increase in costs and manufacturing times are inevitable, but the advantages gained through a more complex manufacturing technique presents some positive aspects, which can be regarded as vital leaving the increase in costs and time redundant.

The model can be further developed by still using a 2-axis CNC machine.

The complex geometric forms of pieces

The “*non-standard quality”* of pieces can be formed via “*non-standard parts,”* through using 2-axis CNC technologies by utilizing the sectioning technique, in order to have complex three-dimensional forms by successive planar “parts.” This can be achieved by changing the ribs into multi-layered formations. For the sectioning process, the orientation of the sections should repeat the orientation of the initial piece. Sectioning technique would create numerous “parts,” repeated among all pieces and they would produce a “*standard*” piece for the construct. In addition to the formal outcomes of this approach, it would also present advantages in structural terms for a more intact interlocking quality of pieces. The implementation of sectioning technique can be considered as an intermediary phase prior to using a 6-axis robot arm for the production of intricate pieces.

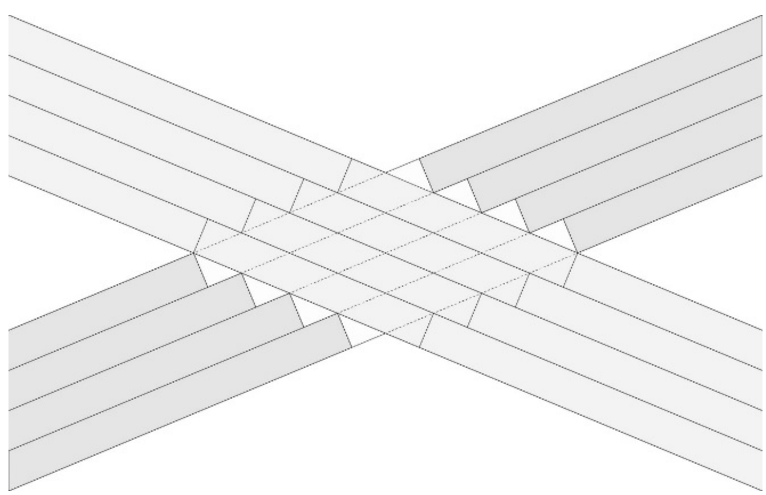


Figure70. Multi-layered formation (Image created by the author).

As the proposed model mainly focuses on the geometrical qualities of the system, it is limited with the formational aspects of the model. Currently, the devised model is only applicable to infrastructures of small-scale constructs. The transition from small-scales to life-sized buildings would eventually bring forth new criteria to consider, but the advantages offered by the algorithm will still be preserved. Structural aspects of the model have to be worked in detail for large constructs and finite element analysis (FEA) has to be made to fathom the model's abilities and limits. The proposed model is expected to perform effectively also in larger scales with accurate details and dimensions.

The nonspecific scalar condition of the proposed technique enables it to be implemented in various scales, ranging from an urban construct to small-scale interior design application. It is for sure that the functions attained to the construct would highly differentiate, but the common core qualities of the technique would be preserved at all scales.

CHAPTER 6

CONCLUSION

"The White Rabbit put on his spectacles. "Where shall I begin, please your Majesty?" he asked. "Begin at the beginning," the King said, very gravely, "and go on till you come to the end: then stop."

an excerpt from Alice in Wonderland (Carroll, 1869, p. 182)

This study covers the intrinsic relation of "form" and "part" in architecture, through the analysis of concepts "standard" and "non-standard." All four are described concisely in this thesis with their historical backgrounds. Additionally, a quadripartite relation model is formed by the permutation of the two groups and based on this model, an algorithm is introduced. The main intent of the thesis is two-fold. First, to develop a framework for architecture of "form" / "part," and "standard" / "non-standard." Second, to devise a generic algorithm for surfaces of revolution, based on the quadripartite relation.

The proposed relation has the potentials to cover all works of architecture and introduces a unique way of evaluating and classifying projects at all scales. For architecture, a classification of such presents a highly valuable information in a period, in which the differentiation of “standard” and “non-standard” become increasingly more blurred with the established techniques and methods. The dissolution of the separation can be denoted as an outcome of the lessened efforts needed to obtain a “standard” quality even in “non-standard” forms, but the existence of such terms still demonstrates the presence of both qualities. Regardless of how rapid and simple can the transformation from “non-standard” to “standard” be, there exists a process required for the transformation at the scale of both “form” and “part.”

In this thesis, “form” and “part” are investigated through their formal characteristics, instead of a theoretical standpoint. The “form” is considered as the whole that is being analyzed, whether a coffee table or a huge skyscraper; and the “part” as the constituent of a building, like a brick, a story plate or the repeating residential units. Both “form” and “part” are studied in depth, in terms of their scalar relations to the other, accompanied with tectonic dependencies. A topological stance is taken within the study, to reach the core attributes of the concepts, leaving aside scalar qualities and thus the concept of topology is included to the thesis. In the second chapter, various types of surface geometries are encompassed such as the Platonic solids, surfaces of revolution, ruled surfaces and freeform surfaces.

In addition, the historical significant concepts for architecture, “standard” and “non-standard” are investigated with their establishment processes, effects and implementations in architecture. With a chronological approach, the concept of “standard” is introduced tracing its roots back to the Second Industrial Revolution. Then, “standardization” is studied, being one of the most influential developments for the industry and henceforth, for architecture. In addition to standardization in the 20th century, mass-production is discussed. Then, mass-customization is examined also in relation to non-standardization and the concept of mass-customization are examined, as within the last 20 years both non-standardization and mass-customization have become the most dominant concepts of architecture in terms of form, means of construction, and computer-aided design and manufacturing.

Currently, in manufacturing there exist several techniques utilized for manufacturing any “form.” Four of these techniques are presented with their advantageous qualities, requirements and exemplary implementations. These four techniques have an essential function in the generation of “parts,” regardless of the shape of the “forms.” The formal and technical abilities of these four techniques comprise all possible applications in architecture, with a large degree of scalar variation.

Prior to the documentation of the devised model, a quadripartite relation is presented. It is generated through the permutation of “form” and “part,” with the concepts “standard” and “non-standard.” Each quarter of the quadripartite relation presents diverse qualities in architecture. The description of different geometries in the second chapter establish a framework in the quadripartite relation for a clear definition of the buildings and their constituting elements. Within the analysis, scalar qualities of both “form” and “part” are left aside. The negligence of scalar qualities enables the analysis to cover a wider range of scales; such as comparing a pavilion to an opera house built in a period of 40 years, and to attain comprehensive findings. The framework produces a method to analyze and categorize a building, regardless of its scale, function, location or period of construction.

By investigating the potentials of the relations, various advantages and disadvantages of each quarter have been found, and based on a specific partition, a model is devised. The model generates the required pieces for the assembly of a surface of revolution infrastructure. In its current situation, the model only generates small-scale infrastructures but it is expected that it can also be adapted to larger scales. Although the model is produced based on the last partition of the quadripartite relation, the algorithm can be altered by minute differentiations to fit other partitions. In such a case, still sectioning technique is expected to be utilized.

The proposed model shows that an abstract and geometrical approach has the potential to create a generic approach to surface rationalization. The standardization of support structure pieces makes it highly adaptable with a great degree of economic considerations regardless of the cross-section. While the current rationalization processes are mostly case specific, this kind of generic systematizations would be preferable for designers. While it may seem that the model has a limited variance potential, the parameters and cross-sections of surfaces highly differentiate the end results, making it highly adaptable and rich in terms of alternatives.

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APPENDIX A

GRASSHOPPER ALGORITHM

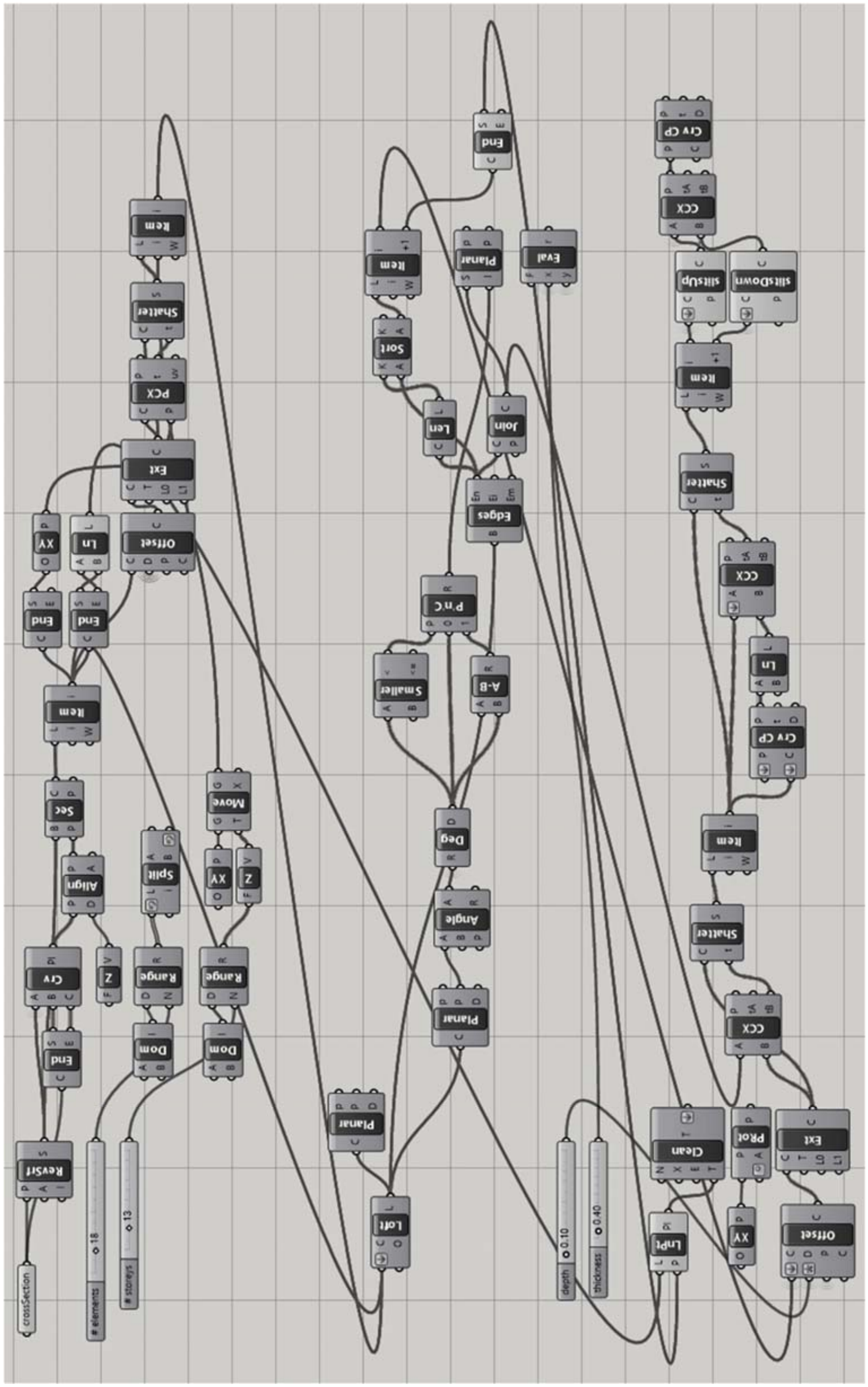

Figure A1. Grasshopper algorithm screenshot.

APPENDIX B

GLOSSARY

algorithm

set of commands executing a deliberate intent in a specified number of steps.

constituents

the parts that make up a whole.

contouring technique

a type of discretization, in which the form is divided into parallel planar sections that are possible to be manufactured.

cross-section

the intersection of a three-dimensional object with a plane.

discretization

the process of dividing geometry into smaller finite elements to prepare for analysis and manufacturing process.

double-curved surface

a surface that has curvilinear cross-sections from all points.

folding technique

a type of discretization, in which the form is created from a planar element and shaped via number of folds.

form

the overall geometry of a thing.

forming technique

a type of discretization, in which the form is created from numerous parts, which are manufactured via molding.

freeform surface

a surface that cannot be defined via concise mathematical equations and has various curvatures.

homeomorphic

two entities having equal topological qualities

infrastructure

the structural geometry underlying the surface.

mass-customization

a technique of industry denoting repetitive, fast and differentiated fabrication.

mass-production

a technique of industry denoting repetitive, fast and standardized fabrication.

morphological

related to form.

non-standard

a part that is differentiating throughout its instances, or a form that is not confined with the simple geometric shapes.

parameter

a variable, which has the potential to change the algorithm's end result.

parts

elements that constitute a form.

platonic solids

basic geometric shapes, like cube, cone, cylinder and sphere.

quadripartite

a division with four parts.

rationalization

reformulation of the form by a mathematical formula that has the potential to be manufactured and standardized.

ruled surfaces

a surface that is created by extruding a line along a linear or curvilinear curve.

sectioning technique

a type of discretization, in which the form is created from numerous planar elements generated via successive cross-sections.

single-curved surface

a surface that contains a line from all points on it, and can be created from a planar material by bending.

standard

a repeating quality in a construct.

surfaces of revolution

a surface that is created by rotating a cross-section along an axis.

technique

a method of obtaining something.

tectonics

inquiry of the relation of two separate parts in a work architecture.

three-dimensional construct

an assembly containing height, width and depth.

topology

an area of mathematics that deal with intrinsic features of a geometry, beyond scalar quantities.