THE ASSESSMENT OF A NEW RELATIONSHIP BETWEEN FORM AND STRUCTURE IN DIGITAL ARCHITECTURAL DESIGN AFTER 1990'S

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Yelin DEMİR

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We approve the thesis of **Yelin DEMİR**

Examining Committee Members:

Instr. Dr. Ülkü İNCEKÖSE
Department of Architecture, Izmir Institute of Technology

Assoc. Prof. Dr. Mustafa Emre İLAL
Department of Architecture, Izmir Institute of Technology

Assoc. Prof. Dr. Deniz GÜNER
Department of Architecture, Dokuz Eylül University

08 July 2013

Instr. Dr. Ülkü İNCEKÖSE
Supervisor, Department of Architecture
İzmir Institute of Technology

Assoc. Prof. Dr. Şeniz ÇIKIŞ
Head of the Department of Architecture

Prof. Dr. Tuğrul SENGER
Dean of the Graduate School of
Engineering and Sciences

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ABSTRACT

THE ASSESSMENT OF A NEW RELATIONSHIP BETWEEN FORM AND STRUCTURE IN DIGITAL ARCHITECTURAL DESIGN AFTER 1990'S

From the beginning of 1960's, architects are using computers in architectural design processes. Initially, architects used them as design tools for representation and modelling purposes. However from the beginning of 1990's, architects started to use computers as design mediums where the whole design process evolves starting from design ideation to construction.

Digital technologies enabled architects to design wide range of forms in digital design environments and therefore, form-based design processes appeared. Architects mostly focused on form generation concerns. However, this form based approach brought forth problems in relation to constructability. Complex irregular forms challenged engineers to find optimal structural solutions. Architects and engineers started to work on a unified architectural and structural design process and offered new structural system solutions with the help of digital technologies for overcoming the constructability problem. This process and solutions presented different form-structure relationships.

The main aim of this thesis is to reveal the form-structure relationships in digital design processes focusing on constructability of digitally designed forms. Constructability is related to structural system design. Therefore, this thesis examines design, manufacturing and construction processes of structural systems to understand how architectural designs/forms are realized and constructed. It examines the whole process of design to construction of structural systems including models, tools, structural system solutions, and fabrication and construction methods. The examination is done over case studies which are digitally designed and constructed building examples. Each case study exemplifies a different model, tool, structural system and design process which also defines a different type of form-structure relationship.

Key words: digital architectural design, structural design, form, structure, construction

ÖZET

1990’LARDAN SONRA, DİJİTAL MİMARİ TASARIMDA FORM VE STRÜKTÜR ARASINDAKİ YENİ İLİŞKİ BİÇİMİ ÜZERİNE BİR DEĞERLENDİRME

1960’lı yılların başlarından itibaren, mimarlar mimari tasarım süreçlerinde bilgisayarları kullanmaktadırlar. Önceleri, mimarlar bilgisayarları sunum ve modelleme amaçlı birer tasarım aracı olarak kullandılar. Fakat 1990’lı yılların başlarından itibaren, mimarlar bilgisayarları tüm tasarım ve üretim süreçlerinin içinde geliştiği bir tasarım ortamı olarak kullanmaya başladılar.

Dijital teknolojiler, mimarların dijital tasarım ortamlarında birçok farklı form tasarlamasına olanak sağladı ve böylece form odaklı tasarım süreçleri ortaya çıktı. Mimarlar çoğunlukla form yaratma kaygısı üzerine yoğunlaştı. Fakat bu form odaklı tasarım yaklaşımı, inşa edilebilirlik problemini de beraberinde getirdi. Karmaşık geometrik düzenlere sahip formlar, uygun strüktürel sistemler bulma yolunda mühendisleri zorladı. Mimarlar ve mühendisler, bütüncül bir mimari ve strüktürel tasarım süreci üzerinde çalışmaya başladılar ve inşa edilebilirlik probleminin üstesinden gelmek için farklı strüktürel sistem önerileri ürettiler. Bu tasarım süreci ve öneriler farklı form-strüktür ilişkileri tanımladı.

Bu tezin amacı; dijital tasarım süreçlerindeki form-strüktür ilişkilerini, inşa edilebilirlik problemine odaklanarak açığa çıkarmaktır. İnşa edilebilirlik problemi strüktürel sistem tasarımıyla ilişkilidir. Böylece bu tez, mimari tasarımların/formların nasıl gerçekleştirildiğini ve inşa edildiğini anlamak için strüktürel sistemlerin tasarım, üretim ve inşa süreçlerini incelemektedir. Tasarımdan üretime kadar geçen tüm süreçteki modelleri, araçları, strüktürel sistemler çözümlerini, üretim ve inşaat yöntemlerini araştırmaktadır. Bu araştırma her biri sayısal ortamda tasarlanmış ve sayısal teknolojiler yardımıyla inşa edilmiş örnekler üzerinden yapılmıştır. Her bir örnek farklı bir model, araç, strüktürel sistem ve farklı bir form-strüktür ilişkisi tanımlayan bir tasarım sürecine örnek oluşturmaktadır.

Anahtar kelimeler: dijital mimari tasarım, strüktürel tasarım, biçim, strüktür, yapım

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CHAPTER 1

INTRODUCTION

1960’s were the years when computers started to take part in designs as design tools in addition to drawing and model making. Initially, architects were using computers for representation and visualization purposes. They were drawing two dimensional plans, sections and elevations of their projects using computers. As technology and computers evolved, architects started to work with computers for three dimensional studies. In addition to representations of two dimensional drawings, they started to create three dimensional models of their designs in digital medium. At the beginning of 1990’s, computers gained a different role in design processes rather than being used as tools. They became the main design mediums and this changing role of computers changed the way of designing.

Together with usage of computers as design environments, architectural design processes started to change. Digital technologies fused into earlier phases of design processes by having a role in constitution of the design idea. Computer aided design became the real design environment and enabled designers to create forms in digital design medium. Now, architects digitally design from the beginning of a design process by using computer as the digital design platform instead of using computer as a tool in the final phase of a project for representation purposes.

Computer aided design empowers architects to design complex curvilinear surfaces and forms which would have been impossible to dream of without the usage of sophisticated computer programs. It makes it easier to create, alter, multiply, rotate, deform and thus control the free formed shapes considering hand drawing. This potentiality of computer aided design causes form based design processes to appear. Architects mostly focus on form creation concerns and this focus on form creation causes constructability problem to appear. Engineering of complex irregular forms challenges engineers in terms of finding suitable structural solutions which meet aesthetic and structural requirements and at the same time remain in the limits of the budget. For constructability of complex forms, the place of structural design in digital architectural design process changes and structural design exists in many different ways in the whole process of design to construction. New types of form-structure relationships are defined in digital architectural design such as the unification of form and structure within an integrated process. Therefore, this thesis aims at revealing the differentiating form-structure relationship within digital architectural design.

As digital technologies enable to design free and complex shapes different from familiar regular shapes, design logic that lies behind the design process also changes as Kolarevic asserts; "the Information Age, like the Industrial Age before it, is therefore not only challenging what we are designing but also how we design."[1] In digital design processes, design is a computational and algorithmic process that proceeds within digital medium. Digital knowledge supports design processes. Design data are input into computers by quantitative values and the way that these quantitative values relate generates the design. The relationship of values are controlled by algorithmic formulas and by changing one value, all the other related values are adjusted and recalculated according to that changing value.[2] With the algorithmic process and help of the programming interfaces, quantitative input values then turn into final form as output. Such a computational approach is clearly expressed by Bernard Cache in his book of "Earth Moves" as he asserts; "objects are no longer designed but calculated."[3] In these computational design processes; the process, the design strategy and the internal generative logic that generates the outcome are important for shape generation.

Architects use parameter based programs such as Softimage, 3D Studio Max, Alias and Maya as design mediums for expressing and controlling the computational design processes. Actually these software programs were not developed for architectural design. They were developed for industries such as aircraft industry, automotive industry, naval industry and movie industry, and then transferred into architecture.[4] These software programs record, organize and store the data numerically during all the processes of planning, designing and construction. Computational logic gives opportunity to architects to control the design processes with easy access. For example, rather than creating many variants of the same project by hand drawing, algorithms can be used to make these processes faster and easier as Fabian Scheurer asserts; "the

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[1] Kolarevic, Branko. "Digital Morphogenesis and Computational Architectures." Proceedigns of the 4th Confernece of Congreso Iberoamericano de Grafica Digital, SIGRADI 2000 - Construindo (n)o Espaço Digital (Constructing the Digital Space), Rio de Janeiró, Brasil, 25-28 September 2000. Eds. José Ripper Kós, Andréa Pessoa Borde and Diana Rodriguez Barros, 2000. 98.
[2] Imperiale, Alicia. 2000.
[3] Cache, Bernard. Earth Moves. Cambridge: MIT Press, 1995. 87.
[4] Lynn, Greg, and Mark Foster Gage, eds. Composites, Surfaces, and Software: High Performance Architecture. New Haven, Conn.: Yale School of Architecture, 2010.

information of a thousand drawings can thus be reduced into one well-defined algorithm and a thousand small sets of only a few parameters" in his article of "Materialising Complexity."[5]

As digital design focused studies increased, designers and architects such as Zaha Hadid, Bernhard Franken, Branko Kolarevic, Greg Lynn and Lars Spuybroek tried to understand, explain and identify the new digital existence of design processes. For example, Kolarevic is one of the presider figures who work on digital architectural design processes. In his studies, he categorizes the processes for identifying the different approaches and methods. According to him there are seven different approaches to design processes which are; parametric architecture, performative architecture, evolutionary architecture, metamorphic architecture, animate architecture, isomorphic architecture and topologic architecture.[6] Many other architects and theoreticians such as Rivka Oxman also categorize digital design processes similar to Kolarevic with new additions or subtractions.

Quantitative values that define digital architectural design processes refer to different concerns. Like in Kolarevic's categorization of computational design processes, every process's input parameters and their relation vary. For example in performative architecture, shape is generated and modified based on performance analyses such as structural optimizations; whereas in animate architecture, force fields in design medium generates and modifies the shape during design process.[7] Based on design concerns, architect can apply one or more than one model at the same time. Therefore, choosing the right approach or approaches and planning the design process are very important factors for form as well as structural design generation.

Digitalizing architectural design processes from design ideation to construction also caused architectural conventions to change. For example, the conventional architectural and structural understanding changed in addition to design processes, based on the new architectural language that digital design focused studies brought along. For explaining and expressing new digital understanding and identifying the outcomes of the design processes, new concepts appear. Rather than statics, stability, certainty and homogeneity; architects use concepts such as irregularity, deformability,

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[5] Scheurer, Fabian. "Materialising complexity." Architectural Design: The New Structuralism-Design, Engineering and Architectural Technologies 80.4 (2010): 89.
[6] Kolarevic, Branko. 2000.
[7] Kolarevic, Branko. "Digital Morphogenesis." Architecture in the Digital Age: Design and Manufacturing. Ed. Branko Kolarevic. New York: Taylor & Francis, 2009. 11-28.

complexity, emergence, dynamism and variation to define the design processes and their end products. Deformability, transformability, complexity, dynamism and emergence are examples to concepts which architects use for defining architectural creation processes. For example, Lynn refers to the concept of deformability in his book Animate Form to define the generation process of his House Prototype in Long Island project. By deformability, Lynn implies the changes that form undergoes for taking its final shape as he states; "these forces produce a gradient field of attraction and repulsion across the site. In this field of forces various flexible house prototypes are placed in order to study their alignments and deformations."[8] Kolarevic also uses the concept of deformability for defining the design process of Foster and Partners's Greater London Authority Headquarters project. He asserts that project has a blobby form which is actually a deformed sphere. The sphere was deformed because of the acoustical analyses and energy performance optimizations of form during design process.[9]

Engineers Klaus Bollinger, Manfred Grohmann and architect Oliver Tessmann refer to the concept of complexity for defining the structure of the digital design process. They assert that; "Complexity characterises systems – sets of elements and their relations – whose behaviour is hardly predictable. The system properties are not defined by individual elements, but rather emerge from intricate interaction without any top-down control"[10] in their article titled "Structured Becoming." They work on the interaction and collaboration of architecture and engineering. Therefore, with the possibility of inputting data from architectural and structural design, design becomes a complex process.[11] The relationships of constituent parameters during a design process are also complex as Kolarevic asserts about the generative design processes that; "their behavior over time can not be explained through an understanding of their constituent parts, because it is the complex web of interdependencies, interactions that define their operation."[12]

Dynamism is another concept that architects refer to define the creation processes. For example, Lynn gives a dynamic role to the design medium and to the design process. He integrates field forces in the design medium into form by recording

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[8] Lynn, Greg. Animate Form. New York: Princeton architectural press, 1999. p. 143.
[9] Kolarevic, Branko. 2009. pp. 11-28.
[10] Bollinger, Klaus, Manfred Grohmann, and Oliver Tessmann. 2010. p. 36.
[11] Ibid. pp. 34-39.
[12] Kolarevic, Branko. 2009. p. 27.

the design information in the surface. Form grows and evolves with its shaping forces.[13] It responds to its context and evolves in interaction with its surroundings as Lynn asserts; "so rather than as a frame through which time and space pass, architecture can be modeled as a participant immersed within dynamical flows" [14] in his book of Animate Form.

Emergence and indeterminacy are other concepts that Kolarevic refers to in his studies. For example, he refers to emergence to define the structure and the characteristic of digital generative processes as he asserts: "instead of working on a parti, the designer constructs a generative system of formal production, controls its behavior over time, and selects forms that emerge from its operation." [15] Klaus Bollinger, Manfred Grohmann and Oliver Tessmann also refer to the concept of emergence to emphasize the role of computational design processes over architectural creation in their article of "Structured Becoming." They assert that;

> Scripting and programming help to access this layer of description where the algorithm (the machine) and the data are represented with similar symbols and syntax. These processes create the conditions for the digital mediation of design emergence through evolutionary structures, thus becoming characteristic of design engineering.[16]

In emergent design processes, final form generally does not have a preplanned or assumed shape. Even though architect identifies the design criteria and organizes the inputs and their relations, design process can end in a way that architect could never imagine of. Jane and Mark Burry asserts in their book titled "The new mathematics of architecture" that; "the key idea of emergence is that it gives something new, more than that which is put into it."[17] The final form emerges indeterminately in digital medium. Planning the design process rather than firstly determining the final shape causes unpredictable results.[18] However, unpredictability does not mean that the final form is arbitrary because the form emerges based on the concept and determined borders. Information is recorded on building surface and every detail on form has a rationale behind it.

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[13] Lynn, Greg. 1999.
[14] Lynn, Greg. 1999. p. 11.
[15] Kolarevic, Branko. 2009. p. 26.
[16] Bollinger, Klaus, Manfred Grohmann, and Oliver Tessmann. "Structured Becoming: Evolutionary Processes in Design Engineering." Architectural Design: The New Structuralism-Design, Engineering and Architectural Technologies 80.4 (2010): 36.
[17] Burry, Jane, and Mark Burry. 2010. p. 56.
[18] Ibid.

In addition to indeterminacy as a concept that architects refer to characterize architectural end products; irregularity and complexity are also other examples that architects use to define end products.[19] For example, architect Jan Edler from the studio of "realities:united" uses the concept of irregularity for defining the form of the Kunsthaus Graz in his article "Communicative Display Skin for Buildings: Bix at the Kunsthaus Graz." He refers to the usage of non-Euclidean geometry in the built form as he states; "the irregularly shaped, biomorphic building structure floats as an independent body, balloon-like, above a glass foyer."[20]

Helen Castle as the editor of the "Architectural Design Magazine; The New Structuralism Design, Engineering and Architectural Technologies" also uses the concept of irregularity for defining the digitally designed forms geometrically as she asserts; "the old order of standardized design and its established processes no longer hold sway; contemporary architectural design can now be characterized by irregularity, and an appetite for producing customized non-standard, complex, curvilinear forms."[21]

Mark Goulthorpe uses the concept of complexity to define the curved forms which is hard to comprehend or hard to analyze in terms of structural behavior. He thinks that complex forms are the striking features of digital architectural design as he states; "certainly the most marked characteristics of digital architecture are its propensity for complex-curved form" in his article of "The New Structuralism Design Engineering and Architectural Technologies."[22]

Rivka Oxman and Robert Oxman refer to variation to define the architectural outcomes and relate it to the computational logic of digital medium. By changing the input parameters, various outputs can be generated as Oxman states; "geometric variants of a class of structures can be generated parametrically by varying the values of its components; for example, the folds of a folded plate, or the grid cells of a mesh structure."[23] For example in digital structural design, forms mostly have irregular characters and therefore, load distribution becomes heterogeneous through the building. For corresponding to load calculations and for being in accordance with the form,

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[19] Oxman, Rivka, and Robert Oxman. "Introduction." Architectural Design: The New Structuralism-Design, Engineering and Architectural Technologies 80.4 (2010): 17.
[20] Edler, Jan. "Communicative Display Skin for Buildings: Bix at the Kunsthaus Graz." Performative Architecture: Beyond Instrumentality. Ed. Branko Kolarevic, Ali M. Malkawi. New York: Spon Press, 2005. 153.
[21] Castle, Helen. "Editorial." Architectural Design: The New Structuralism-Design, Engineering and Architectural Technologies 80.4 (2010): 5.
[22] Goulthorpe, Mark. 2009. pp. 166.
[23] Oxman, Rivka, and Robert Oxman. 2010. p. 20.

structural systems have varying sections.[24] As the section differs; the structural parts of the system also vary over its length, thickness and size. Therefore, by changing the values of input parameters, various and unique parts can be generated easily.

In these changes over architectural and structural design processes, it is seen that architects mostly go towards and focus on form based design processes. The new concepts are being utilized mostly to define these form based design processes and their end products. A design approach is in question where main concern is generally form production. Architects express their form generation concerns in their discourses in various ways such as "exploration into new forms," "form generation," "a new approach to form," "finding of form," "derivation of form" and "form origination." Such a form-based interest is clearly expressed by architect Steve Hatzellis in his article of "Formal Complexity in Digital Architecture." He asserts that; "digital architecture is an area of design that is leading exploration into new forms of non-standard architecture."[25]

Usage of the concepts such as complexity, interactivity, deformability-transformability and variability in architectural discourses of the Zaha Hadid Architects indicate their focus on "form generation."[26] Greg Lynn's definition of "animate form" also indicates his interest on "form generation."[27]

Researchers Francesco de Luca and Marco Nardini focus on "generation of form" in their researches and see digital architectural design as "a new approach to form." They assert in their book titled "Behind the scene: avant-garde techniques in contemporary design" that;

> Though it may seem obvious, the fact must be taken into account that a project using *manual* design is very different from one created by CAD. Not only because of the obvious reason that the use of more elastic tools, able to more rationally manage designers' needs, offers them the chance of organizing their own work better and more profitably, but also for another, perhaps more important reason: a new approach to form.[28]

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[24] Akipek, Fulya Özsel, and Necati İnceoğlu. 2007. pp. 237-253.
[25] Hatzellis, S. "Formal Complexity in Digital Architecture" Digital Architecture and Construction. Ed. A. Ali, Carlos A. Brebbia. Southampton: WIT, 2006. 54.
[26] Schumacher, Patrik. "Arguing for Elegance." Elegance, AD (Architectural Design) 77.1 (2007): 28-37. 22 May 2013 <http://patrikschumacher.com/Texts/Elegance%20argument.htm>.
[27] Lynn, Greg. 1999.
[28] De Luca, Francesco, and Marco Nardini. Behind the Scenes: Avant-Garde Techniques in Contemporary Design. Basel: Birkhäuser, 2002.

Form concern in Bernhard Franken's discourses can also be read as "form generation." He generates forms directly from client's briefing as he asserts; "we translate the client's wishes and demands into a process that leads to a form generated using a computer-supported force-field simulation"[29] in his article of "Real as Data."[30]

Researchers Marine Bagneris, Bernard Maurin and Rene Motro and engineer Nicolas Pauli characterize digital architectural design by the generation of new types of forms in their article titled "Structural Morphology Issues in Conceptual Design of Double Curved Systems." They read digital architectural design over the appearance of irregular and complex forms as they state that; "it is a fact that designers are now in a new architectural era, which is characterized by the appearance of shapes which meet no previous criteria in terms of regularity, orthogonality, planarity etc."[31]

Branko Kolarevic expresses a form based design process as "finding of form." Kolarevic searches for "derivation of form" and its "transformation" over generative processes in digital architecture in his article of "Digital Morphogenesis and Computational Architectures."[32] He also examines the tools and methods for form origination and transformation in his book titled "Architecture in the Digital Age: Design and Manufacturing."[33]

In these form based studies, generated forms may seem arbitrary. However, every contour that the form has mostly has a meaning and an underlying computational logic. Cecil Balmond's definition of dance is a metaphor that can be referred while identifying the organized and planned process of digital architectural design. He states in his article of "Informal Networks" that;

> I am also interested in dance: the idea of movements embedded one into the other — a kind of dynamic symmetry — and the strict geometry of it. If you saw an Indian dancer, for instance, you would see his or her hands moving freely and you might think that this was an improvised free-form movement, but it is actually performed to a set of very rigidly controlled rules. There is a hidden geometry at work, although you do not need to know about it: you merely enjoy the performance.[34]

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[29] Franken, Bernhard. 2009. p. 124.
[30] Ibid. pp. 121-138.
[31] Bagneris, Marine, Rene Motro, Bernard Maurin, and Nicolas Pauli. "Structural Morphology Issues in Conceptual Design of Double Curved Systems." International Journal of Space Structures 23.2 (2008): 84.
[32] Kolarevic, Branko. 2000. pp. 98-103.
[33] Kolarevic, Branko. 2009. pp. 11-28.
[34] Balmond, Cecil. "Informal Networks." Seven Structural Engineers: the Felix Candela Lectures." Ed. Guy Nordenson. New York: The Museum of Modern Art, 2008. 56.

As digital architectural design mostly focuses on "form generation," constructability of these digitally computed, designed and represented forms becomes a crucial problem. Forms that architect designs generally do not include constructability information and therefore, finding a structural system that will carry and support the form of the building challenge architects and engineers in terms of finding optimal structural solutions. Bagneris et al. express constructability problem in their article of "Structural Morphology Issues in Conceptual Design of Double Curved Systems." They state that;

> The flexible forms are mainly characterized by portions of double-curved surfaces. But this is only their formal aspect and is only a geometrical characterization. Problems occur when the mechanical behavior, and moreover, technological solutions have to be handled. Engineers have to solve difficult problems, which can end in nightmares.[35]

Constructability problem necessitates examining the place of structural design within architectural design. Therefore, structural design gains a new insight in digital architectural design. Architects and engineers collaborate from the beginning of the design process and design the structural system in integration with form design. There is not an autonomous structural design process apart from architectural design process. All processes from constitution of the design idea to construction integrate and converge in a common platform that is the digital design environment. Form generation and structural system decisions are given in the same medium. Models, tools and concepts that are valid for architectural design are also applicable to structural design. There is an integrated and unique process rather than a sequential process. Hierarchical nature of design where disciplines are specialized and completed in themselves is demolished. Uğur Tanyeli in his article titled "Mimarlıkta Değişmekte Olan Ne? Biçim Bilgisinden Süreç Bilgisine;" gives the example of Walt Disney Concert Hall of Frank O. Gehry in Los Angeles where aeronautical software CATIA was used in the every phase of the project as the only design medium. Design process acted as a unique process where all the project participants worked in their area of responsibility from form design to construction by using the same software in integration with each other.[36]

Design becomes an integrated and unique process and the existence of structural design within architectural design process changes. Form and structure are thought

[35] Bagneris, Marine, Rene Motro, Bernard Maurin, and Nicolas Pauli. 2008. p. 85.
[36] Tanyeli, Uğur. "Mimarlıkta Değişmekte Olan Ne? Biçim Bilgisinden Süreç Bilgisine." Arredamento Mimarlık 260 (2012): 76-83.

together rather than thinking of a structure after form generation. Form-structure relationship differed through time. Designer Neri Oxman emphasizes the importance of form generation during a design process in her article of "Structuring Materiality Design Fabrication of Heterogeneous Materials." She states that; "the image of the architect as form-giver has for centuries dominated the profession."[37] Based on form design, structural systems were being designed for making the designs constructible and material selection and application were becoming dependent on these structural solutions. According to Oxman, this form first approach emphasizes the hierarchical nature of the design process which starts with form generation, continues with structural design and ends with material decisions. There is a linear design process where architect focuses on form design, while engineer focuses on finding suitable technical solutions. This linear design process was first broken with Sydney Opera House project (1957-73) where structural system was derived from the geometry of covering tiles, and the shape of the roof was formed based on the structural system. The traditional linear design process that puts forward "material, structure, form" was reversed.[38] This non-linear and reversed design process is also a commonly seen approach in today's digital era. The difference is the computational logic of the generation process and the digital design environment in digital architectural design.

Structural systems, organization and characteristic of structural components are also changing with digital technologies in addition to the changes related to existence of structural design in computational processes. Rather than understanding of a homogenous sectioned structure, a more complex structure which has various unique members in length, thickness or size is seen in digital architectural design for accommodating with the irregular forms.[39] By using the parametric approach, the sizes of unique members and their joints can be calculated in a short time by engineers.

With computer aided manufacturing technology (CAM), manufacturing and construction processes of structural systems also take place in computational medium. With connection of CAD to CAM, design is linked with making of architecture and this connection enables the transfer of all digital information in computer to construction site for manufacturing the components of the building. Therefore, design information in

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[37] Oxman, Neri. "Structuring Materiality Design Fabrication of Heterogeneous Materials." Architectural Design: The New Structuralism-Design, Engineering and Architectural Technologies 80.4 (2010): 80.

[38] Oxman, Rivka, and Robert Oxman. 2010. pp. 15-23.

[39] Akipek, Fulya Özsel, and Necati İnceoğlu. "Bilgisayar Destekli Tasarım ve Üretim Teknolojilerinin Mimarlıktaki Kullanımları." Megaron 2.4 (2007): 237-253.

digital medium can be directly used for manufacturing rather than trying to convert every structural member and joints' design information into construction instructions. When parts are ready for manufacturing, they are generally manufactured in factories and assembled on site.[40]

Researches on digital architectural design mostly focus on the new digital design processes. The main focal point on these researches is form generation and digital design medium is understood as a form based medium. For example, Greg Lynn focuses on form and form creation processes in his studies where he studies generation of form with its shaping forces. He integrates motion and forces in site into the form creation process. Branko Kolarevic works on possibilities of finding of form focusing on the models that he uses for controlling the forms and the form creation processes. Peter Szalapaj works on digital architectural design processes where he focuses on the potentialities that software programs offer to design practices in his book of "Contemporary Architecture and the Digital Design Process."[41] However, architectural design process becomes an integrated process where structural design and architectural design proceed together by effecting and verifying each other. Structural design makes architectural design constructible and at this point structural design gains importance. Constructing free and complex forms require the understanding of architectural and structural design processes and also form-structure relationships. The studies that mention constructability of forms including structural systems generally individualize in themselves and have their own structural design solutions. There is not a total study which contains all the structural design and manufacturing approaches, and structural system solutions that make the complex forms realized. Therefore, this thesis aims examining digital structural design and construction processes. By having a different point of view to digital architectural design, this thesis closes the information gap in the area of digital structural design and construction, and also reveals different types of form-structure relationships focusing on constructability of form in digital era.

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[40] Hatzellis, S. 2006. pp. 51-58.
[41] Szalapaj, Peter. Contemporary Architecture and the Digital Design Process. Oxford; Burlington: Architectural Press, 2005.

1.1. Aim and Scope

The main aim of this thesis is to examine form-structure relationships in digital architectural design and thus assess constructability of digitally designed forms in order to reveal different types of relationships between form and structure. Constructability is related to structural system design. Therefore, this thesis examines design, manufacturing and construction processes of structural systems in addition to examining form-structure relationship. It is important in this study that, how digital technologies were used in form creation and structural design processes, and if the conventional linear relationship of form to structure was effected.

For studying form-structure relationship and constructability, structural design and construction processes are examined in detail for realization of forms. For understanding structural design processes; design models and design tools that control architectural and structural design processes are explained. The existence of structural design in architectural design process is analysed over different form-structure relations by doing classifications. Different types of structural systems that are compatible with irregular forms are revealed. Finally for realization of forms; digital manufacturing, construction and assembly processes are examined.

For understanding different form-structure relationship in digital architectural design, digitally designed or digitally constructed building examples which were designed and constructed after 1990's are analysed within the thesis. Significant examples which are discussed and examined mostly by architects, engineers and designers in literature are selected. Digital design processes were started to be discussed in architectural discourses after 1990's, and the building examples were also constructed mostly after 1990's. That's way the thesis focuses on after 1990's.

In the case study chapter which is the fourth chapter, each case study discusses a different form-structure relationship. All the cases are selected in a way that all the analysed topics in the thesis from design to construction can be discussed with all their differentiations. Therefore, each case has a different design model, tool, structural system, and manufacturing and construction technology. Another criterion for the selection of cases is related to the accuracy and reliability of the information. Every case study is represented with the first-hand statements of the architects and the engineers who worked in the project.

1.2. Methodology

Digital architectural design is studied over form-structure relationship in this thesis. Form-structure relationship is read over different examples. All the cases are selected from digitally designed and realized buildings because of the discussed problem of constructability.The ones which have common characteristics are collected under same titles, and thus, categorizations are made based on the data that comes from the examples for understanding the topics better. Data is collected by analysing the discourses of architects and their project descriptions about the design processes and the buildings.

In the case study chapter which is the fourth chapter, every case discusses a different form-structure relation. They are analysed over their general view, design phase, structural system organization and manufacturing technology. For analyzing the case studies, architects' discourses and project descriptions are examined. Architects', designers' and theoreticians' firsthand statements are generally taken as primary sources for the research. In addition books, articles, thesis and conference declarations are referred which are related with the topic. In the direction of case studies, the research questions below are answered.

How does computer aided design challenges constructability of free forms?

How does structural design exist in digital architectural design processes?

What are the models and tools for digital structural design?

What are the new types of relationships between form generation process and structural generation process?

What are the types of structural systems that are compatible with free and complex forms?

How forms and structural systems are produced and constructed?

What are the different form-structure relationships in digital architectural design and construction processes?

As a consequence of the methodology, the thesis consists of five main chapters. The first chapter is introduction and will focus on the changes that digital technologies brought forth into architectural design.

The second chapter will focus on comprehension of digital structural design with new models and tools. The models that rule structural design processes and the tools that are used for designing, modeling and analyzing will be examined in detail.

In the third chapter, form-structure relationship will be searched over structural design's digital applications. The existence of structural design in the whole design and construction processes will be explained. Different types of structural system solutions will be analyzed and categorized considering their working principles. Fabrication and construction processes will be explained over Computer Aided Manufacturing (CAM) technology including different ways of fabrication and methods of construction.

In the fourth chapter, case study will be done. Case studies will be explained in detail considering all the topics that were examined in chapters two, three and four. Therefore, each case study will be discussed over its main design model, tool, form-structure relationship, design process, structural system solution and fabrication process.

Consequently, the fifth chapter is an analysis of how the digital technologies have affected form-structure relationship during design and construction phases. The analysis further focuses on constructability of forms taking base digital structural design, fabrication and construction processes.

CHAPTER 2

DIGITAL STRUCTURAL DESIGN KNOWLEDGE

Form creation process, structural creation process or both of them are controlled by models and tools. Models determine the boundaries of the design process and establish the rules of generation. Tools become the main design mediums where digital architectural and structural design processes evolve.

2.1. Models

Architects and engineers use models for managing design processes. They use them both for controlling the design processes and controlling the forms. The internal generative logic of the model generates the final outcome. Therefore, the design logic and the process gains importance as Kolarevic states; “the emphasis shifts from the making of form to the finding of form.”[42] The choice of design parameters and the type of relationship between the parameters differ in terms of the chosen generative model. Input parameters refer to different concerns in every design model. There are five main design models which are taken as base during digital design processes. These models are; biological models, motion and force based models, performance based models, parametric models and evolution based models.

2.1.1. Biological Models

Architects borrowed software programs from other industries such as movie industry, automotive industry, naval industry, aircraft industry etc. These software programs offered new languages to architects such as surface design technology from automotive industry or the polygonal faceting language of folding programs from origami. However, these programs have limitations and are being used in their industries just for specialized functions. For example in movie industry, biological-

[42] Kolarevic, Branko. 2009. p. 13.

looking forms are generally being generated because of the need for animal characters or creatures in movies; and in automotive industry, forms of cars are being generated. The adopted programs allow to design only in accordance with their purpose and capacity.[43] In digital design, because of the software programs that are borrowed from other disciplines such as movie industry, biological looking forms appear. Thus, architects base their projects' conceptual, formal and structural designs on the shapes of biological models such as water drop and living organisms.

2.1.1.1. Water Drop

In biological models, water drop is one of the inspirational starting points for the design process. Like when two water drops come closer and relate with a cohesion force, conceptual blobs that stand for water drops also relate with each other during design process. As blobs come together and interact with each other, surfaces of the blobs deform and constitute a single continues surface. With the help of digital technologies, both blobs and their influence fields can be modeled. In addition, the interaction between blobs and the generation of a new form can also be visualized.

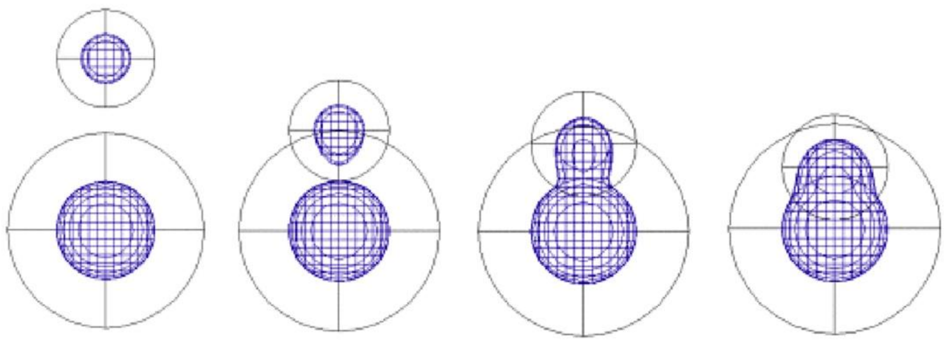

Figure 2. 1. Interaction and addition of blobs constituting a single surface
(Source: Kolarevic, 2000)

Lynn works with blob models in his studies and calls them in many different ways such as isomorphic polysurfaces, meta-clay or meta-balls models. Each blob has

[43] Lynn, Greg, and Mark Foster Gage, eds. 2010.

its own determined mass. Blobs' internal forces and external relations with each other contribute to their definition. Every blob's center, surface area, mass and organization are determined based on each other's influence fields. A blob's interior volume defines a zone where it can connect with other blobs by constituting a continuous surface. Outer volume defines a zone where other blobs can affect the surface of the blob. There are two types of interaction between blobs; fusion and inflection. When blobs are related to each other, they can either fuse into a single continuous surface based on the interaction of their centers or their surfaces can deform and curve inward based on each other's gravitational properties.[44]

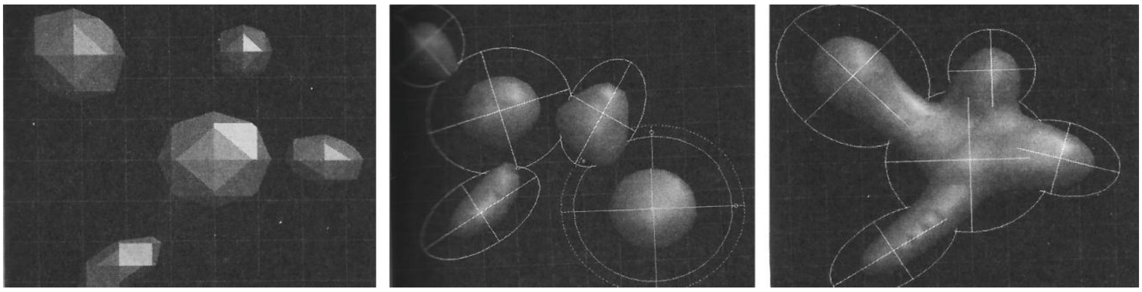

Figure 2. 2. Fusion of blobs with attraction forces
(Source: Lynn, 1998)

Kolarevic also works with blob models and defines the study of blob like forms as isomorphic architecture. He makes a definition of blobs as; "blobs or metaballs, as isomorphic surfaces are sometimes called, are amorphous objects constructed as composite assemblages of mutually inflecting parametric objects with internal forces of mass and attraction."[45] Blobs are in relation with each other and influence themselves. As Lynn states there are two types of influence between blobs such as fusion and inflection; Kolarevic identify the relation types as additive (positive) and subtractive (negative). With addiction or subtraction, new forms can be generated. There is always an opportunity for a new blob to be added and the whole is always open to variation. Therefore, the isomorphic surface boundary can be identified as dynamic.[46]

[44] Lynn, Greg. "Blob Tectonics, or Why Tectonics is Square and Topology is Groovy." Folds, Bodies & Blobs: Collected Essays. Ed. Michele Lachowsky, Joel Benzakin. Bruxelles: La Lettre vole, 1998. 169-182
[45] Kolarevic, Branko. 2000. p. 99.
[46] Ibid. pp. 98-103.

Bernard Franken's "Bubble BMW Exhibition Pavilion" is an example for the biological model where water drop is taken as a conceptual start for the design process. Dynamic balance of two water drops and finally fusion generated the final form and therefore the structural system, which was abstracted from the main geometry. [47]

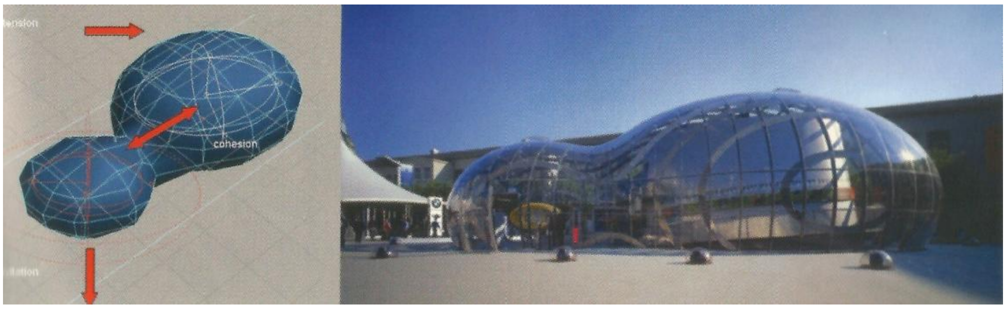

Figure 2. 3. Interaction of two water drops constituting a built form, The Bubble, BMW Exhibition Pavilion, Frankfurt, Germany, Bernhard Franken and ABB Architekten (Source: Kolarevic, 2009)

2.1.1.2. Living Organisms

Living organism is another biological model that architects use to define and control the design processes. Animals, plants, human body can be examples for living models where they are taken as conceptual references. Iidabashi Subway Station project by Makoto Sei Watanabe is a building example whose design process is based on formally and structurally on the shape of a plant. He thought that the way living organism develops, architectural design could also develop in that way. Therefore, the mechanism of growth became the model for the design team.[48]

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[47] Kloft, Harald. 2006. p. 250.
[48] Watanabe, Makoto Sei. "Subway Station / Iidabashi 2000" Algorithmic design / Induction design. 7 March 2013 < http://www.makoto-architect.com/subway/subway_2e.html>

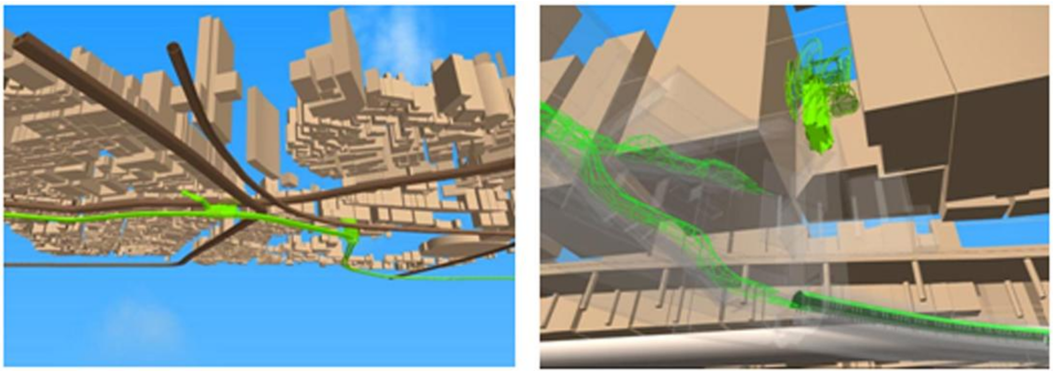

Figure 2. 4. Growing of a seed from underground to ground level
(Source: http://www.makoto-architect.com/subway/subway_2e.html)

Growing logic of a plant became the starting point. Designer thought of a seed conceptually. Extending roots of the seed became the pedestrian circulation in underground. The leaves of the plant called as the wing became the ventilation tower. The wing above ground consists of the ventilation and air-conditioning equipments for the subway station, such as a respiratory organ for the plant.[49]

Figure 2. 5. The wing above ground
(Source: http://www.makoto-architect.com/subway/subway_2e.html)

Structural design of the wing was also generated using computer programs. For creating a structural frame, a grid-work was designed and analyzed over stresses based

[49] Ibid.

on structural dynamics. Where stresses were great, tubular members of the framework became thicker, and where forces were weak, tubular members of the framework became thinner.[50]

2.1.2. Parametric Models

Parameters and their relations constitute the basis for parametric models. The relations between parameters are defined by algorithms and shape is generated by inputting parameters into the algorithmic formulas. Parameters can be sun angle, wind direction, pedestrian movement or car traffic. As parameters are computationally and geometrically related to each other; if the value of one parameter changes, all the other related parameters change and adapt to new situation based on the defined algorithmic formulas. In his article of "Paramorph," Mark Burry emphasizes the importance of the relation of parameters by stating that; "the ability to define, determine and reconfigure geometrical relationships is of particular value."[51] Therefore, by changing parameters, various shapes can be generated. In addition, rather than inputting different parameters, changing the type or the degree of the relationship also affects the final product.

Parametric model can be used both for generating form and designing structural system. Therefore, parameters can be member size, length, joint type, height, site constraints etc. Channel Tunnel Railway Terminal by Nicholas Grimshaw and Partners is an example to the usage of parametric model for structural design where parametric equations and relations generated the outcome during computational design process.

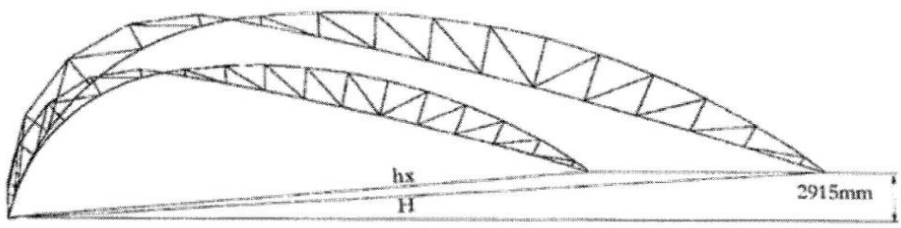

Figure 2. 6. Parametric definition of the scaling factor for the truss geometry; hx = ((29152 + (B + C)2)½ where B is the minor truss span, and C is the major truss span (Source: Kolarevic, 2009)

[50] Ibid.
[51] Kolarevic, Branko. 2009. p. 18.

It is advantageous to use parametric model for the design of a system which is required to be adjustable and changes continually through the building like the Channel Tunnel Railway Terminal. Thus, rather than assigning rigid values such as dimension, size or length to the structural system, parameters are assigned which can be changed at any time based on the design criteria such as site constraints, changing span or height of the building.[52]

2.1.3. Motion and Force Based Models

Motion and force based models rely on the relationship between architectural object and its environment. Design evolves in relation with its environment considering external affects and forces as Kolarevic states; "architectural form, in other words, is not only a manifestation of its internal, parameter-driven relational logics, but it also has to engage and respond to dynamic, often variable influences from its environmental and socio-economic context."[53] External forces can be environmental forces that exist in the site such as wind direction, pedestrian flow, car traffic and gravity, or can be conceptual forces that do not originate within the context but related with the program. Forces are recorded as numerical data into the digital design process and then stored on the surface of form by the integration of the form and the context. The design process of The Paramorph Project of Mark Goulthorpe from dECOI is an example where motion and force based model was used. Form was generated in interaction with field forces such as movement of people and sound which were the results of the dynamic character of the site.[54]

[52] Burrows, Stephen, and Martin Simpson. "The Stadium geometry." The Arup Journal 44.1 (2009): 19.
[53] Kolarevic, Branko. 2009. p. 19.
[54] Goulthorpe, Mark. 2009. pp. 163-180

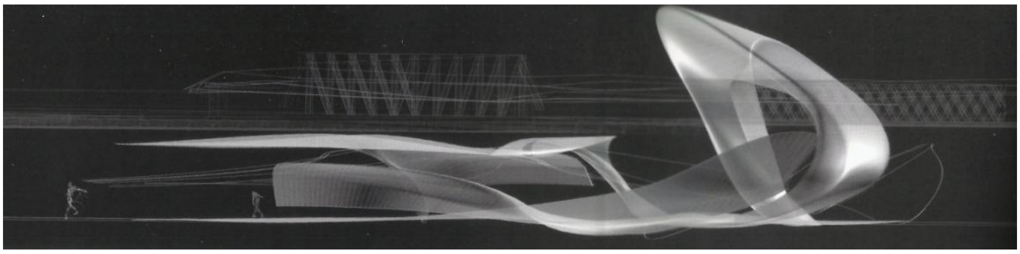

Figure 2. 7. The Paramorph Project, Mark Goulthorpe
(Source: Goulthorpe, 2009)

Selection of environmental forces for form generation is based on architect's judgment. While an architect can use the pedestrian and car movement in the site, another can use the wind direction and eliminate pedestrian flow. According to the main idea that lies behind the design or aesthetic concerns of the designer, the chosen forces are inserted into the design medium. For example, while architect Lars Spuybroek in his Water Pavilion project generates the building geometry based on movement of the visitors and site influences;[55] Lynn in his House Prototype in Long Island generates the form of the building based on only environmental forces without an emphasis on movement of people.[56]

Lynn defines the usage of force and motion in the design field for deformation and generation of a system as animate architecture. He uses some motion-based modeling techniques such as keyframe animation, forward and inverse kinematics, dynamics (force fields) and particle emission for creating animate architecture and modeling the design medium as a space of interacting forces. In kinematics, there is the study of motion of an object without considering the forces acting on it. In dynamic simulation, there is the study of motion of an object including the effects of environmental forces which were recorded as input data into the surface of the form.[57] All these animation techniques give opportunity to designer to see the deformations of form as a result of the affecting forces in the medium. End product can be one of the instances over time or it can be the unification of all different configurations in one single fusion like in Greg Lynn's Port Authority Gateway Competition Project.[58] The structural design process of the Port Authority Gateway Competition Project is an

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[55] Spuybroek, Lars. NOX: Machining Architecture. New York: Thames & Hudson, 2004.
[56] Lynn, Greg. 1999.
[57] Kolarevic, Branko. 2000. pp. 98-103.
[58] De Luca, Francesco, and Marco Nardini. 2002.

example where a force and motion based model was used and therefore, attraction and repulsion forces in the site shaped the building. During design process, particles were located into the site and force fields were applied for a time. Based on the external forces in the site including pedestrian movements, car and bus flows, particles changed their locations. The different instances and the location of particles at those instances during application of force fields were captured and superimposed. As a result of the superimposition, curvilinear lines were generated which became the tubular members of the structural system.[59]

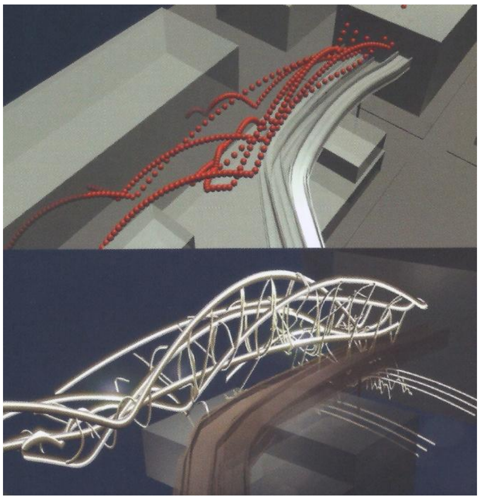

Figure 2. 8. Superimposed instances constitute the structural design, Port Authority Gateway Competition Project, Greg Lynn (Source: Kolarevic, 2009)

The Dutch firm MVRDV, who also uses motion and force based models in their designs, puts forward a concept of “Datascapes.” By “Datascapes,” they visualize the field forces and study their relations with built environment. For every type of external force, they construct a different datascape and at the end they superimpose all the datascapes. Thus, MVRDV uses the generative potential of this complex superimposition in their designs.[60] Kolarevic also emphasizes the importance of “Datascapes” by stating that; “these informational landscapes become essential in understanding how these intangible influences manifest themselves in the built

[59] Lynn, Greg. 1999.
[60] Kolarevic, Branko. 2009. pp. 11-28.

environment and how societal, economic, political and cultural fluxes and shifts influence contemporary architecture."[61]

2.1.4. Performance Based Models

In performance based models, design process develops based on performance analyses. Financial, cultural, social, spatial, technical or material performances are examples to performance criteria. While form can take shape based on ecological performances considering sun angle or wind direction, it can also take shape based on technical performances including structural system analyses over strength and stability.[62] Performance analyses take place in performance-based simulation and analysis softwares such as Finite Element Method (FEM) and computational fluid dynamics (CFD). While structure, energy and fluid dynamics analyses take place in FEM; airflow analyses take place in CFD.[63]

In digital design processes, which are based on performance based models, geometric alterations can be seen over form. Form can deform in response to optimizations and performance analyses.[64] In addition, choosing the performance type is based on the concept of the project and design intention of the architect. For example, the form of the Kunsthaus of Peter Cook and Colin Fournier in Graz was optimized considering structural analyses by consulting engineers Bollinger + Grohmann. For improving structural performance of the building such as increasing its geometrical stiffness, and to address manufacturing issues; roundness of the roof was increased.[65]

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[61] Ibid. p. 22.
[62] Kolarevic, Branko. 2000. pp. 98-103.
[63] Kolarevic, Branko. 2009. pp. 11-28.
[64] Ibid.
[65] Chaszar, André. "Cooperation of Bernhard Franken with Klaus Bollinger and Manfred Grohmann." B+G Ingenieure Bollinger und Grohmann GmbH.

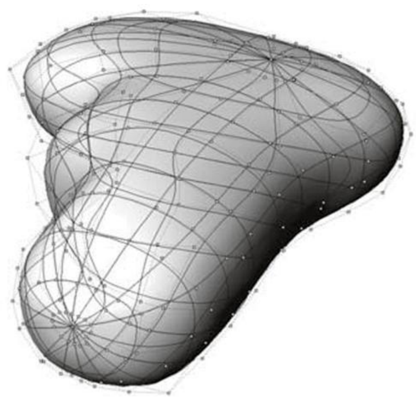

Figure 2. 9. Modified form, Kunsthaus Graz, Peter Cook and Colin Fournier
(Source: Kolarevic, 2005)

2.1.5. Evolution Based Models

Evolution based model takes genetic algorithm and biological growth as the bases for form generation. As living organisms have DNA where humans' genes are encoded in, architectural design process also has string like structures like DNA where design information are encoded as parameters. As processes such as gene crossover and mutation occur for information change over humans' genes, same processes occur in architectural design processes for generating various forms. Therefore, organizing and controlling the inner logic is important rather than the final outcome in evolution based models as in all the digital models. John Frazer is an example who advocates the application of generative process of nature into architectural design processes in his book of "Evolutionary Architecture."[66]

Design parameters can be length, width, height and color which are recorded as numerical data into design process. After parameters are recorded, rules of reproduction, gene crossover, and mutation are applied to the parameters based on the rules of evolution based model. At the end of the design process, many similar forms are generated which belong to same family. According to fitness criteria, the most suitable forms are selected.[67] Same processes of reproduction and mutation are again

[66] Kolarevic, Branko. 2009. pp. 11-28.
[67] Kolarevic, Branko. 2000. pp. 98-103.

applied to these selected forms for generating more efficient and optimum designs which took beneficial and survival-enhancing features of former generations.[68]

For example, an evolution based model was applied to the design for a new architecture faculty building in Stuttgart (2009) by the Laboratory for Visionary Architecture (LAVA) in collaboration with Bollinger + Grohmann. Evolutionary design process enabled parameter input both from architectural design and structural design. Different organizations of floor slabs and shear walls in a three dimensional matrix became the input parameters which were analyzed during design process considering functional and structural requirements. By changing the organizations of floor slabs and shear walls based on reproduction and mutation, various alternative design solutions were generated. The results were analyzed and eliminated in terms of structural performances, and the ones which had the smallest bending moments and the best composition of shear walls were selected for the following generation process. The generation process continued for the generation of an optimum solution which satisfied all the architectural criteria as well as structural constraints. [69]

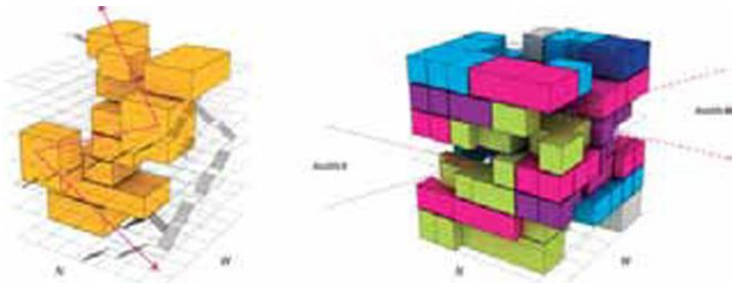

Figure 2. 10. Three dimensional diagrams of solid and voids, Architecture Faculty Building, Stuttgart, LAVA (Source: Bollinger, Grohmann, Tessmann, 2010)

2.2. Tools

Architects use design tools for generating and controlling the forms. Whether manual or computational, tools are needed in every phase of design, starting from design ideation to manufacturing and construction. Computational geometrical studies,

[68] Kolarevic, Branko. 2009. pp. 11-28.
[69] Bollinger, Klaus, Manfred Grohmann, and Oliver Tessmann. 2010. pp. 34-39.

computer programs, physical drawing and model making are examples to tools that are used in digital architectural and structural design.

2.2.1. Geometry

Geometry has been integral into architecture throughout centuries. Architects use geometry as a design language for designing and controlling shapes. Geometry is a tool for shape creation and also representation. However, there are some differences in today's digital era such as complexity of mathematical functions and the disappearance of defined geometric descriptions.[70] Digitally designed shapes are the result of the usage of non-Euclidean geometry. Assistance of digital technologies to architectural design which has a mathematical and computational background has a role in departure from the Euclidean geometry. By computer aided design, architects are able to design various shapes in a short time that could not be imagined of in the absence of digital technologies. Usage of non-Euclidean geometry enables architects and engineers to design various irregular shapes and forms. Irregularity of non-Euclidean geometry takes place regularity of the Cartesian grid system and the Euclidean geometry which composes of basic shapes such as circles, squares and rectangles.

For using irregular geometries in creation of complex shapes, background information is needed in terms of geometry. Complex geometric software programs require further knowledge for architects to control the geometry for the shape creation process.[71]

2.2.1.1. Identifying Geometry in Digital Design Processes

In architects' project descriptions, it is seen that non-Euclidean geometry is expressed in many different ways. For example, Kolarevic expresses non-Euclidean geometry as "complex curvilinear geometry" in his book titled "Architecture in the digital age". He compares the easiness of shape creation with non-Euclidean geometry

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[70] Steele, Brett. "Weapons of the Gods – The Paradoxical Mathematics of Contemporary Architecture." The New Mathematics of Architecture. Jane Burry, Mark Burry. London: Thames & Hudson, 2010. 6-7.
[71] Pottman, Helmut. "Architectural Geometry as Design Knowledge." Architectural Design: The New Structuralism-Design, Engineering and Architectural Technologies 80.4 (2010): 72-77.

and Euclidean geometry by stating that; "complex curvilinear geometries are produced with the same ease as Euclidean geometries of planar shapes and cylindrical, spherical or conical forms."[72]

Greg Lynn also emphasizes the shift from linearity to curvilinearity in his book "Animate Form". By using the concepts of "flexible" and "continuous," he defines the digitally designed forms. By "flexible" and "continuous," he also refers to the usage of non-Euclidean geometry in the surfaces of the forms.[73]

Lars Spuybroek sees architecture as an art of line. In his book "Machining Architecture," he works on "complex lines" and "complex tectonics" which are the end products of computational processes. His uses of "complex lines" and "complexity" are mathematical references to non-Euclidean geometry.[74]

"Non-Cartesian," "non-hierarchical," "asymmetrical" and "non-linear" are the concepts that Nina Rappaport uses in her article of "A Deeper Structural Theory." She refers to the mathematical and generative logic behind the forms which is non-Euclidean geometry.[75]

Wolf Mangelsdorf uses the term of "geometrically complex" to identify the forms, and "complex geometry" to refer to the usage of non-Euclidean geometry in these forms in his article of "Structuring Strategies for Complex Geometries".[76] Helmut Pottmann also uses the concept of complexity to refer to the usage of non-Euclidean geometry during digital processes in his article of "Architectural Geometry as Design Knowledge." He identifies the designed shapes as "highly complex geometries."[77]

2.2.1.2. Controlling Geometry in Digital Design Processes

In digital architectural and structural design processes, geometry can be controlled by two ways. Architects can use NURBS for manual intervention, or they can enter the parameters and then the computational software generates the outcome automatically.

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[72] Kolarevic, Branko. 2009. p. 13.
[73] Lynn, Greg. 1999.
[74] Spuybroek, Lars. 2004.
[75] Rappaport, Nina. "A Deeper Structural Theory." Architectural Design: The New Structuralism-Design, Engineering and Architectural Technologies 80.4 (2010): 122-129.
[76] Mangelsdorf, Wolf. 2010. pp. 40-45.
[77] Pottman, Helmut. 2010. pp: 72-77.

2.2.1.2.1. With NURBS

In pre-digital era, architects were drawing curvilinear lines from regular circles. They were grounding their designs on Euclidean geometries. For creating curvilinear lines, they were either bisecting circles to create arches or dividing them into more than two pieces and then connecting to create more complex curvilinear lines.[78] They were also drawing concatenating tangent circular arcs and straight line segments within them on papers to create curvilinearity.[79] Although curvilinear lines were complex, the origin was still regular geometries.[80]

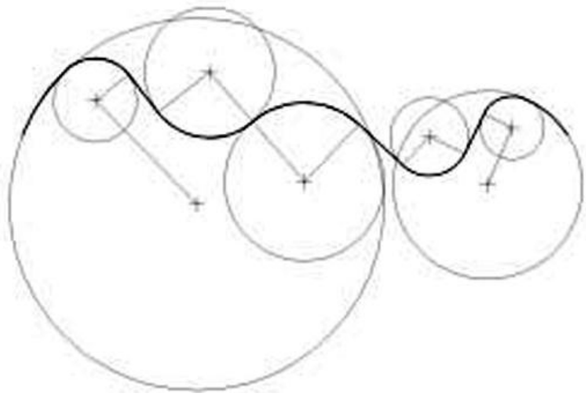

Figure 2. 11. Concatenating tangent circular arcs and straight line segments
(Source: Kolarevic, 2009)

With introduction of digital technologies into architecture, computer aided design gave opportunity to architects to design the desired forms freely with continuous curves and surfaces of non-Euclidean geometry. Defining these irregular curves and surfaces was not possible with the basic shapes of Euclidean geometry. Therefore, specialized splines were started to be used in digital design processes which are described mathematically as NURBS (Non-Uniform Rational B-Splines). Initially NURBS were being used in disciplines such as naval design and automotive industry, which was then transferred into digital architectural design process.

[78] Lynn, Greg, and Mark Foster Gage, eds. 2010.
[79] Kolarevic, Branko. 2009. pp. 11-28.
[80] Lynn, Greg, and Mark Foster Gage, eds. 2010.

Rogers and Earnshaw define NURBS as; "a very flexible mathematical instrument for the construction of complex shapes in a computational scope"[81] in their book of "State of the Art in Computer Graphics: Visualization and Modeling." NURBS can be controlled with control points, weights and knots on it. By changing the defined location of these control points, weights and knots, various curves and finally shapes can be created including a straight line as well as a complex curvilinear surface.[82]

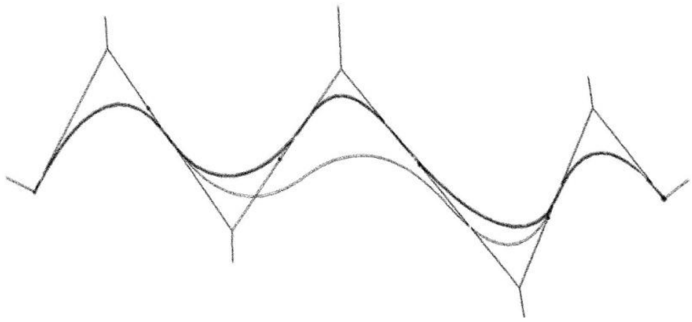

Figure 2. 12. Varying NURBS curves
(Source: Kolarevic, 2009)

NURBS curves are controlled primarily by the control points. Changing the location of the control points deforms the curve. Weights related to these control points determine the control point's influence over the curve. For example, if the weight of a control point increases, the corresponding curve approaches to that control point. Changing the location of the knots is another factor which determines the control point's influence over the curvature. Knots link the control points.[83]

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[81] Papi, D. G. "Infoarchitecture." Digital Architecture and Construction. Ed. A. Ali, Carlos A. Brebbia. Southampton: WIT, 2006. 150.
[82] Kolarevic, Branko. 2009. pp. 11-28.
[83] Ibid.

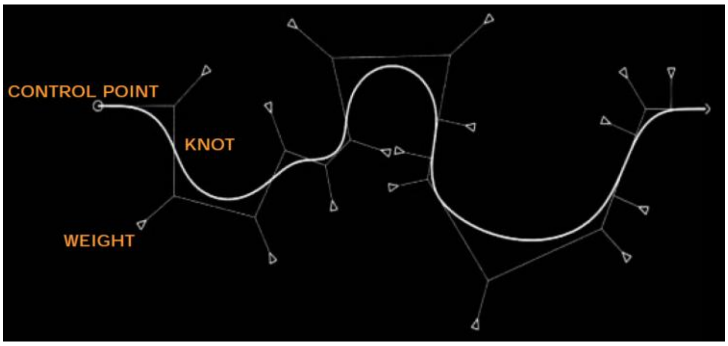

Figure 2. 13. Control points, knots and weight on NURBS
(Source: Kolarevic, 2005)

Kolarevic emphasizes the importance of NURBS and the reason behind its widespread usage within today's software programs in his book titled "Architecture in the Digital Age." According to him, NURBS generate and model the surfaces with minimum amount of data relying on only few steps for shape computation.[84] By using NURBS, surfaces can be modified easily and architects can design surfaces and shapes which could never be imagined of without the usage of computer aided design. Rhino is an example to NURBS based modeling programs that gives ability to architects to manage a variety of free surfaces and forms.

2.2.1.2.2. Parametrically Calculated

Geometry can also be controlled and generated by algorithmic definitions and codes. Internal generative logic is important in parametric processes. Parameters and their relations generate the final geometry. Based on the parameters and the determined relationships between the parameters that come from the computational design model, final form emerges. By assigning different values to parameters, designer is able to see an infinite number of possible options. There is no manual attempt to design process such as modifying NURBS with their control points. Architect only identifies the parameters and their relations in the beginning of the design process and simulates the process for the generation of shapes.

Even though architects control geometry in digital design processes in two different ways, there is a common point in both of them. Whether digital design process

[84] Ibid.

involves the study of NURBS or parameters; the resulting form always has the NURBS surface.[85]

2.2.2. Computer Programs

Computer programs such as CATIA, Rhino and Maya are tools that architects use in digital architectural and structural design processes for generating and controlling the shapes. Actually, these programs did not develop for architectural design purposes. They were borrowed from other disciplines such as automotive industry, aircraft and naval industries.[86] They became the design mediums for architects and engineers where they construct their designs.

Computer programs can be collected under three main headings according to their functions. They can be used for generating structural design, modeling structural design and analyzing structural design.

2.2.2.1. For Generating Structural Design

Programs like eifForm, MoSS, Genr8 and ParaGen have generative functions. Architects use them in digital design processes for generating structural systems rather than using them to analyze an already proposed design. They enter the input data and let the program work to create the final output based on design criteria. For example, eifForm program generates 3-D truss systems from linear members joined by pin connected nodes. Parameters such as size and type of the members are inputted into design process. Based on criteria including economy, stiffness and stability; eifForm optimizes the design and gives its final shape. For example, the material volume of the structure can be decreased for optimizing the structure topologically and geometrically under determined load conditions. eifForm program also has a capability to offer more than one solutions that satisfy the design criteria.[87]

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[85] Colajanni, B., G. Pellitteri, and S. Concialdi. "Which New Semantic for New Shapes?" Digital Architecture and Construction. Ed. A. Ali, Carlos A. Brebbia. Southampton: WIT, 2006. 1-10.
[86] Imperiale, Alicia. 2000.
[87] Leuppi, Judith, Shea, Kristina. "The Hylomorphic Project." The Arup Journal 43.1 (2008): 28-30.

The structural system built in the courtyard of the Academie van Bouwkunst is an example project where eifForm was used for generation of the building. Initially, design criteria were recorded computationally such as the ground support points, height, and length. After parameters were recorded, designers unleashed the program and a structural organization was emerged which satisfied all the design and structural considerations.[88]

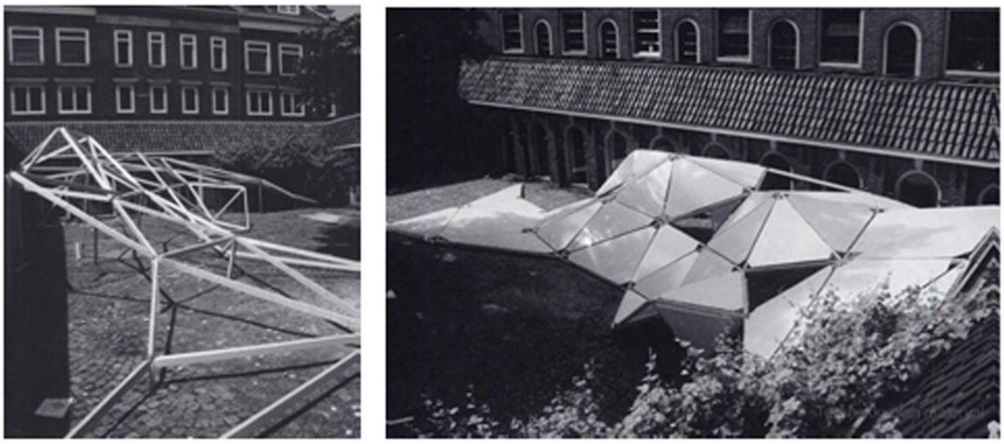

Figure 2. 14. Construction process of the structural system
(Source: Leach, 2002)

Neil Leach emphasises the importance of the generative process based on input parameters and design constraints in the book of "Swarm Tectonics." He states that; "the designer merely establishes certain defining coordinates, and then unleashes the program which eventually crystallizes and resolves itself into a certain configuration."[89]

2.2.2.2. For Modeling Structural Design

Architects use modeling software to model an existing structural system which was designed and generated already by other generative programs. These modeling programs are mostly used for producing construction drawings by detailing the

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[88] Leach, Neil. "Swarm Tectonics." A/S/L: architectuur, stedebouw, landschapsarchitectuur: jaarboek Academie van Bouwkunst Amsterdam/Maastricht 2001-2002. Ed. Laurens Jan ten Kate, Eric Luiten, Ellen Marcusse, Aart Oxenaar. Rotterdam: Uitgeverji 010 Publishers, 2002. 125.
[89] Leach, Neil. 2002. p.125.

structural systems. Material choices are recorded into the system and connection elements such as bolts and screws are modeled in detail till their locations and sizes. Therefore, the whole system can be modeled with its connection details and structural members including columns, beams and slabs.

Bentley PowerRebar and ProSteel are two software examples that are used for modeling purposes. They differ in terms the modeled material. Bentley PowerRebar application realizes modeling and detailing of reinforced concrete systems. It can be applied to a wide range of structures such as buildings, bridges and foundations.[90] Bentley's ProSteel also realizes modeling and detailing of systems for producing shop drawings. Different from reinforced concrete systems, structural steel and metal works can be modeled in this program.[91]

2.2.2.3. For Analyzing Structural Design

Architects use analysis programs for predicting the behavior of their designs in desired and planned way within physical world. Results of the analyses show the way building will behave under live and dead loads such as wind load, seismic load, thermal load, people load and snow load. Architects make analyses either during design process or in construction phase after the completion of design. During design process, analyses cause revisions on structural design whereas in construction phase, analyses over structural system cause minor optimizations on structural design. Optimizations are integrated into design as technical feedback, maintaining design intention, and supporting constructability.[92]

Before computer based analysis programs, architects were making empirical analyses by themselves using prototypes. Compasses, curved plastic aids (french curves), pens-tied-to-ropes and clay models were some of the methods that were used for making the prototypes of the complex irregular forms. Builders' superior craftsmanship and their relation with the architect were also important for construction. In addition, construction was following trial and error methods and buildings were

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[90] Bentley. "Reinforced Concrete Detailing and Scheduling." BentleyPowerRebar. 29 Apr. 2013 <http://www.bentley.com/tr-TR/Products/Bentley+PowerRebar/>.
[91] Bentley. "Structural Steel Detailing and Fabrication." ProSteel. 29 Apr. 2013 <http://www.bentley.com/tr-TR/Products/ProSteel/>.
[92] Al-Haddad, Tristan Farris. "PerFORMance: Integrating Structural Feedback into Design Processes for Complex Surface-Active Form." MA Thesis. Georgia Institute of Technology, 2006.

being demolished and rebuilt again until architect gained his desired form.[93] With availability of the computational software, architects became able to make analyses easier and faster than before over their designs with also greater accuracy.

Finite Element Method (FEM) can be given as an example that is used for the computational analyses of structural performances, material qualities, and energy and fluid dynamics. Finite Element Analyses environments consist of three discrete parts which are; pre-processor, solver, and post-processor. First part is the inputting part. The designed structural system is imported into the analysis program as the Finite Element Model from the design environment with the help of algorithms. A Finite Element Model is a three dimensional model that consists of small, interconnected mesh elements (Finite Elements) such as two-dimensional mesh elements, volumetric mesh elements and nodes;[94] representing the geometry's structural arrangement, components, details and connections. Solver is the part where the determined type of analysis takes place such as analyses of stability, cost, stiffness etc. Finally, post-processor is the part where the results of the analyses are expressed with representations such as visual and colourful graphics, behavioural animations, and so on.[95] In the colourful representations of the FEM analyses, every colour has different meanings. For example, in the FEM analysis of the envelope of the Bubble Pavilion, the red area over the surface shows where highest stresses and greatest deformation are.[96]

[93] Penttilä H "Describing the Changes in Architectural Information Technology to Understand Design Complexity and Free-Form Architectural Expression." ITcon, Special Issue: The Effects of CAD on Building Form and Design Quality 11 (2006): 395-408. 3 May 2013 <http://www.itcon.org/data/works/att/2006_29.content.02253.pdf>.
[94] Bechthold, Martin. Innovative Surface Structures_Technologies and Applications. Abingdon, Oxon: Taylor and Francis, 2008.
[95] Al-Haddad, Tristan Farris. 2006.
[96] Kloft, Harald. 2006. pp. 248-255.

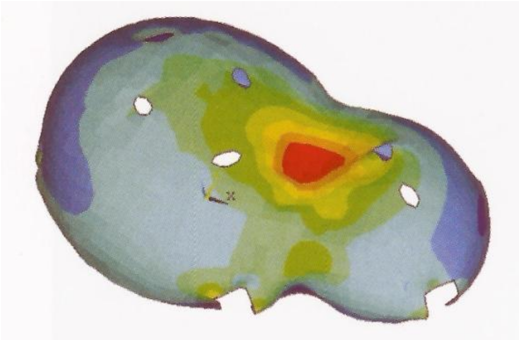

Figure 2. 15. The FEM analysis of the envelope, Bubble BMW Pavilion, Frankfurt, Germany, Bernhard Franken and ABB Architekten (Source: Kolarevic, 2009)

Swiss Re building by Foster and Partners is another example where Finite Element Analysis was used. FEA was used in this project for analyzing the stresses within the structural façade.[97] The triangulated structural system was modeled using mesh elements and their connection nodes with their actual thicknesses and material properties for keeping the validation of the analysis. The nodes were able to rotate during analysis process to let the mesh model deform under stress and load calculations. At the end, displacements of each node and member were calculated and the whole deformation of the system was computed.[98] The analysis results were used to revision and evaluate the system, and finally create a more structurally efficient shape.

[97] Kolarevic, Branko. “Computing the Performative.” Performative Architecture: Beyond Instrumentality. Ed. Branko Kolarevic, M Ali Malkawi. New York: Spon Press, 2005. 193-202.
[98] Bechthold, Martin. 2008.

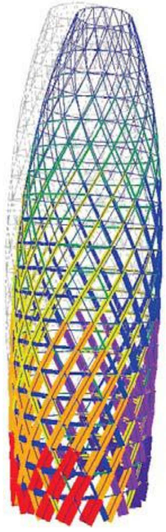

Figure 2. 16. The FEA analysis, Swiss Re, London, Foster and Partners
(Source: Kolarevic, 2005)

Architect Tristan Farris Al-Haddad also points out that, prototypes of the objects should be created in order to support the Finite Element Analyses. As FEM works with approximations, it can contain machine and human errors. Therefore, by using Rapid Prototyping, physical objects are constructed and tested in real world with real material, and the results of the tests are used to validate the FEM results. Thus, Finite Element Method and Rapid Prototyping complement each other.[99]

2.2.3. Physical Drawing-Model Making

Whether it is seen that architectural and structural design proceed in digital medium of computers, some architects still make use of physical drawing and model making in contemporary architecture. They design with hand drawing and make physical models to support their design ideas in three dimensions. Then, they benefit from digital technologies for the manufacturing and construction processes of the building. They scan the physical model by three dimensional scanners and transfer the design from two dimensionality of paper to three dimensionality of digital medium. In some cases, analyses are done over the three dimensional model for testing the behavior of the design in terms of structural stiffness, rigidity, energy consumption etc. As a

[99] Al-Haddad, Tristan Farris. 2006.

result of the analysis results, form can be modified. When design and analysis processes are completed, information in digital medium can be directly used for fabrication.

Frank Gehry is an example who uses computer as a design tool rather than as a partner. In the book titled "Gehry Talks: Architecture and Process," Gehry asserts his thoughts about digital architectural design. He remains skeptical about the generation capability of computers. He thinks that computers are not for inventing surfaces and forms.[100] Indeed, they are for making the designs rational and constructible. He designs with hand drawing and makes models of his drawings. In construction phase, he makes use of digital technologies for translating his handmade models into digital data. Therefore, forms of his models become the input data whereas digital construction drawings and instructions for manufacturing become the output data.

For digitizing physical models, three-dimensional scanning techniques are used. As a result of the scanning, a point cloud is created in digital medium which means a pattern made of points. With the help of software programs, the point cloud is converted to the geometry of the scanned form. The conversion is generally made by the use of NURBS. Points generate NURBS curves and NURBS curves create NURBS surfaces and finally the main form. At the end of the process, created form can be analyzed and compared with the point cloud to see if there is a deviation through the process of conversion.[101]

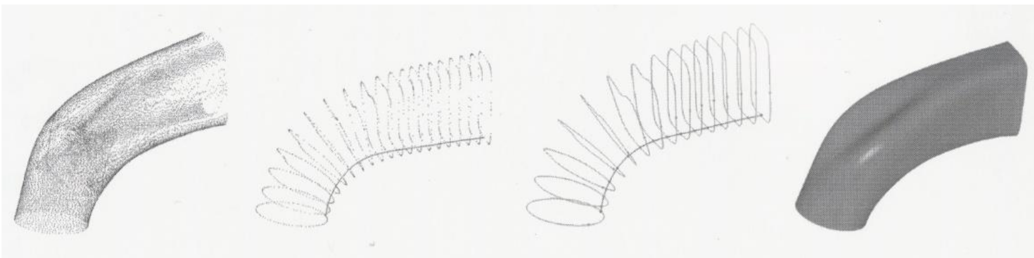

Figure 2. 17. Generation process from point cloud to final form
(Source: Kolarevic, 2009)

[100] Porter, D., and R. Hanna. "Methods for Investigating Architecture: From the Physical to the Digital." Digital Architecture and Construction. Ed. A. Ali, Carlos A. Brebbia. Southampton: WIT, 2006. 59-68.
[101] Kolarevic, Branko. 2009. pp. 29-54.

Three dimensional digitizing arm and Coordinate Measuring Machine (CMM) are two examples that can be used for three-dimensional scanning. They trace the surface features of the model mechanically by staying in contact with the surface. There are also non-contact scanning methods that use laser light to scan and transfer the physical model into digital medium. By laser light, surfaces get illuminated, a pattern of bright dots appear on screen and with the help of optical recognition techniques, a three dimensional form emerges from that pattern.[102]

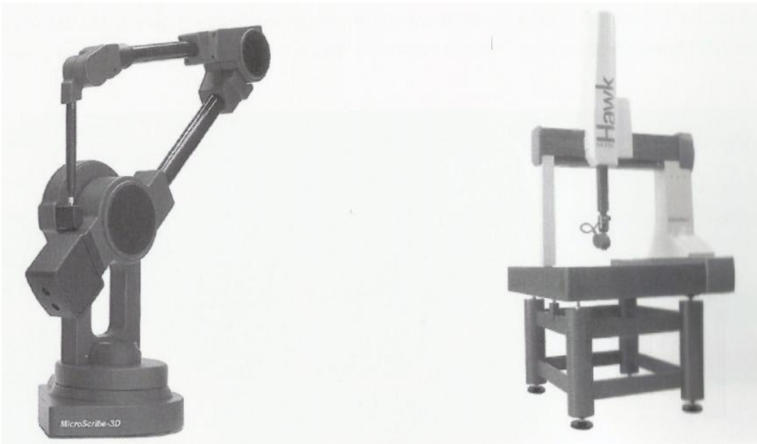

Figure 2. 18. Three dimensional digitizing arm and three dimensional laser scanning machines (Source: Kolarevic, 2009)

Bay House by Miranda Leonard with Walker Moody Architects in San Francisco Bay is a monocoque structure example in which design process started with a physical model and continued digital. At the beginning of the design process, a physical model was created from plaster. Then, plaster model was scanned by laser scanners and transferred to digital medium.[103] By using Rhino3D software, complex geometry of the self-supportive form was defined with NURBS surfaces computationally. The digital data was then transferred to AutoCAD software for preparation of construction

[102] Ibid.
[103] Lynn, Greg, and Mark Foster Gage, eds. 2010.

drawings. Based on construction drawings, nine structural molded fiberglass-skinned sandwich panels were fabricated, transferred and assembled on site.[104]

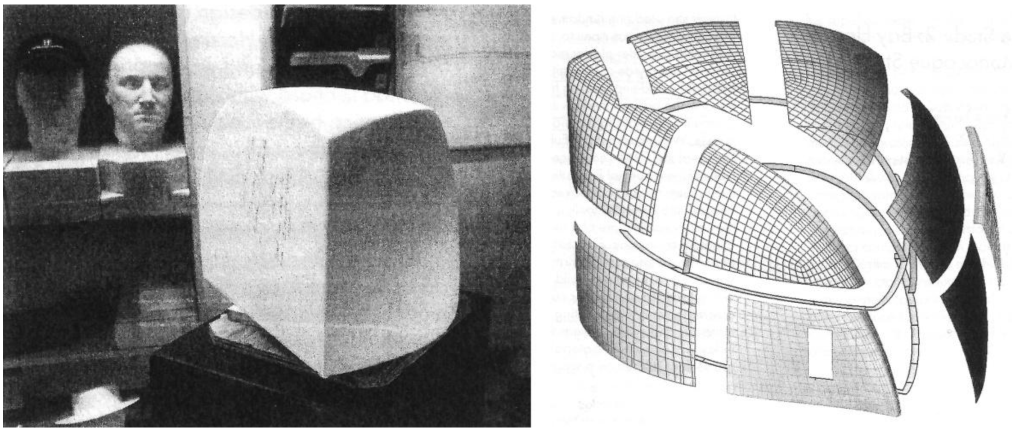

Figure 2. 19. The physical and the digital model, Bay House, San Francisco, Miranda Leonard with Walker Moody Architects (Source: Lynn, Gage, 2010)

[104] Composites Technology. “Residential Construction Breakthrough: Composites Find a Home.” Composites Technology (April 2010). 7 March 2013. http://www.compositesworld.com/articles/residential-construction-breakthrough-composites-find-a-home>

CHAPTER 3

DIGITAL APPLICATIONS IN STRUCTURAL DESIGN

Form-structure relationship is analyzed over structural design's digital applications in this chapter. The existence of structural design in the whole architectural design and construction processes are examined in detail over digitally designed and constructed building examples. Different types of form-structure relations, structural system solutions that carry the complex forms, and finally different ways of manufacturing and construction that make the complex forms realized are revealed.

3.1. Structural Design Process

Design processes in digital architecture become computational and therefore, the ways that structural design exist in these computational design processes becomes an important aspect for construction of buildings that should be examined. There are various form-structure relationships in digital architectural design processes. Architects and engineers can design the structural system in interaction with form creation process or design the structural system in construction process just to make the already designed form constructible. These different design processes can be collected under three main topics which are composite design process, structure based design process and linear design process, based on the relation between structural design and architectural design.

3.1.1. Composite Design Process

In composite design process, structural design and architectural design are integrated with each other. Form and structure evolve in collaboration during computational design process. There is an integrated development of form, structure, materiality, fabrication and construction. Structural analyses and optimizations are allowed to make modifications on the form of the building during form generation. Therefore, structural design is involved into the whole computational process from design ideation to construction. Even though structural design is essential for the realization of the building, it is not involved in the initial architectural form generation process.[105]

Integrated computational process enables to think about form, structure, and material at the same time on the same model. Design process acts as a unique process where all the project participants work in their area of responsibility in relation with each other from form design to construction by using the same software. Models, tools and concepts that define architectural design processes and their end products, direct and control all the process as a whole.[106]

Associate professor Kevin R. Klinger from Ball State University emphasizes the composite and the interrelated structure of digital architectural design in his article of "Relations: Information Exchange in Designing and Making Architecture." According to Klinger, all the participants work in relation with each other for realization of a building starting from the beginning of the design process as he states "analysis, simulation, fabrication, and assembly information are revealed at earlier stages in the process of formulating architecture."[107] Software programs enable consistent exchange of information over participants, therefore; including a wide range of expertise and feedback into the computational design process.[108]

The integrated model in digital architectural design is called as Building Information Modeling (BIM). Architect Jon Pittman describes BIM as; "a model that takes into account performance characteristics, cost and other issues related to the construction and operation of a building, as well as its design"[109] in his article titled "Building Information Modeling: Current Challenges and Future Directions." BIM collects all the useful data through entire design, construction and maintenance processes and provides the opportunity to present the necessary information when it is needed. BIM is accessible by all project participants from designers to manufacturers and tradespeople via online databases such as project websites.[110] If any participant

[105] Kloft, Harald. 2006. pp. 248-255.
[106] Tanyeli, Uğur. 2012. p. 76-83.
[107] Klinger, R. Kevin. "Relations: Information Exchange in Designing and Making Architecture." Manufacturing Material Effects: Rethinking Design and Making in Architecture. Ed. Branko Kolarevic and Kevin Klinger. New York: Routledge, 2008. 26.
[108] Ibid. pp. 25-36.
[109] Pittman, Jon. "Building Information Modeling: Current Challenges and Future Directions." Architecture in the Digital Age: Design and Manufacturing. Ed. Branko Kolarevic. New York: Taylor & Francis, 2009. 256.
[110] Ibid. pp. 253-258.

makes a change on the model, all the other participants are informed with this change with the updates in the program. Therefore, all the actors are in integration with the earliest generative stages.

For keeping the integration between architectural design and structural design, some specialized techniques are needed as architectural historian and critic Nina Rappaport emphasizes in her article of “A Deeper Structural Theory.” She asserts that; for complex and free forms, a structural syntax technique is required in order to provide collaboration between different disciplines.[111] For example, software programs such as MoSS and GENR8 by Peter Testa and Devyn Weiser from the Emergent Design Group (EDG) incorporate structure with form during computational processes. With availability of entering different parameters such as geometrical definition of form, dimensions of structural system and specifications of the material to the design process, a complex contemporary design approach is assisted. These two programs can be used in conjunction with other software programs such as AliasWavefront Studio and Maya platforms which are capable of designing, modeling, rendering etc.[112]

As the relation between form and structure becomes crucial for constructability, new attitudes should be developed that interrelate structure with skin such as using the folds and contours of the form for supportive purposes. In this way, form can also serve as a support itself.[113] Bagneris et al. also argue that weaving the link between form and structural system is the essential point in architectural designs in the article titled “Structural Morphology Issues in Conceptual Design of Double Curved Systems.” He offers a solution which is to design a self-sustaining skin. Apart from that he adds that, rather than designing a self-sustaining skin, also new methods should emerge that keep the coupling between form and structure.[114] For example, architect and civil engineer Wolf Mangelsdorf offers four design strategies that provide the integration of structure, architecture and fabrication in his article titled “Structuring Strategies for Complex Geometries.” The strategies, which are form-finding, simple mathematical geometry, free form and hybrid approach, provide the inclusion of structural behavior into the

[111] Rappaport, Nina. 2010. p. 122-129.
[112] Testa, Peter, and Devyn Weiser. “Emergent Structural Morphology.” Architectural Design: Contemporary Techniques in Architecture 72 (2002): 13-16.
[113] Balmond, Cecil, and Jannuzzi Smith. Informal. Munich: Prestel, 2002.
[114] Bagneris, Marine, Rene Motro, Bernard Maurin, and Nicolas Pauli. 2008. pp. 79-87.

beginning of the design process and therefore, enable generation and engineering of complex geometries.[115]

Architect Lorenz Lachauer and senior researcher Toni Kotnik also study integration of structural behavior into architectural form over a geometric method in their article of "Geometry of Structural Form." They use the "graphic statics" method for analyzing and visualizing the force flows within the structural systems in their study. They also integrate the "graphic statics" method into parametric computer aided design programs such as Grasshopper and present that architectural geometry and structural constraints can be taken into consideration at the same time during architectural design. They name this integrated approach as "direct approach" where structural criteria such as stability, strength, resistance to dead and living loads shape the building, in addition to architect's design decisions and intents.[116]

In the development of a complex design process, performance based model is a generally used model where performance analyses and optimizations are effective on the generation of the form of the building. Based on technical performances such as structural system analyses over strength and stability, form can be modified. For example, Kunsthaus Graz by Peter Cook and Colin Fournier has a composite design process. During design process, the form was optimized and the level of curvilinearity of the surface was increased for improving the structural efficiency of the building.[117]

Design process of Island City Central Park by Toyo Ito & Associates in Fukuoka, Japan is an example to composite design process where structural behavior and architectural considerations are interrelated with each other. During design process, Ito made sketches and physical models based on his interest on complexity and fluid forms of waves. [118] To develop the design and integrate it with structural constraints, the physical model was three-dimensionally scanned to create the digital design data which would be used for the application of structural simulations. [119] Evolutionary Shape Optimizer and Structural Analysis Modelling programs were used for analyzing the

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[115] Mangelsdorf, Wolf. 2010. pp. 40-45.
[116] Lachauer, Lorenz, and Toni Kotnik. "Geometry of Structural Form." Advances in Architectural Geometry 2010. Ed. Cristiano Ceccato, Lars Hesselgren, Mark Pauly, Helmut Pottmann, Johannes Wallner, et al. NewYork: Springer Wien, 2010. 193-203.
[117] Chaszar, André. "Cooperation of Bernhard Franken with Klaus Bollinger and Manfred Grohmann." B+G Ingenieure Bollinger und Grohmann GmbH.
[118] Burry, Jane, and Mark Burry. 2010.
[119] Ito, Toyo. "The New 'Real': Toward Reclaiming Materiality in Contemporary Architecture." Architecture Words 8: Tarzans in the Media Forest & Other Essays. Ed. Thomas Daniell. London: Architectural Associations, 2011. 163-171.

complex shell structure of the building which consists of three greenhouses. The programs sought out the possible solutions which would cover the maximum volume of space with least material possible.[120] In addition, the optimization programs also aimed to minimize the strain energy over the surface thus, creating the stiffest structure.[121]

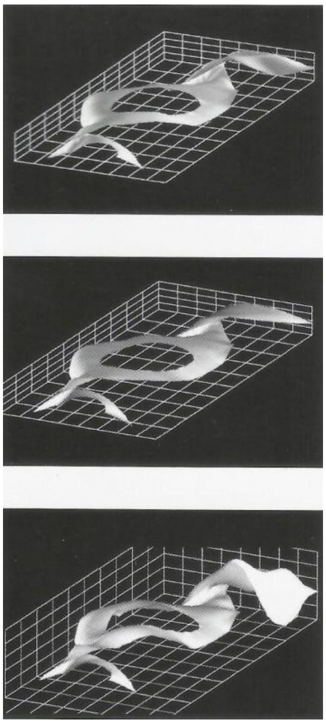

Figure 3. 1. Deformation process of form
(Source: Burry, 2010)

Based on analyses and structural optimizations, the free-form surface that covers the three greenhouses was deformed to take a more efficient shape. Finally, an optimal solution was found which satisfied both the technical needs and design requirements.[122]

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[120] Burry, Jane, and Mark Burry. 2010.
[121] Bechthold, Martin. 2008.
[122] Burry, Jane, and Mark Burry. 2010.

Figure 3. 2. Island City Central Park, Fukuoka, Japan, Toyo Ito & Associates
(Source: Burry, 2010)

Municipal Funeral Hall's design process by Toyo Ito in Kakamigahara, Japan is also an example to composite design process where the design process of the roof of the building was evolved in collaboration with the architect and the structural engineer Mutsuro Sasaki. The design process started with simple sketches which were based on Ito's intent to create a cloud like complex form that would float over the spaces inside. The sketches were then transferred to digital medium for the application of structural analyses. Many calculations were done by structural analyses programs that modified the shape.[123] The shape of the roof was modified also by applying "repeated passes of a refinement algorithm" to give the roof the most structurally efficient form.[124] Based on structural considerations undergoing in digital medium, a final optimum form emerged. As architects and engineers only determined the criteria and run the optimization and analysis programs without any intervention, the final form emerged quite unexpected.[125]

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[123] "Municipal Funeral Hall in Kakamigahara." Detail 2008.5 (2008): 498-502.
[124] Turnbull, Jessie, ed. Toyo Ito: Force of Nature. New York: Princeton Architectural Press, 2012.
[125] Detail. 2008. pp. 498-502.

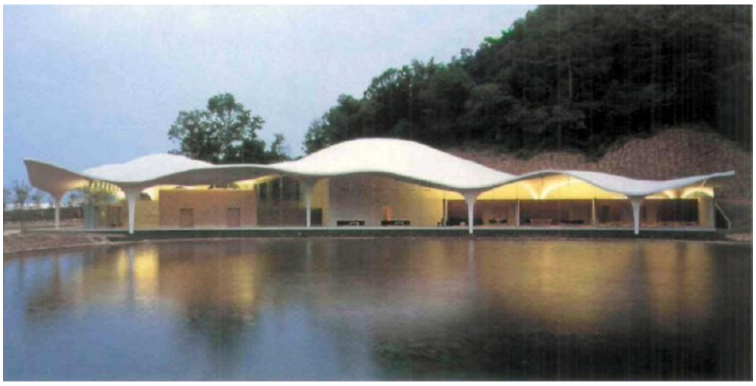

Figure 3. 3. Municipal Funeral Hall, Kakamigahara, Japan, Toyo Ito & Associates (Source: Detail, 2008)

Another example that has a complex design process is British Museum Great Court's glazed roof by Foster and Partners in London, UK where architectural considerations were integrated with structural constraints during design process. There were design constraints such as rectangular plan of the roof with a circular space in the middle and height limits. There were also support conditions of the roof which resulted in an integration of structural constraints and architectural intentions.[126] As the roof would be located onto existing walls, it should not create horizontal thrusts to the building. Therefore, the shell structure that would be constructed over the courtyard would have to resist significant bending moments and shear forces, and had to have a singularity in surface curvature at corners. Based on architectural and structural constraints, the roof form was developed within a parametric design process. It was deformed during design process based on the stress analyses including application of different load conditions, to determine the stiffness of the geometry. As a result, to eliminate the bending moments of the initial flatter roof form and improve its structural efficiency, curvature of the roof was increased.[127]

[126] Burry, Jane, and Mark Burry. 2010.
[127] Szalapaj, Peter. 2005.

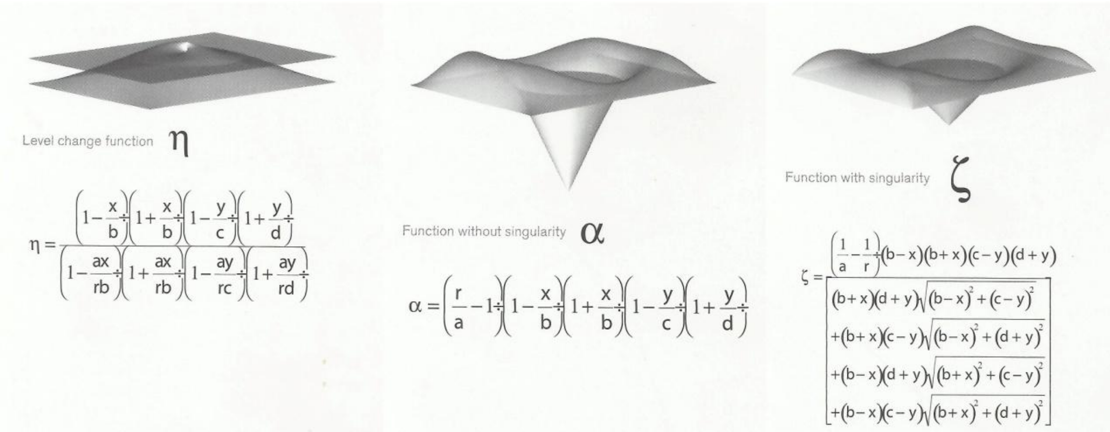

Figure 3. 4. Form studies on height and curvature
(Source: Burry, 2010)

After the surface of the form took its final shape, structural grid studies were started. The grid was generated by locating radial lines over the surface at equal distances which start from the center circle and end at the rectangular perimeter. These radial lines were then subdivided each having an equal number of segments.[128] Many options were studied, but with *relaxation* which is an optimization method, grid system evolved from a coarse surface grid to a finer grid representation. The most efficient grid system based on performances of structural and environmental criteria was found by applying optimization algorithms. The result was a triangulated grid system which was used because of its structural efficiency.[129]

[128] Ibid.
[129] Burry, Jane, and Mark Burry. 2010.

Figure 3. 5. British Museum Great Court, London, UK, Foster and Partners
(Source: Sandaker, Eggen, Cruvellier, 2011)

3.1.2. Structure Based Design Process

In structure based design processes, structural design becomes the main concern. It controls the whole design process from the beginning of constitution of the design idea by giving shape to the overall form. Architects and researchers Rivka and Robert Oxman emphasize the shift of importance from form design to structural design in their article of "The New Structuralism Design, Engineering and Architectural Technologies." They state that; "The new structuralism designates the cultural turn away from formalism and towards a material practice open to ecological potential. This is an architectural design that is motivated by a priori structural and material concepts and in which structuring is the generative basis of design."[130]

Works of the engineers such as Arup, Buro Happold and Kristina Shea can be given as examples where structural design drives the design of the form. Shea expresses the importance of structural design in design processes in the article titled "Creating Synthesis Partners." She states that; "rather than creating the form and then considering structural options, structure is now treated explicitly and drives the definition of the exterior and interior form." [131] In this reversed process, Shea uses computational

[130] Oxman, Rivka, and Robert Oxman. 2010. p. 23.
[131] Shea, Kristina. "Creating Synthesis Partners." Architectural Design: Contemporary Techniques in Architecture 72.1 (2002): 45.

techniques like the program of eifForm for generating structural systems.[132] EifForm generates and also analyses structural designs such as the most structural design programs do in terms of topology and geometry for finding the most efficient and economic organization.[133]

The Hylomorphic Project by Open Source Architecture (OSA) is an example which has a structural design process. During design process, eifForm was used for generation of the structural canopy. Initially, a planar triangulated truss system was defined as design input into the program. This planar system pushed off itself off the ground during generation process, for creating a space for people. Based on the design constraints such as ground connections, spatial limitations, and number and length of the members; generation process evolved.[134]

Figure 3. 6. Generation process, The Hylomorphic Project, Open Source Architecture (Source: Leuppi, Shea, 2008)

Three alternatives were proposed by eifForm as a result of the parametric model. Then, structural analyses were carried by Arup for minimizing the member lengths of the structure. Based on the analyses, the most suitable proposal was selected.[135]

[132] Ibid. pp. 42-45.
[133] Leuppi, Judith, Shea, Kristina. 2008. pp. 28-30.
[134] Ibid.
[135] Ibid.

Figure 3. 7. The Hylomorphic Project, the Central Court of the Schindler House, Open Source Architecture (Source: Leuppi, Shea, 2008)

The entrance of the Qatar Education City Convention Center by Arata Isozaki in Doha, Qatar is another building example which has a structural design process. Although there are architectural parameters such as the existence of two ground supports and a flat roof, design of the entrance was developed based on structural performances as architects Mark Burry and Jane Burry assert that; “the exact nature of the voluptuous, tree-like shape of the building is far from arbitrary, at least structurally.” [136] During design process, optimization method EESO (extended evolutionary structural optimization) was used and the most efficient supporting tree form was created considering structural loading and structural stiffness criteria. [137]

[136] Burry, Jane, and Mark Burry. 2010. p. 130.
[137] Ibid.

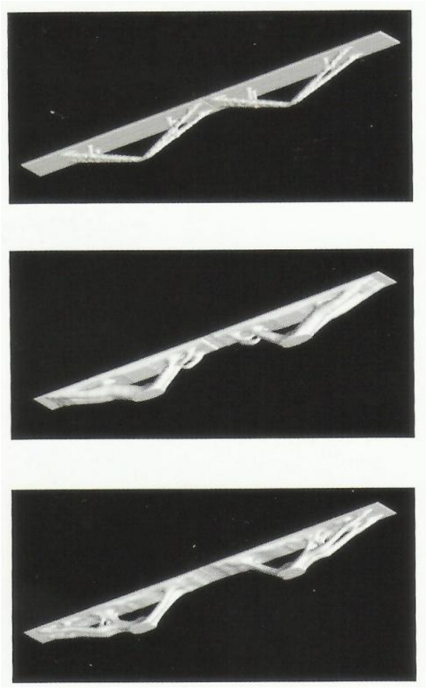

Figure 3. 8. Form development process by EESO
(Source: Burry, 2010)

Finite element analysis was also used during design process to enable the usage of least material possible by identifying and removing the areas of no use structurally from the main geometry and leaving an efficient self-supporting system.[138]

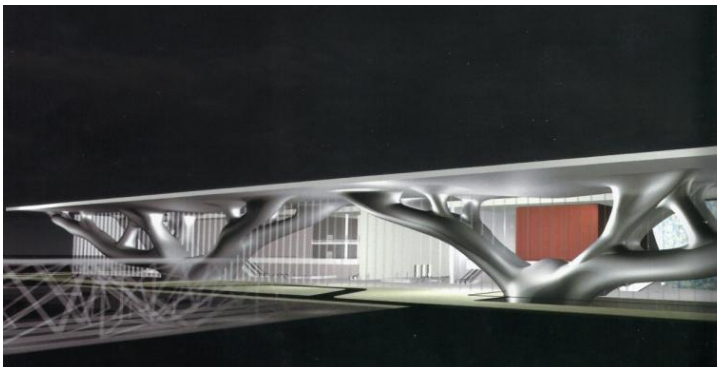

Figure 3. 9. Qatar Education City Convention Center, Doha, Qatar, Arata Isozaki
(Source: Burry, 2010)

[138] Ibid.

Another building that has a structural design process is the envelope of The Watercube-National Swimming Center by PTW Architects in Beijing, China. During structural design process, the design team worked on the proposal of Irish physicists Denis Weaire and Robert Phelan. Their proposal aimed at filling a space with similar three-dimensional cells that subject to each other with minimal surface area. Based on this generative logic, the designers wrote a script that would develop a structure made of Weaire-Phelan cells, then rotate the structure in three dimensions, cut the system by vertical and horizontal planes and finally, remove the interior volumes to create the structural envelope.[139]

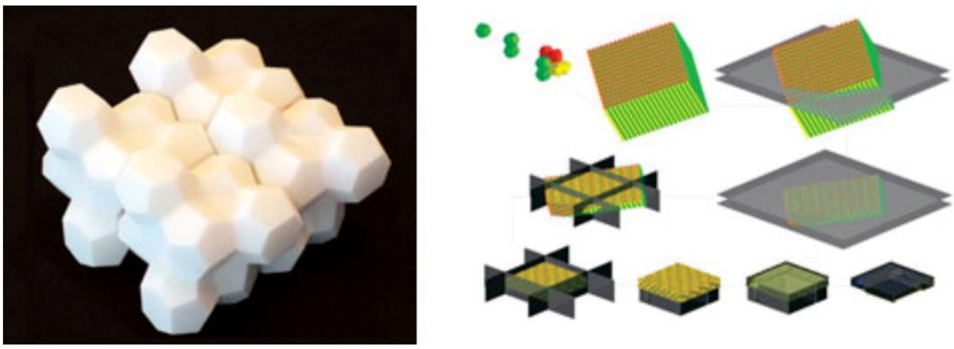

Figure 3. 10. Proposal of Denis Weaire and Robert Phelan, and the generation process of the structural envelope (Source: Gonchar, 2008)

The generated envelope was analyzed structurally with a specialized software that Arup's engineers developed in-house for this project. Various loading scenarios were applied to the structural envelope. Final characteristics of the steel members that constituted the bubble cells were determined by parametrically established relations between size, shape and weight.[140]

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[139] Gonchar, Joann. "Inside Beijing's Big Box of Blue Bubbles." Architectural Record. July 2008. Continuing Education Center. 3 May 2013 <http://continuingeducation.construction.com/article.php?L=5&C=418&P=1>

[140] Ibid.

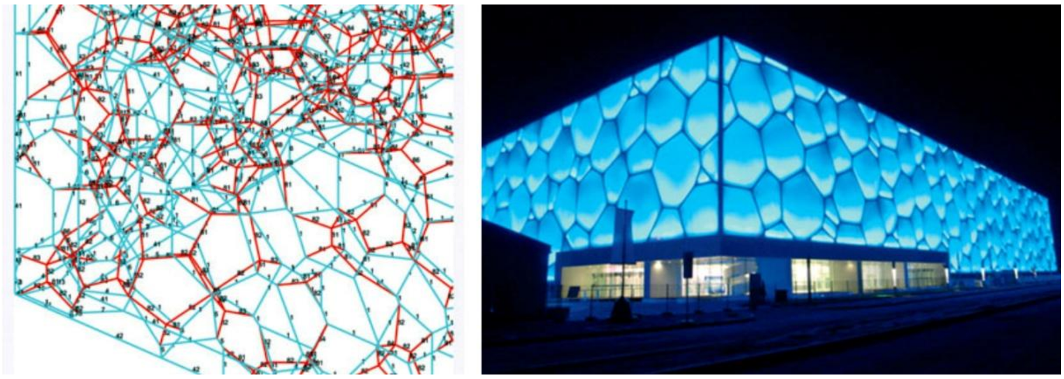

Figure 3. 11. Optimization of steel frame and the final form, The Watercube, Beijing, China, PTW Architects (Source: Gonchar, 2008)

Beijing National Stadium by Herzog and de Meuron in Beijing, China that is located right next to the National Swimming Center is another example where structural logic derives the whole design process of the envelope. Firstly, the inner bowl was designed in the project. Then, the structural system of the envelope was designed and took its shape based on the geometric logic of the bowl structure. Therefore, it had an elliptical plan and an inclined form that warped around the bowl structure. For the organization of the envelope structure, designers were inspired from the patterns and appearances of the local Chinese art forms which were crackleglazed pottery and the scholar stone. They organized primary, secondary and tertiary members of the structural system in a layout similar to the pattern of a 'crazed' pottery. During design process, primary structural system made of columns and beams were designed firstly. Then, secondary and tertiary members were located over the surface and superimposed each other constituting a complex geometric appearance.[141]

[141] Burrows, Stephen, and Martin Simpson. 2009. pp. 16-19.

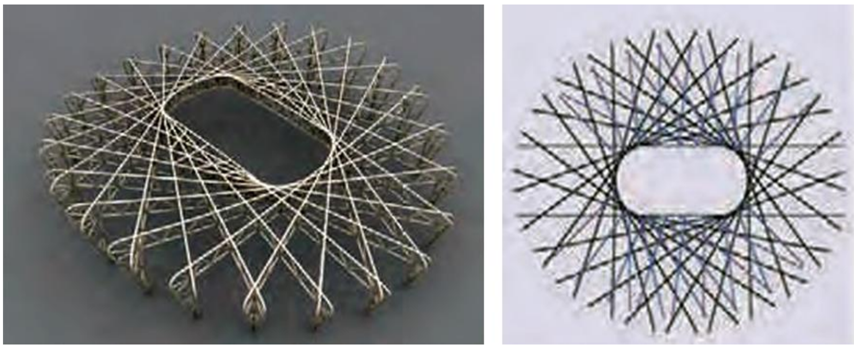

Figure 3. 12. Primary structure and secondary members
(Source: Burrows, Simpson, 2009)

Structural design process of the National Stadium evolved in parametric design platform of CATIA. All the design information was inputted into CATIA from structural members to their details. Therefore, if there was a change in one of the parameters, all the changes on the related parameters were adjusted through the model. The digital design model was also used to control the geometry and test the details such as assembly points.[142] For static and dynamic analyses, a 3D structural model was generated in Arup's *GSA* software and analysed under various load conditions such as live and dead loads. For studying the stress distribution, finite element analysis was applied to the members and their connection points. Finally, structural system was optimized according to the results of the analyses.[143]

[142] Ibid.
[143] Lam, Kylie, and Thomas Lam. "Analysis model and results." The Arup Journal 44.1 (2009): 20-23.

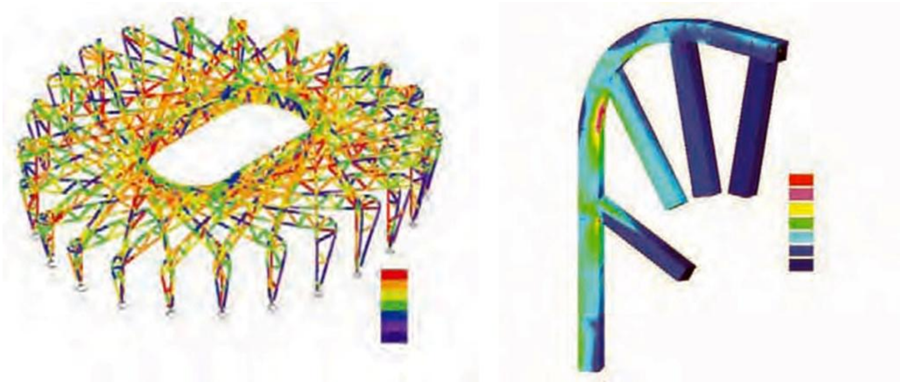

Figure 3. 13. GSA analysis and Finite Element Analysis over the structure
(Source: Lam, 2009)

3.1.3. Linear Design Process

In linear design processes; form is designed firstly, a structural system is designed based on the geometrical constraints of the form, and materiality decisions are made finally. In these processes, structural design, its analyses and optimizations are not allowed to make changes on form. Architects design the form of the building without considering the ways of structuring it whether realization of the form is dependent on a suitable and an efficient structural system design. The generated form after a form design process generally does not feature any information related to its construction. For making the form constructible; architects and engineers design a structural system, give material decisions for covering purposes and therefore, give thickness to the one layered skin.[144]

HtwoO Expo by Lars Spuybroek from NOX in Neeltje Jans, Netherlands can be given as an example which had a linear design process based on a performance based model. Initially, a tube made of ellipses was defined into design process which was then deformed based on the internal program and external influences on the site such as wind direction and movement of visitors. After the interactive and deformative process of ellipses, they were connected each other with straight lines constituting the final form.[145]

[144] Kloft, Harald. 2006. pp. 248-255.
[145] Spuybroek, Lars. 2004.

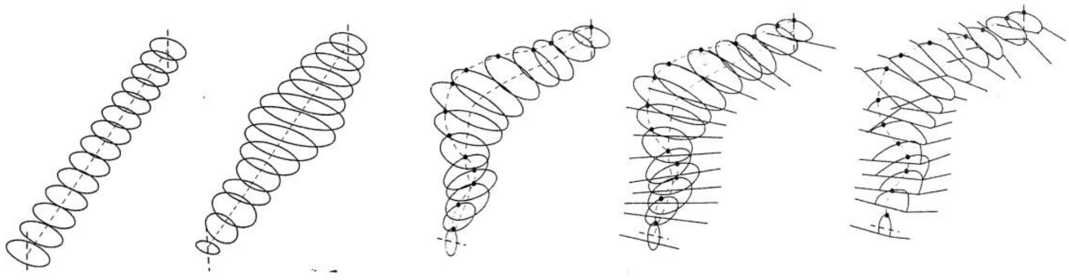

Figure 3. 14. Deformation of ellipses throughout the building
(Source: Spuybroek, 2004)

After form design was completed, architects generated the structural system by transforming each ellipse to a structural frame. The ellipses and therefore the frames were defined in the AutoCAD 11 program. For defining the frames, circle segments were used. The straight lines that were used to connect the circles became the secondary structure. Therefore, the structural system of the building was generated from the main form which took the geometry of the curvilinear skin.[146]

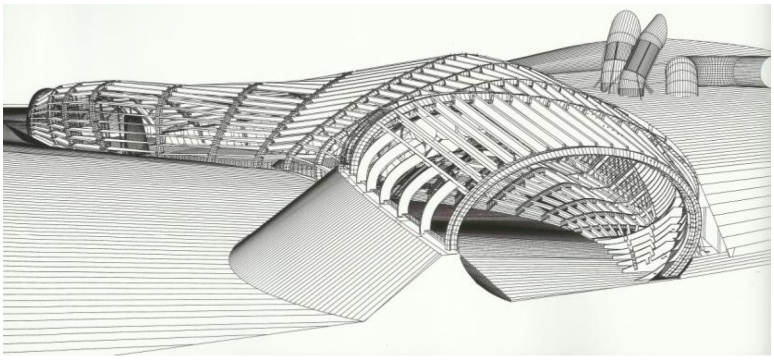

Figure 3. 15. Structural system, HtwoO Expo, Netherlands, Lars Spuybroek
(Source: Burry, 2010)

The BMW exhibition pavilion "Bubble" for the IAA 1999 by Bernhard Franken and ABB Architekten in Frankfurt, Germany is another example that had a linear design process. Form of the building, which had no reference to structural logic in its geometry, was generated firstly in the software program Maya. During form generation process, two water drops interacted with each other conceptually based on a biological

[146] Ibid.

model. As a result of the interaction, a single surface was generated. The generated form became the master geometry which would not be changed anyway.[147]

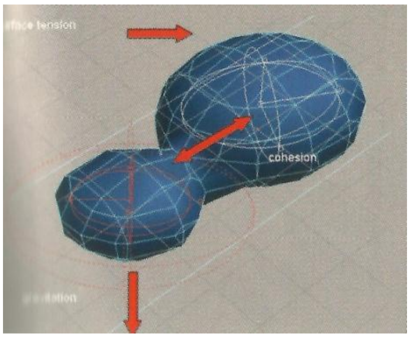

Figure 3. 16. Interaction of two water drops constituting a built form
(Source: Kolarevic, 2009)

Structural design studies started after form generation by taking reference the master geometry. Since structural optimizations would not cause deformation over the form, a supportive system was tried to be found for maintaining the main geometry.[148] The structural system was designed as a frame system which followed the contours of the master geometry. Kloft defined this process of structuring a determined formal geometry as; “a secondary process of materializing the generated shape and blowing up the digital model to its structural proportion.”[149]

[147] Kloft, Harald. 2006. pp. 248-255.
[148] Ibid.
[149] Ibid. p. 250.

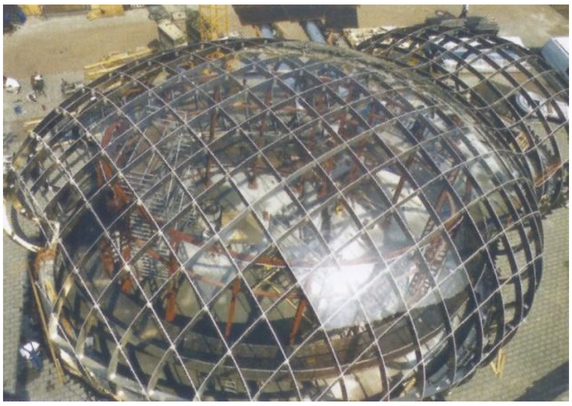

Figure 3. 17. Orthogonal frame layout, The Bubble, Frankfurt, Germany, Bernhard Franken and ABB Architekten (Source: Franken, 2009)

Frank Gehry's Marta Herford Museum in Herford, Germany is also a result of a linear design process. Different from other projects above, the form of the building did not designed in digital medium. Physical models were made which then digitally scanned and transferred into the computational design environment of CATIA. Digital model was then analyzed based on the internal program and the site. After the form took its final geometry as a result of the optimizations, structural design studies started. During structural design process, Gehry defined an internal and an external envelope that the space between these two envelopes would contain the structural system. Therefore, based on the determined boundaries, a structural system was tried to be designed without intervening to the form of the building.[150] Because of these spatial constraints and the difficulties that structural engineers had faced in case of finding a suitable structural solution that works with the complex curves of the main geometry, structural system was designed independently from the main form. Main geometry did not taken as a geometrical reference for the structural organization such as in the BMW exhibition pavilion "Bubble" project. Although the form has a curvilinear character, structural system has an orthogonal organization and is irrelevant to the curvilinear form.[151]

[150] Ibid. pp. 248-255.
[151] Bagneris, Marine, Rene Motro, Bernard Maurin, and Nicolas Pauli. 2008. pp. 79-87.

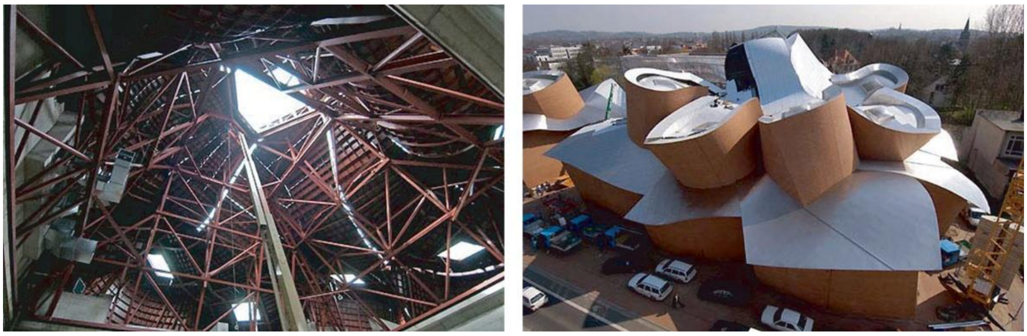

Figure 3. 18. Structural layout and curvilinear outer envelope, MARta Herford Museum, Germany, Frank Gehry (Source: Bagneris, Motro, Maurin, Pauli, 2008)

Walt Disney Concert Hall in Los Angeles, USA is another example of Frank Gehry that had a linear design process where form of the building was designed with the help of physical models, and then the models were transferred into digital medium for design of the structural system and preparation of the construction drawings. During architectural design process, different configurations of concert halls were studied for finding out the most suitable solution for a symphony hall in terms of acoustics and also aesthetics. After the symphony hall took its final form, the rest of the building and the exterior surfaces were developed based on the form of the symphony hall. Gehry reflected the shape of the interior volumes to the exterior.[152]

[152] Glymph, Jim. "Evolution of the Digital Design Process." Architecture in the Digital Age: Design and Manufacturing. Ed. Branko Kolarevic. New York: Taylor & Francis, 2009. 101-120.

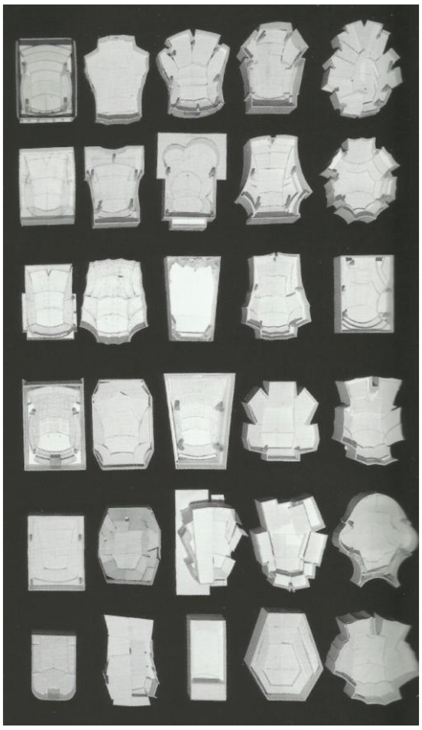

Figure 3. 19. Different configurations of models
(Source: Glymph, 2009)

After completion of form generation process, Gehry and his team digitized the physical models and optimized them in digital medium in terms of constructability. Structural system was designed digitally based on the surfaces of the form. The structural system took the final form of the building like a surface structure by following the curves of the surfaces. Detailing of the steel wire-frame structure proceeded through a three-pronged process which was controlled by three different detailers. One worked over manual drafting, one worked over two-dimensional drawings in Autocad and other worked with XSteel that is a steel-detailing software. Splitting job into three operational processes caused incoordination that exceeded the limits of the project schedule and thus, steel was accepted as the schedule-driver for the project.[153]

[153] Ibid.

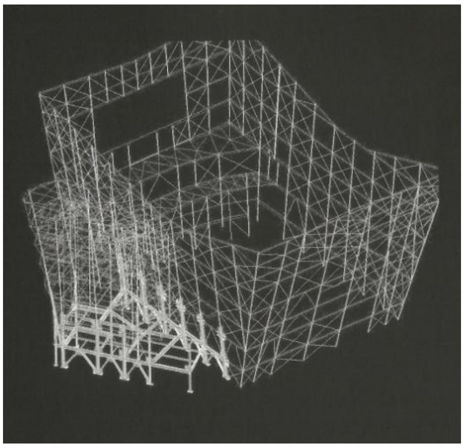

Figure 3. 20. Braced frame structural system of the concert hall, Walt Disney Concert Hall, Los Angeles, USA, Frank Gehry (Source: Glymph, 2009)

3.2. Structural Systems

Structural design gains special importance for construction of a building. Complex forms require special structural systems for supporting curvilinear surfaces. Structural systems generally take the shape of the form and exist as surface structures in buildings. If the surface has an irregular form that bends or twists, structural system also bends or twists for being in accordance with the form, maintaining the geometry and responding to load calculations. Therefore, the shapes of the structural systems can also have irregular forms which “challenge orthodox methods of structural engineering.”[154]

In digitally designed and constructed buildings, it is seen that frames, grid systems, solid shell systems and three dimensional systems such as space frames are mostly used. Frames cover the whole building and span long distances without any internal supports. They take the shape of the form by being curvilinear and therefore, get additional support from the folds of the form. Braced frame systems cover the façade of the buildings and carry the cladding material. In addition to carrying the cladding material, braced frame systems also provide lateral support to the building and work against to the horizontal spread of the building structure. Such as frame systems, grid shell systems also cover the buildings and span long distances without any internal supports. However, grid shells are mostly preferred because of their ability to transmit sun light and the possibility to be covered with flat glass panels. Solid systems are also

[154] Oxman, Rivka, and Robert Oxman. 2010. p. 17.

shell systems that are generally chosen for providing privacy and separating interior from exterior. In braced frames and grid shells, whether form has a complex geometry, structural members do not have to be curvilinear as the frame structures. Members join with nodes and nodes enable the connection of straight members with different angles thus, creating curvilinearity.

In digital structural design, it is possible to see various structural system solutions for carrying the curvilinear forms. These various structural systems are categorized in architectural discourses based on design criteria such as way of receiving, transferring and transmitting load, organization of elements, and shape and geometry of the design. For example, Heino Engel classifies structures based on structural action considering how loads are received, transferred and transmitted in his book of "Tragsysteme." In his classification, there are four types of structures that are form-active structures, vector-active structures, section-active structures and surface-active structures. Form-active structures include arch structures, flat trusses, curved trusses and transmitted flat trusses. Vector-active structures include space trusses, beam structures, rigid frame structures and beam grid structures. Section-active structures include slab structures and plate structures, and surface-active structures include folded plate structures and shell structures.[155]

Fuller Moore also classifies structural systems considering how structures work and react to applied loads in his book "Understanding Structures." He studies on modes of action of structural systems in relation to material qualities. Based on structural principles, he collects different categories under four main titles which are; trussed systems, framed systems, funicular systems and shell systems.[156]

A different approach can be seen in the classification of the structural engineer Martijn Veltkamp. In his book of "Free Form Structural Design Schemes, Systems & Prototypes of Structures for Irregular Shaped Buildings," Veltkamp categorizes structural systems by doing case study. He analyses the structural systems of the existing buildings and collect the ones, which have similar characteristics such as geometry and material, under the same title. His categorization includes; space frames, systems with twisting members, curved timber structures, structures that are constructed with formwork, planar sectioned systems and miscellaneous systems.[157]

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[155] Veltkamp, Martijn. 2007.
[156] Moore, Fuller. Understanding Structures. Boston: McGraw Hill, 1998.
[157] Veltkamp, Martijn. 2007.

In this thesis, to understand and explain structural system solutions for digitally designed forms, structural systems are categorized based on their working principles. They are collected generally under four main titles which are; two-dimensional frame structures, space frames-space trusses, grid structures and solid structures. Two-dimensional frame structures work with planar force distribution, space frames-space trusses work with three dimensional force distribution, grid structures work with linear force distribution with compressive membrane action and solid structures work with continuous surface resistance again with compressive membrane action.

3.2.1. Two-Dimensional Frame Structures

Frame is a two-dimensional structure that consists of a beam and two columns. Frames are located at regular intervals through the building and organized to span the structure in the shortest direction for the efficient load transfer. They transfer the applied load to the ground by one-way action. The connections within frames such as the connections between column-beam and column-ground are rigid that this rigidity cause flexural deformations over the members. [158]

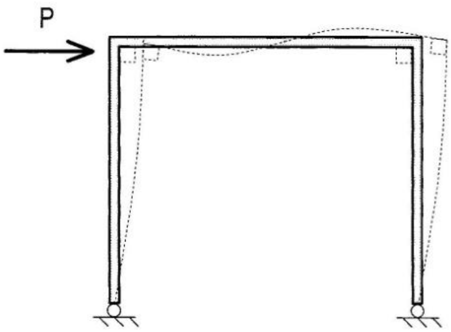

Figure 3. 21. The behavior of a frame under applied loads
(Source: Sandaker, Eggen, Cruvellier, 2011)

Frames generally are not stable on their own. Secondary structural elements are needed between primary frames to provide lateral support against forces such as wind

[158] Sandaker, Bjørn Normann, Arne Petter Eggen, and Mark R. Cruvellier. The Structural Basis of Architecture. 2nd ed. Oxon: Routledge, 2011.

and earthquake. Secondary elements that are called as bracings also serve the purpose of carrying the cladding material.[159]

Steel frames enable construction of digitally designed complex forms with their capability of having various geometries and also ability to span long distances. In digital structural design, frames generally do not have the conventional orthogonal organization where horizontal beam is carried by two vertical columns. Frames become curvilinear for being in accordance with the complex forms of the digital medium.

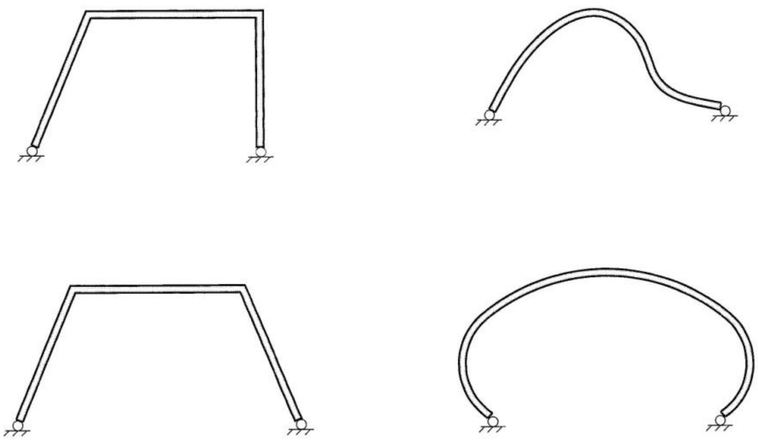

Figure 3. 22. Various types of rigid frames
(Source: Sandaker, Eggen, Cruvellier, 2011)

Two-dimensional frame structures are also used for creating an undivided and a total space that frames span the long distances without any intervening structure.[160] As frames take the shape of the curvilinear skin, they also benefit from the folds and contours of the form and gain more strength to span the distance.

In the project of BMW exhibition pavilion “Dynaform” for the IAA 2001 by Bernhard Franken and ABB Architekten in Frankfurt, Germany, steel frames were used to create a continuous and undivided space for the visitors. Frames took the complex character of the form by tracking the lines of the main geometry. [161] Frames have inner and outer outlines that connect each other with additional members by creating the

[159] Ibid.
[160] Ibid.
[161] Bollinger und Grohmann Ingenieure. “BMW Dynaform.” Projects. 29 Apr. 2013 <http://www.bollinger-grohmann.de/homepage/index.php?page=374&language=EN&bg_project=4CB87842-6B7E-1A06-A47F-417E27B80417>.

vierendeel system including beams with quadrangle holes in it.[162] There are fifteen hollow sectioned steel frames in the structure. They are located at regular intervals of 8m and span the width of 25m transversely without any intervening structure. Rigid round pipes connect the frames to each other providing lateral stability to the structure. The 18m high structural system has a length of 135m.[163]

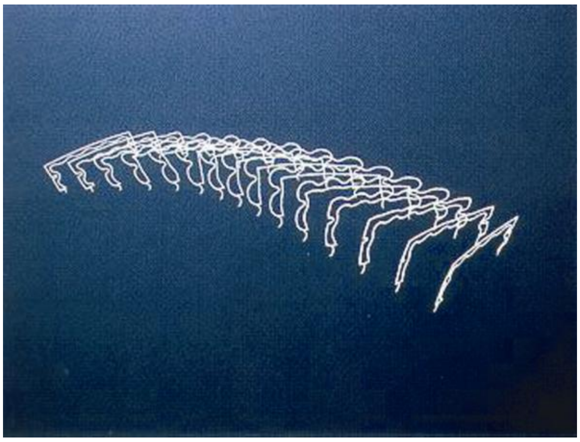

Figure 3. 23. Structural frames, BMW exhibition pavilion “Dynaform,” Frankfurt, Germany, Bernhard Franken and ABB Architekten (Source: © B+G Ingenieure Grohmann GmbH)

Experience Music Project that was designed by Frank Gehry in Seattle, Washington is another example where curvilinear frames were used in the structural design. The building structure took the shape of the complex form providing a continuous and an undivided space for users such as the curvilinear frames of the BMW exhibition pavilion “Dynaform.” Curvilinear steel frames are located parallel to each other through the building and then connected to each other with secondary members. Primary frames have “I” sections which consist of cut plate elements.[164]

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162 Kloft, Harald. “Non-Standard Structural Design for Non-Standard Architecture.” Performative Architecture: Beyond Instrumentality. Ed. Branko Kolarevic, M Ali Malkawi. New York: Spon Press, 2005. 135-148.

163 Bollinger und Grohmann Ingenieure. “BMW Dynaform.” Projects. 29 Apr. 2013 <http://www.bollinger-grohmann.de/homepage/index.php?page=374&language=EN&bg_project=4CB87842-6B7E-1A06-A47F-417E27B80417>.

164 Shelden, Dennis R. “Digital Surface Representation and the Constructibility of Gehry’s Architecture.” Diss. Masachusetts Institute of Technology, 2002.

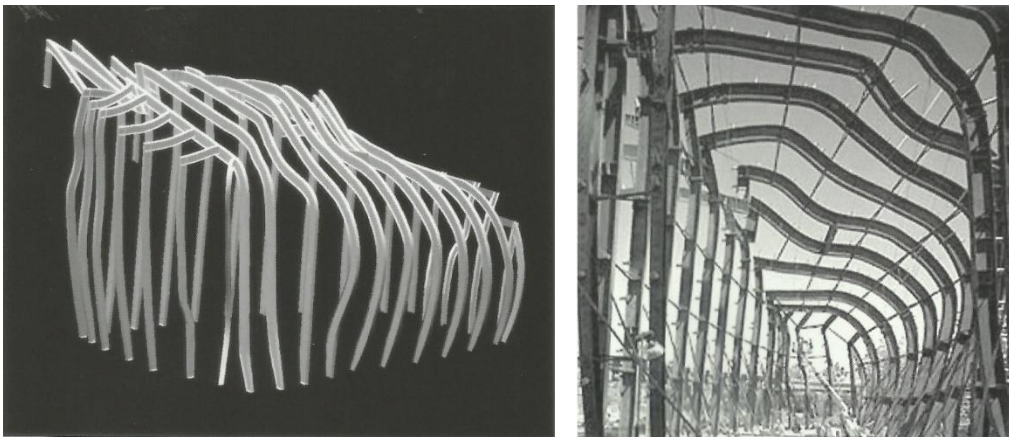

Figure 3. 24. Curvilinear frames, Experience Music Project, Seattle, Washington, Frank Gehry (Source: Kolarevic, 2009)

The free form of the Experience Music Project has some highly curved areas that if ribs would follow the skin form, this would cause disruption over the load path and excessive bending forces. Therefore, the geometry of the frames was rationalized and rib geometry differentiated from the main geometry in these highly curved areas. Steel extensions were located over the ribs for accommodating the deviation of structure and skin.[165]

Lars Spuybroek’s H_2O Expo Pavilion in Neeltje Jans, Netherlands also consists of two dimensional frames which were used to present a continuous pathway to the visitors through the exhibition.[166] There are fourteen curvilinear primary frames in the structural system. All the frames have different curvatures for accommodating with the free form of the building. They are all located at different angles through the 60m long building and connected with 280 secondary I sectioned beams. The straight I-sectioned beams are bolted to primary frames for the stability of the structure.[167]

165 Ibid.
166 Burry, Jane, and Mark Burry. 2010.
167 Spuybroek, Lars. 2004.

Figure 3. 25. Frame system, H2O Expo Pavilion, Netherlands, Lars Spuybroek (Source: Hadia, 2007)

In Blow Out Toilet Block project by Lars Spuybroek in Neeltje Jans, Netherlands, there is also a frame structure made of steel plates. In addition to provide a continuous space for users, plate frames provide privacy with their solidness in this project. There are ten steel frames from solid plates that are located parallel to each other. Steel plates have voids inside for circulation. They are connected with secondary elements which are welded to the primary frames.[168]

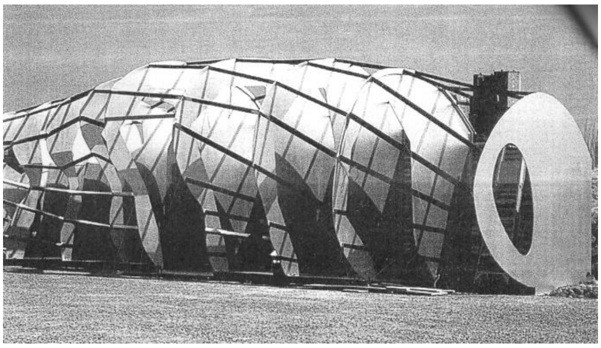

Figure 3. 26. Frame system made of plates, Blow Out Toilet Block, Netherlands, Lars Spuybroek (Source: Spuybroek, 2004)

Popstage Mezz Breda concert hall building by Erick van Egeraat Associated Architects in Breda, Netherlands is another example where there are curvilinear frames that create an undivided space for the users, but this time the frames define a centripetal

[168] Ibid.

space; the concert hall. The building has two free form structural envelopes that the internal envelope ceiling is hung from the outer envelope. The outer envelope has primary frames that consist of I-sectioned steel members. Steel frames are located parallel to each other and timber planks are located as secondary elements between the I-sectioned frames.[169] There is a 100mm of poured concrete over the structure because of acoustic reasons.[170] Inner structural envelope also has a structural system made of steel frames, however; polygonal sectioned frames are located in a radial organization different from outer envelope's parallel organization.[171]

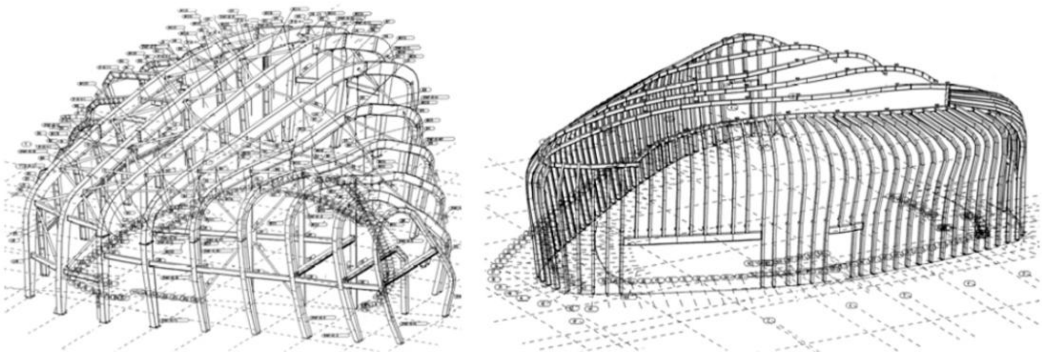

Figure 3. 27. Exterior and interior building envelopes, Popstage Mezz Breda, Breda, Netherlands, Erick van Egeraat Associated Architects (Source: Veltkamp, 2007)

The frame system of Kunsthaus Graz by Peter Cook and Colin Fournier in Graz, Austria covers a skeletal load-bearing system that is made of columns and beams. Frames are used for spanning the exhibition area without any supports inside and therefore, provide the visitors an undivided space. There are primary and secondary girders in the system. Primary frames have rectangular box sectiones that are located paralel to each other at regular intervals. Secondary square sectioned girders fill the space between the frames by constituting a triangulated pattern. The triangulation of the grid shell provides extra stiffness to the structure and supports the creation of column free interior exhibition spaces. [172] Frame system has a width of 60m and hight of 23m.[173]

[169] Veltkamp, Martijn. 2007.
[170] Erick van Egeraat. "Popstage Mezz Breda." 25 Apr. 2013 <http://www.erickvanegeraat.com/#/projects/popstage_mezz_breda>.
[171] Veltkamp, Martijn. 2007.
[172] Szalapaj, Peter. 2005.

Actually, the structural system of the Kunsthaus is a hybrid system that works both as a bending system made of frames and a shell structure made of triangles.[174]

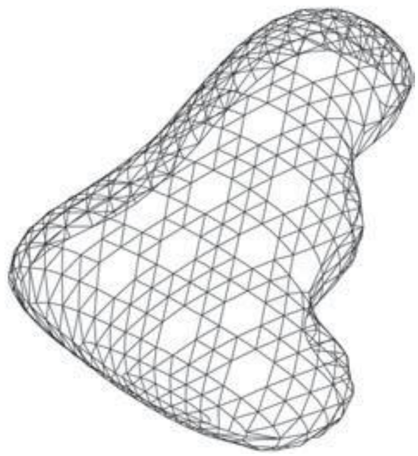

Figure 3. 28. Primary frames and triangularly organized secondary members (Source: Kolarevic, 2005)

Different from planar one-way load transfer in frames that are located at regular intervals, two-way load transfer can also be seen in some building structures. Load is transferred in two-directions through two sets of intersecting frames. The reason behind the selection of a two-way system is to create a stiffer and a stronger system by increasing the load-bearing capacity of the structure.[175] The BMW exhibition pavilion "Bubble" for the IAA 1999 by Bernhard Franken and ABB Architekten in Frankfurt, Germany is an example which has two sets of intersecting frames. Bubble has a structural system made of aluminum frames that are located in an orthogonal layout, parallel to each other at certain intervals. [176] The frames of the structure follow the outer contour of the form that has a maximum height of 8m. The system is also 24m long and has a maximum width of 16m.[177]

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[173] "Kunsthaus Graz." arcspace 14 Jan. 2013. 26 Apr. 2013. <http://www.arcspace.com/features/spacelab-cook-fournier/kunsthaus-graz/>.
[174] Kloft, Harald. 2006. pp. 248-255.
[175] Sandaker, Bjørn Normann, Arne Petter Eggen, and Mark R. Cruvellier. 2011.
[176] Franken, Bernhard. 2009. pp. 121-138.
[177] Bollinger und Grohmann Ingenieure. "BMW Bubble." Projects. 25 Apr. 2013 <http://www.bollinger-grohmann.de/>.

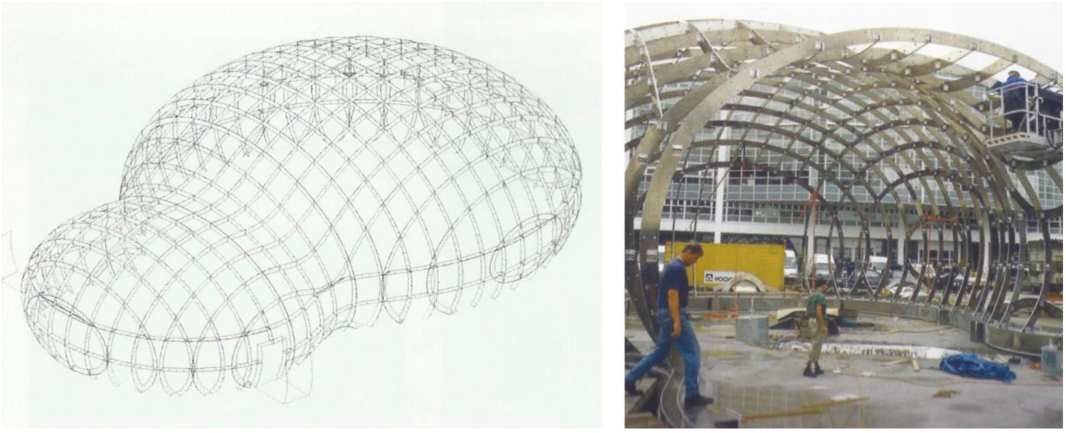

Figure 3. 29. Orthogonal frame layout, BMW exhibition pavilion “Bubble,” Germany, Bernhard Franken and ABB Architekten (Source: Franken, 2009)

There are various types of frame systems in digital structural design that one of them is called as braced frame. Braced frames are vetically spanning truss systems. The triangulation of the system provides lateral stability to the structure. In braced frames, there are generally columns and beams that are organized in an orthogonal layout. Diagonal members are added to create triangulation, therefore providing strength against horizontal loads. The joint types in these kind of braced frame systems are generally hinge connections.[178]

Frank Gehry’s Guggenheim Museum in Bilbao, Spain and Disney Concert Hall in Los Angeles, California are two examples that have braced frames in their structural systems. Braced frame systems were chosen for these two projects for making the designed forms constructible by supporting the curvilinear skins. In Guggenheim Museum, the structural system was generated through contouring method where the wire-frame cross sections over the building form became the traces for the building’s structural framework.[179] The structural system is made of straight elements, which are spaced approximately 3 meters, are connected with nodal points. Vertical columns are connected to horizontal bearing plates, and tubular bracings are located diagonally for lateral support.[180]

[178] Sandaker, Bjørn Normann, Arne Petter Eggen, and Mark R. Cruvellier. 2011.
[179] Kolarevic, Branko. 2009. pp. 29-54.
[180] Veltkamp, Martijn. 2007.

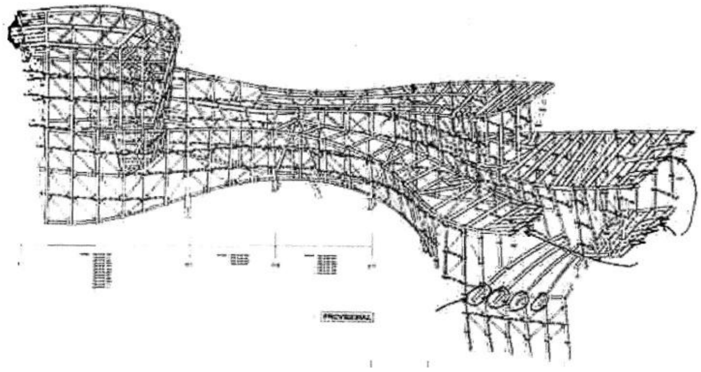

Figure 3. 30. Braced frame system, structural schema, Guggenheim Museum, Bilbao, Frank Gehry and Associates (Source: Kolarevic, 2009)

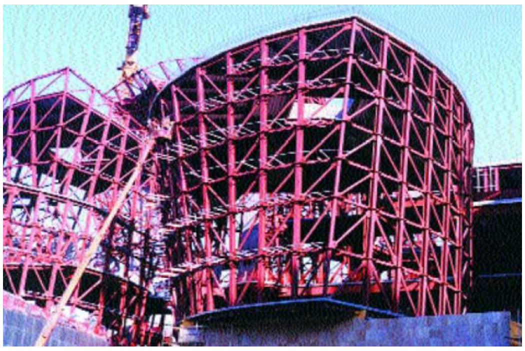

Figure 3. 31. Braced frame system, detail, Guggenheim Museum, Bilbao, Spain, Frank Gehry and Associates (Source: Veltkamp, 2007)

Disney Concert Hall by Frank Gehry also has a braced frame system which consists of straight steel elements like the Guggenheim Museum. Structural design presents a tessellation of the main form over the surface and takes the shape of the curvilinear surface geometry. I-sectioned columns and beams constitute the structural grid.[181]

[181] Shelden, Dennis R. 2002.

Figure 3. 32. Braced frame system, Disney Concert Hall, LA, California, Frank Gehry (Source: Burry, 2010)

The connection details between steel elements are complex and hard to comprehend in Disney Concert Hall, because elements do not frame together orthogonally. Therefore, this type of connection required “difficult end bevels and complicated plate and clip assemblies” during construction.[182]

Figure 3. 33. Connection details of the braced frame system, Disney Concert Hall, Los Angeles, California, Frank Gehry (Source: Shelden, 2002)

Diagrid is another type of braced frame where diagonal members are organized in a triangular layout. Diagrid systems resist to vertical and horizontal loads, which are applied to its plane, and are suitable to tall buildings. The connections between diagonal

[182] Ibid.

members are mostly pin connections.[183] City Hall London and 30 St. Mary Axe (Swiss Re) in London, UK by Foster and Partners are two examples where diagrid frame systems were used. For example in the 45m high City Hall London building, the atrium part of the building has a diagrid frame system for supporting the glass façade.[184]

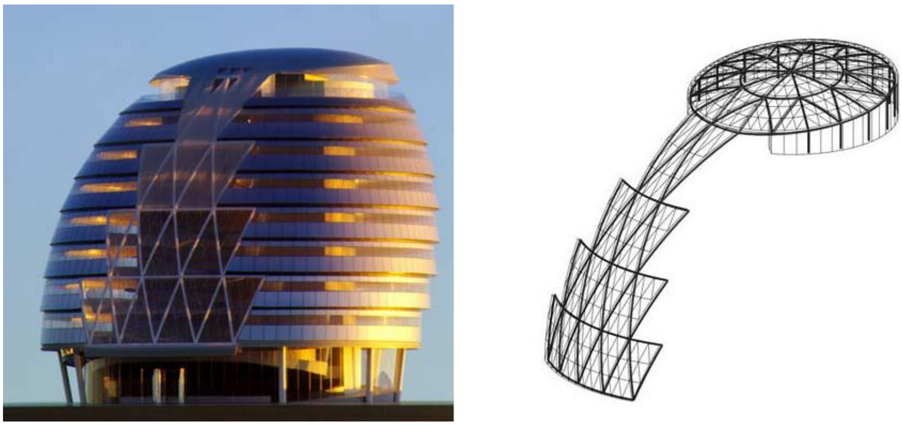

Figure 3. 34. City Hall London, London, UK, Foster and Partners
(Source: http://www.fosterandpartners.com/projects/city-hall/)

In 30 St. Mary, triangulated diagonal frames are used over the whole form to realize the 180m tall curvilinear shape of the building.[185] Diagrids provide lateral strength to the building by the contribution of the triangulated pattern. They also allow column-free interior spaces. The system consists of tubular sectioned straight steel members which connect at nodes. The horizontal members act against tension forces and are opposed to the horizontal spread of the building structure. The nodes are identical at every floor level. However, the building has floors of varying perimeters and therefore, the node sizes change based on varying perimeter in each floor.[186]

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183 Sandaker, Bjørn Normann, Arne Petter Eggen, and Mark R. Cruvellier. 2011.
184 Foster+Partners. "City Hall." Projects. 25 Apr. 2013 <http://www.fosterandpartners.com/projects/city-hall/>.
185 Richards, Brent. New Glass Architecture. New Haven: Yale University Press, 2006.
186 Sandaker, Bjørn Normann, Arne Petter Eggen, and Mark R. Cruvellier. 2011.

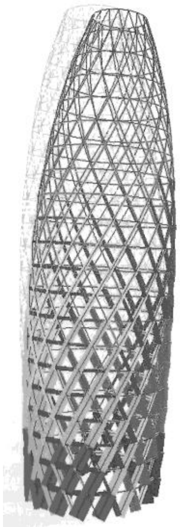

Figure 3. 35. Diagonal braced frame system, structural schema, 30 St. Mary Axe, UK, Foster and Partners (Source: Kolarevic, 2009)

Figure 3. 36. Diagonal braced frame system, detail, 30 St. Mary Axe, London, UK, Foster and Partners (Source: Sandaker, Eggen, Cruvellier, 2011)

3.2.2. Space Frames and Space Trusses

Space frames are three-dimensional systems where axial members interlock with each other forming a geometric pattern made of polyhedral units. These polyhedral units can have various shapes such as tetrahedrons or octahedrons and generally have four or more faces. The edges of polyhedra become the members of the structural system that connect with hinge joints. Generally in space frames, there are top and bottom plane grids which are connected with diagonal members constituting a three-dimensional network. The depth of space frames between top and bottom planes provide bending stiffness to the structure. Therefore, a roof structure from a space frame can span long distances by maintaining its lightness as well.[187]

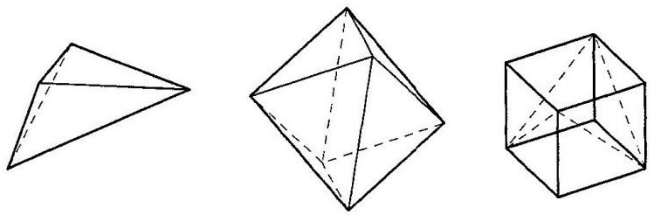

Figure 3. 37. Some polyhedrals: the tetrahedron, the octahedron, the cube
(Source: Sandaker, Eggen, Cruvellier, 2011)

Whether it seems designing space frames with repetitive regular polyhedral units is advantageous in terms of standardized fabrication; computer aided design and manufacturing make easier to design and fabricate unique members of complex structures with mass-customization.[188]

The reason of choosing and using steel space-frames is their lightness and the possibility to span big and open spaces without any need for internal supports in buildings such as exhibition and sports halls. The Beijing National Swimming Center referred as “Water Cube” for the 2008 Olympic Games by PTW Architects in Beijing, China is an example where space frame was used both aesthetically and structurally for spanning the long distance in the project. Space frame is both the roof and the façade of the box shaped building which has dimensions of 177 by 177 by 31m. The walls are 3.6m deep and the roof is 7.5m thick. Bubble modules constitute the structural system which are 12-sided and 14-sided polyhedrals having pentagon and hexagon shaped flat sides.[189] The edges of the bubbles are the steel tubes. 22.000 tubes connect each other with 12.000 nodes using the method of welding.[190] As the system does not consist of

[187] Ibid.
[188] Ibid.
[189] Ibid.
[190] Subramanian, N. “Olympic Structures of China.” NBM&CW November 2008: 246-264. 17 May 2013 <http://www.thestructuralengineer.info/library/OlympicStructures08.pdf>.

stable triangle forms and does not include diagonals; the stiffness of the structural system was provided by the rigid connections between the members and the nodes.[191]

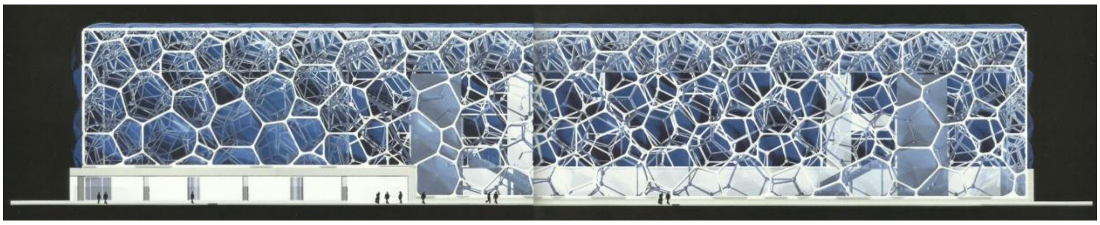

Figure 3. 38. Elevation of the space frame structure, The Beijing National Swimming Center, Beijing, China, PTW Architects (Source: Burry, 2010)

Space frames are also used for carrying and supporting curvilinear skins of complex forms in addition to regular cubic forms. For example, The Acoustic Barrier by Kas Oosterhuis in Utrecth, Holland has a complex curvilinear form which is supported by a space frame.

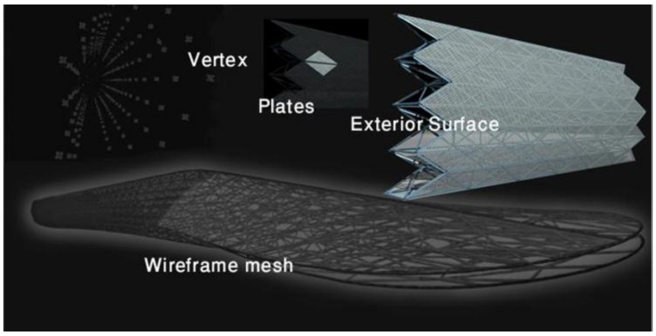

Figure 3. 39. Acoustic Barrier, Utrecth, Holland, Kas Oosterhuis
(Source: Hadia, 2007)

Acoustic Barrier is a sound-reflecting barrier that runs along 1.5 km. It embodies an industrial building in it. Curvilinear complex form of the barrier, which has varying cross-sections along the site, has a polygonal space-frame. It consists of a triangulated

[191] Sandaker, Bjørn Normann, Arne Petter Eggen, and Mark R. Cruvellier. 2011.

three-dimensional grid. It is made of steel profiles that meet at nodes.[192] Different from the building's space frame system, the industrial cockpit building's façade has a two-dimensional triangulated grid structure.

Figure 3. 40. Space frame of the Acoustic Barrier, Utrecth, Holland, Kas Oosterhuis (Source: Oosterhuis, 2008)

Space trusses are another type of three-dimensional structures. They are three-dimensional trusses that have triangular cross sections. Truss systems consist of axially loaded linear elements that are arranged in a triangulated manner. The elements of trusses connect each other with pin joints, however; this does not mean that truss systems are movable. Triangles are stable structures under applied loads in any direction, which is a desirable geometric property for a structural system. Pin joints allow the members to rotate and this rotation prevents the creation of bending forces on members. Space trusses have two upper compression chords that are connected for lateral support and one tension chord; or one compression chord and two tension chords within their structure. They provide more lateral and torsional stiffness according to plane trusses.[193]

[192] Oosterhuis, Kas, and Ilona Lénárd. Onlogic: Speed and Vision. Mulgrave Vic.: Images Publishing, 2008.
[193] Sandaker, Bjørn Normann, Arne Petter Eggen, and Mark R. Cruvellier. 2011.

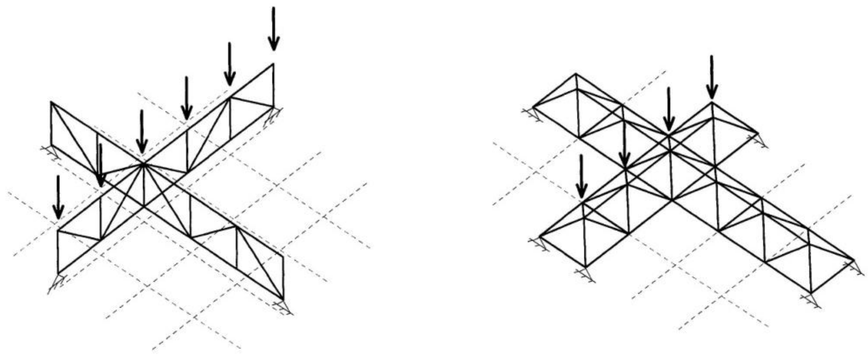

Figure 3. 41. Planar truss and space truss
(Source: Sandaker,Eggen, Cruvellier, 2011)

The structural design of the Channel Tunnel Railway Terminal by Nicholas Grimshaw and Partners in London, UK consists of arches that every arch module includes two bowstring space trusses within its structure. The bowstring space trusses within the arches are made from steel members, and connected with mild-steel pin connections. One of the reasons of using space trusses was to create a light system which crossed the span without any interior supports. Another reason was to overcome bending moments and resist to buckling.[194] There are 36 unique arches in the structural system spanning a changing width of 35m to 50m. The arches are located through the 400m long building at regular intervals.[195] They are connected with circular-hollow sectioned tubes as secondary elements which are welded to the arches. Secondary elements provide lateral restraint to the structure.[196]

[194] Moore, Rowan, and Kenneth Powell, eds. Structure, Space and Skin: The Work of Nicholas Grimshaw and Partners. London: Phaidon, 1993.
[195] Kolarevic, Branko. 2009. pp. 11-28.
[196] Macdonald, Angus. The Engineer's Contribution to Contemporary Architecture Anthony Hunt. London: Thomas Telford Publishing, 2000.

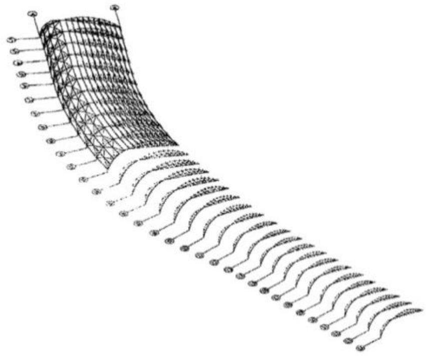

Figure 3. 42. Structural schema, Channel Tunnel Railway Terminal, London, UK, Nicholas Grimshaw and Partners (Source: Kolarevic, 2009)

Figure 3. 43. Bowstring space trusses, Channel Tunnel Railway Terminal, London, UK, Nicholas Grimshaw and Partners (Source: Kolarevic, 2005)

Beijing National Stadium by Herzog and de Meuron in Beijing, China is another example which has a complex envelope structure made from space trusses and frames. The envelope structure is separated from the bowl structure inside and carries only its own load with its own supportive system. The 69.2m high structural system of the stadium has a length of 330m and a width of 220m. The reason behind the usage of space truss is its ability to span large distance and leave a big opening for the sports area. There are 24 columns in the structural system, which are located at regular intervals around the building's perimeter constituting an ellipse shape. Every column has three booms within its structure and the booms are connected each other with diagonals forming a space truss. There are also horizontal beams that span the building leaving a central opening with dimensions of 190m x 124m. These 12m deep planar trussed beams join with the columns and constitute a series of interlocking primary portal frames.[197] The spaces between the columns and the beams are filled with secondary and tertiary trusses for supporting the roof structure.[198] The truss system at the roof has top and bottom booms connecting with diagonal struts. It has a depth of 10m.[199]

The steel members of the structural system in Beijing National Stadium have 1.2 by 1.2m box sections that consist of steel sheets. These members are connected with the help of the square extremities of the 'nodes,' and they twist in order to maintain the form of the structural system.[200]

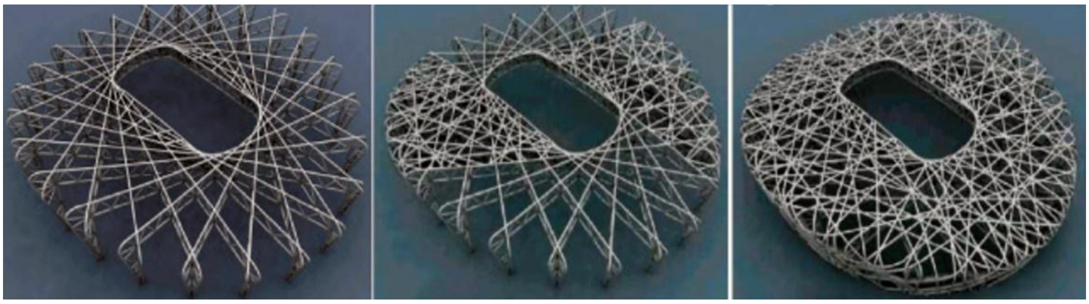

Figure 3. 44. Primary frames with secondary and tertiary members, Beijing National Stadium, China, Herzog and de Meuron (Source: Subramanian, 2008)

3.2.3. Grid Systems

Grid systems are shell structures that consist of intersecting linear elements creating a two-dimensional grid pattern. They enable to open up solid shell surfaces and take natural light into interior. Grids become the members of the structural system that provide strengh and stiffness to the structure and also carry the covering material. With the help of digital technologies, various forms can be designed and constructed using grid shell systems.[201]

[197] Subramanian, N. 2008. pp. 246-264.
[198] Veltkamp, Martijn. 2007.
[199] Subramanian, N. 2008. pp. 246-264.
[200] Veltkamp, Martijn. 2007.
[201] Sandaker, Bjørn Normann, Arne Petter Eggen, and Mark R. Cruvellier. 2011.

Grid shells generally have curvilinear forms, as long spans can not be passed with horizontal forms because of the bending moments and stresses. Therefore, curvilinear grid shells benefit from the folds of the skin to support additional strenght and carrying capacity to the form. They work in compressive membrane manner by concentrating the compressive stresses into the forces in linear members of the grid shell.[202]

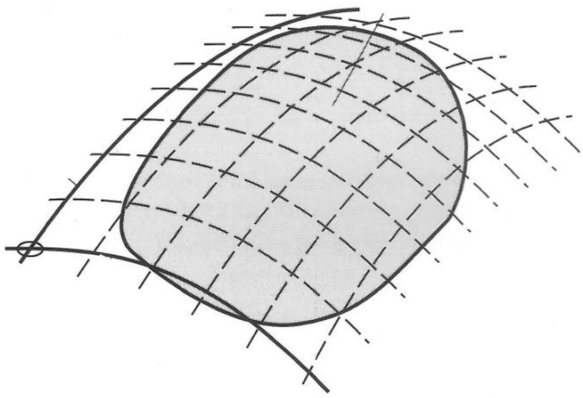

Figure 3. 45. Double curved grid system
(Source: Bechthold, 2008)

There are mainly two ways to create a grid system. In the first method, grids are handled as two-dimensional planar surfaces at the beginning of the design process. During computational design process, grids are deformed via the field or conceptual forces and take their final form. Another way to generate grid systems is to tessellate an already generated curvilinear surface.

The most encountered types of the grid shells are triangular and quadrangler grid systems. As quadrangle is not a stable structure such as a triangle which is stable under applied loads in any direction, joints of quadrangler grids should be tightened to create a rigid-frame like system.[203]

The glass roof of the British Museum Great Court by Fosters and Partners in London, UK is an example which has a triangulated grid shell structure. The reason behind the triangulation is triangle's efficiency for stability. In addition, the grid shell

[202] Ibid.
[203] Ibid.

enables the roof to be fully glazed and therefore, let sunlight into the atrium.[204] The courtyard has dimensions of 92x73m and encloses an area of 6,700m^2.[205] The free form structure, which covers the area, consists of 6000 straight steel beams that have box sections. They join with 1800 finger-shaped nodes.[206] Beams are welded to these nodes for the stability of the structure. As the grid structure has a complex geometry and the curvature changes through the structure, the sizes of steel beams and the geometry of their connection nodes differ and therefore, become unique. For example 80mm wide beams have different depths changing within the range of 80mm and 200mm.[207] In the middle of the courtyard, there is the Reading Room building. There is a compression ring around the dome of this building to act against radial compression of the glass roof. On the outside edges of the courtyard, the glass roof is carried on sliding bearings that enable horizontal movement for preventing the distressing or overloading on the existing walls.[208]

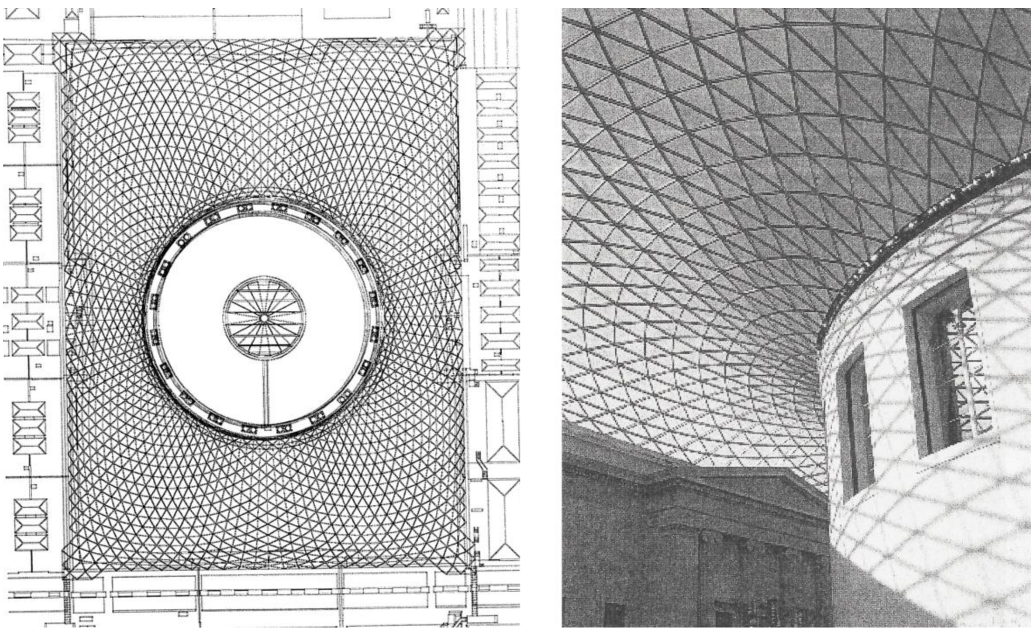

Figure 3. 46. British Museum Great Court, London, UK, Foster and Partners (Source: Szalapaj, 2005)

[204] Burry, Jane, and Mark Burry. 2010.
[205] Buro Happold. “Queen Elizabeth II Great Court, British Museum.” Projects. 25 Apr. 2013 <http://www.burohappold.com/projects/project/queen-elizabeth-ii-great-court-british-museum-169/>.
[206] Sandaker, Bjørn Normann, Arne Petter Eggen, and Mark R. Cruvellier. 2011.
[207] Veltkamp, Martijn. 2007.
[208] Sandaker, Bjørn Normann, Arne Petter Eggen, and Mark R. Cruvellier. 2011.

The grid shell structure of the Kogod Courtyard at the Smithsonian Institution Patent Office Building by Foster and Partners in Washington, DC, USA consists of quadrangles. The grid shell enables the roof surface to be fully glazed. Therefore, glass roof both enables sunlight to enter into the courtyard and provides visual access to sky. The roof form consists of three domed areas that are connected with curved valleys. The structure is supported on eight columns and there is no lateral restraint at the edges. The prefabricated fins and nodes are all unique within the complex structure. Because of environmental considerations such as taking natural light into the building, steel fins twist differentially through the grid structure. They become horizontal close to the columns where the structural forces are greatest. [209] The courtyard that quadrangler grid shell structure covers has the dimensions of 80m x 40m.[210]

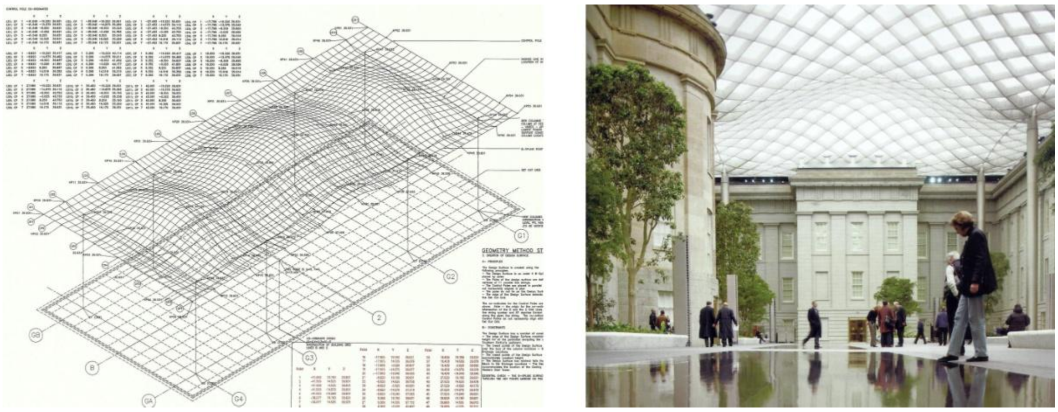

Figure 3. 47. Grid shell structure of the Kogod Courtyard at the Smithsonian Institution Patent Office Building, USA, Foster and Partners (Source: Burry, 2010)

Yas Hotel by Asymptote Architecture in Abu Dhabi, United Arab Emirates is another example which has a quadrangler grid shell structure. The quadrangular grids are made from steel tubes that have rectangular hollow sections. [211] There are 10,700 unique thin steel tubes in the grid structure. [212] Even though the grid structure of Yas

[209] Burry, Jane, and Mark Burry. 2010.
[210] Buro Happold. “Smithsonian Institution Patent Office Building.” Projects. 25 Apr. 2013 <http://www.burohappold.com/projects/project/smithsonian-institution-patent-office-building-113/>.
[211] Schlaich Bergermann und Partner. “Yas Hotel.” Build. 25 Apr. 2013 <http://www.sbp.de/en#build/show/1694-Yas_Hotel>.
[212] Waagner-Biro. “Yas Marina Hotel.” Project Details. 26 Apr. 2013 <http://www.waagner-biro.com/en/divisions/steel-glass-structures/about>.

Hotel consists of quadrangles, there is a major triangulated beam layout through the structure. Beam provides the structural stability to the grid structure by its triangulated arrangement. [213] The structure is supported from ground by 10 columns having V-forms. 8 of the supports are able to slide for corresponding to the temperature movements and the other 2 supports are fixed. In addition to the vertical column supports, horizontal struts are added for transferring the wind loads to concrete structure of the hotel buildings. The whole grid shell structure has a maximum length of 217m, width of 44m and height of 35m. [214]

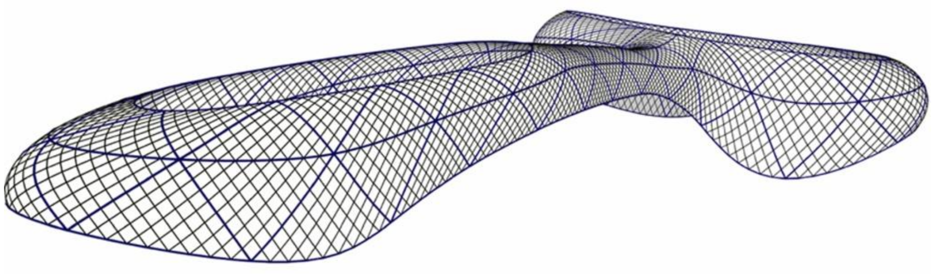

Figure 3. 48. Triangular beam layout over the quadrangular grid structure, Yas Hotel, Abu Dhabi, Asymptote Architecture (Source: Pottmann, 2009)

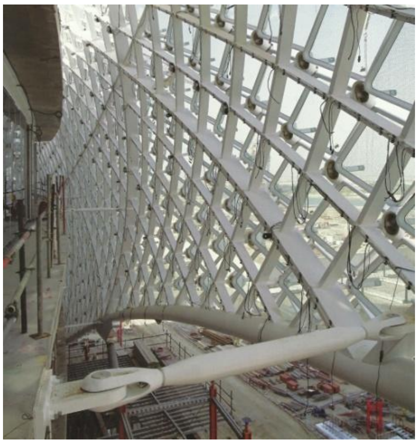

Figure 3. 49. Quadrangular grid of the structure, Yas Hotel, Abu Dhabi, Asymptote Architecture (Source: Burry, 2010)

[213] Pottmann, Helmut. "Geometry and New and Future Spatial Patterns." Architectural Design 79.6 (2009): 60-65.
[214] Schlaich Bergermann und Partner. "Yas Hotel." Build. 25 Apr. 2013 <http://www.sbp.de/en#build/show/1694-Yas_Hotel>.

Some grid systems necessitate the usage of tension rods to further stabilize the structure against tensile stresses which tend to unfold the system horizontally causing cracks in the surface. Rods pull the structure towards inside and also enable the structure to be lighter and thinner. The grid shell over the courtyard of the DZ Bank Building by Frank Gehry & Associates in Berlin, Germany is an example where fanning tension rods are attached at certain intervals to the arched ribs for maintaining the form of the grid shell.[215]

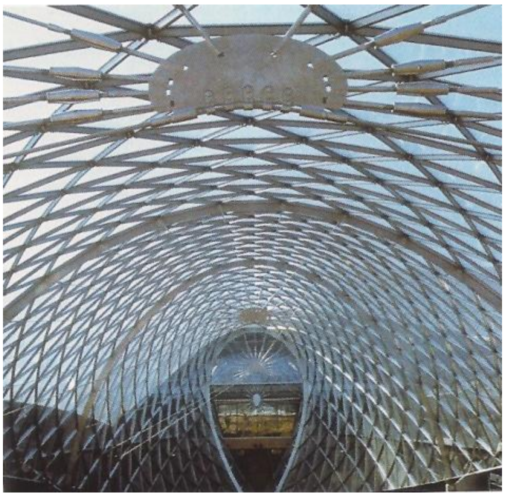

Figure 3. 50. Usage of stiffening tension rods, DZ Bank Building, Berlin, Germany, Frank Gehry & Associates (Source: Schlaich, 2008)

The grid shell in DZ Bank Building has a triangulated grid system which was generated by tessellation of the curvilinear surface. In the grid structure, there are stainless steel mullions that are connected each other with milled joints. Mullions are screwed to the joints for stability.[216]

[215] Sandaker, Bjørn Normann, Arne Petter Eggen, and Mark R. Cruvellier. 2011.
[216] Schlaich Bergermann und Partner. "Glass Roof for DZ Bank." Build. 25 Apr. 2013 <http://www.sbp.de/en#build/show/102-Glass_Roof_for_DZ-Bank>.

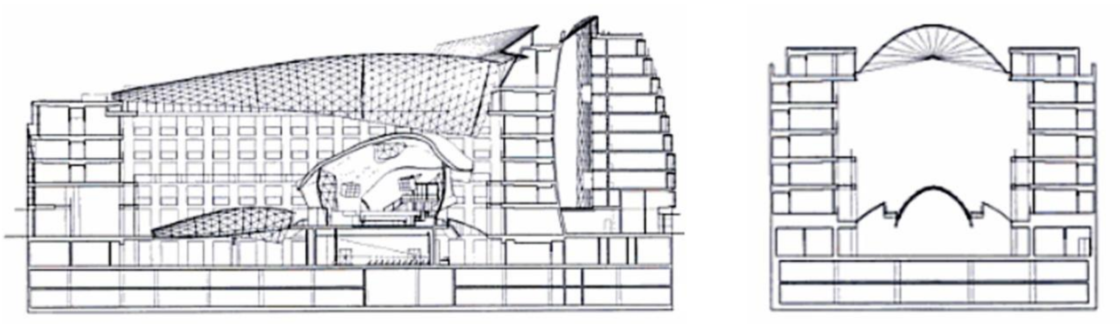

Figure 3. 51. Longitudinal and cross section of the grid roof, DZ Bank Building, Berlin, Germany, Frank Gehry & Associates (Source: Myerson, Ross, 2003)

Figure 3. 52. The grid shell, DZ Bank Building, Germany, Frank Gehry & Associates (Source: http://www.gartnersteel.com/content/references/completed_projects/dgb.htm)

Grid shells are not used only to cover courtyards for enabling sunlight and visual access to interior. They also have the flexibility to be covered both with glass and solid panels, therefore provide privacy in desired areas. Admirant Entrance Building by Massimiliano and Doriana Fuksas in Eindhoven, Netherlands has a 4 story high triangulated grid shell that covers concrete structure of the building being both the roof and the facades. The form of the complex grid structure is abstracted from the curvilinear skin, and is covered by aliminum and glass panels. The grid structure consists of steel members having rectangular sections. These steel members have the sizes of 65 x 50 mm.[217] They are connected to the joints with welding.[218]

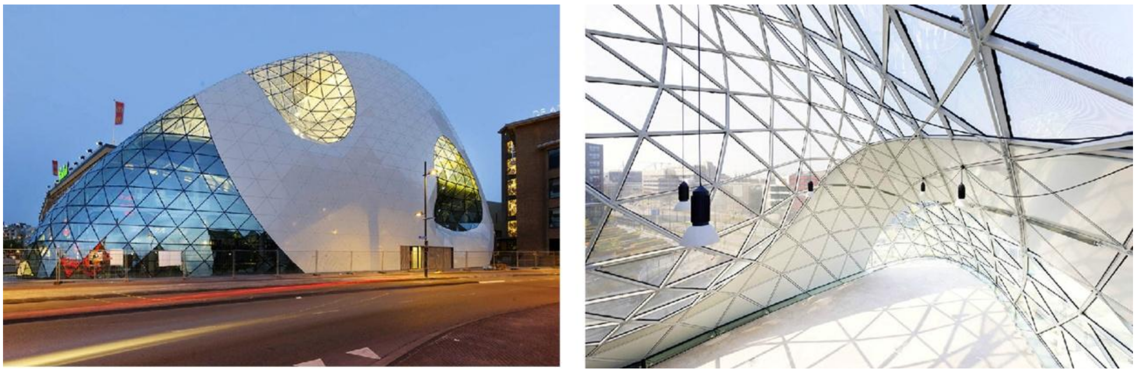

Figure 3. 53. Triangulated grid shell structure, Admirant Entrance Building
(Source: http://www.fuksas.it/#/progetti/0506/)

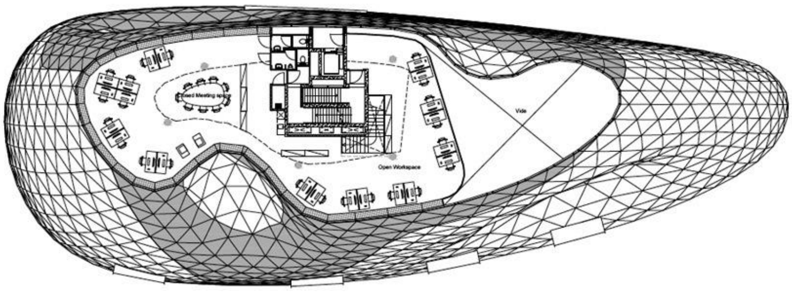

Figure 3. 54. Plan view, Admirant Entrance Building, Massimiliano and Doriana Fuksas
(Source: http://www.creactivistas.com/2010/11/massimiliano-fuksas-de-blob-en.html)

In the projects of Brandscape BMW Pavilion at the 2000 Auto Show and The Wave BMW Pavilion at the Expo 2000 by Bernhard Franken and ABB Architekten, there are experimental approaches to grid shells. For example, the grid structure of the Brandscape BMW Pavilion in Geneva, Switzerland consists of iso-parametric lines. These iso-parametric curvilinear lines were handled linear at the beginning of the design process and organized in an orthogonal layout. They were deformed by force fields in

[217] Knippers Helbig. “Admirant, Eindhoven, Netherlands.” Projects. 26 Apr. 2013 <http://www.khing.de/projekte_dacher.php?id=66&page=2&start=>.
[218] Waagner-Biro. “The Blob.” Project Details. 26 Apr. 2013 <http://www.waagner-biro.com/en/company/references>.

the site during design process and took their final curvilinear grid form.[219] Aluminum extruded profiles constitute the grid structure of the Brandscape BMW Pavilion. The edge supports are made from steel-pipe elements based on moment analyses of the structure. Even though the aluminum profiles and steel pipes are unique in their form, they are connected to each other with identical joints. [220]

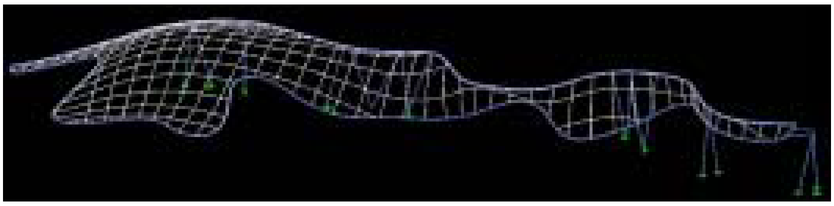

Figure 3. 55. Structural schema, Brandscape BMW Pavilion, Geneva, Switzerland, Bernhard Franken and ABB Architekten (Source: Kolarevic, 2009)

Figure 3. 56. Grid system in detail, Brandscape BMW Pavilion, Geneva, Switzerland, Bernhard Franken and ABB Architekten (Source: Franken, 2009)

[219] Franken, Bernhard. 2009. pp. 121-138.
[220] Ibid.

3.2.4. Solid Systems: Monocoque and Semi-Monocoque Structures

Solid systems are "rigid surface structures."[221] They work in compressive membrane manner such as grid systems but this time compressive stresses are transferred to the ground by the whole surface. Folds of the curvilinear forms provide additional stiffness to solid systems. Concrete is generally used for constructing solid surfaces because of its strength and resistance against compressive forces. There are two types of solid systems which are monocoque and semi-monocoque structures. Monocoque structures unify form and structure. Structure is embedded into the skin and there is no need to have an additional stiffening system. Skin acts structurally and absorbs all the stresses.[222] Semi-monocoque structures, which are also defined as "stressed skin-on frame construction," consist of form and structural ribs."[223] Both the surface and ribs act structurally. They are connected rigidly to each other that ribs provide additional strength to the skin considering monocoque structures.[224]

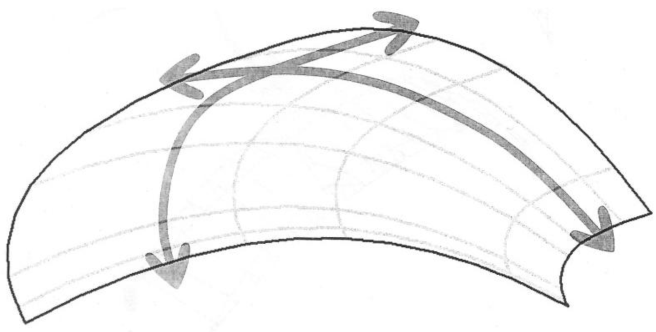

Figure 3. 57. Double curved shell form with its compressive forces
(Source: Szalapaj, 2005)

Solid shell systems generally have double curvatures and work against compressive membrane stresses. However, in structures where curvature is modest compared to span, skin also has to work against bending moments. For example, Toyo Ito's Island City Central Park "GRIN GRIN" in Fukuoka, Japan has a solid structure

[221] Bechthold, Martin. 2008.
[222] Kolarevic, Branko. 2009. pp. 29-54.
[223] Bechthold, Martin. 2008.
[224] Ibid.

that works both as a shell system and a slab in bending.[225] The free form solid structure of the building involves one story high three greenhouses and covers approximately an area of 5,000 m^2. [226] The maximum distance that the 400mm thick solid structure spans is 50m.[227] The skin has a monocoque character that the complex form of the reinforced concrete shell is both the structural system and the skin. There are no additional bearing elements; the skin is the main bearer itself. [228]

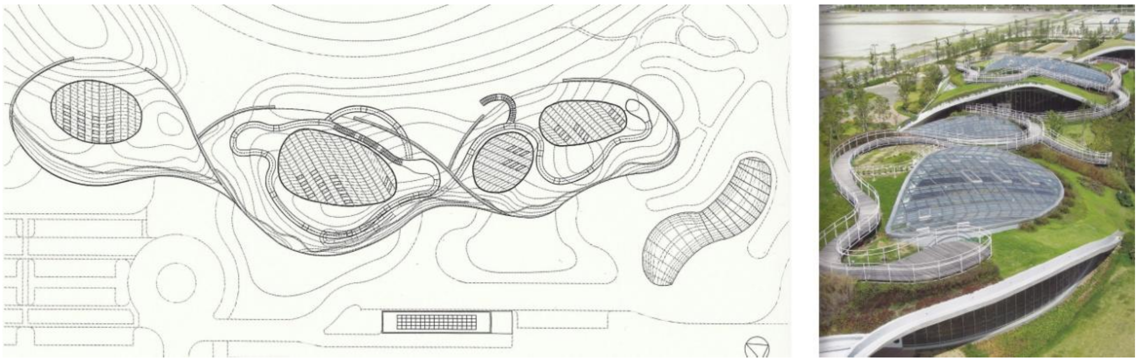

Figure 3. 58. Concrete shells, Island City Central Park, Fukuoka, Japan, Toyo Ito (Source: Burry, 2010)

Toyo Ito’s Meiso no Mori Crematorium in Kakamigahara, Gifu, Japan is another example where Ito used solid shell system for the roof. The solid roof acts structurally as a monocoque system. It is made from reinforced concrete and has a thickness of 20cm. Twelve tapered columns and four structural cores carry the curvilinear shell roof.[229]

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[225] Ibid.

[226] Toyo Ito & Associates, Architects. “Building for Island City Central Park, GRIN GRIN.” Projects. 25 Apr. 2013 <http://www.toyo-ito.co.jp/WWW/Project_Descript/2005-/2005-p_01/2005-p_01_en.html>.

[227] Bechthold, Martin. 2008.

[228] Burry, Jane, and Mark Burry. 2010.

[229] Detail. 2008. pp. 498-502.

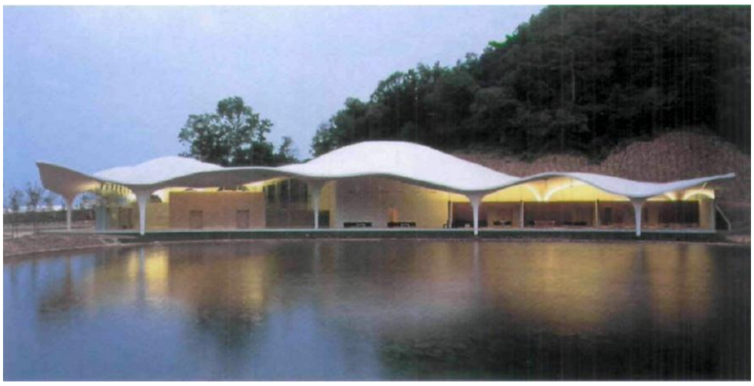

Figure 3. 59. Solid shell, Meiso no Mori Crematorium, Kakamigahara, Japan, Toyo Ito (Source: Detail, 2008)

California Bay House by Leonard and Walker & Moody Architects in San Francisco, CA also has a solid structural system. Different from aesthetic and conceptual reasons, selection of monocoque system in this project is related to budget. Because of the inexpensiveness, a monocoque solution without internal framework was accepted with usage of composites. The two storey high shell structure is a laminated structure that consists of "a balsa-cored sandwich panel, with 2-inch/50-mm thick core and 0.1875-inch/4.76-mm thick woven fiberglass/glass mat skins wet out with vinyl ester resin." [230] Nine laminated panels form the main shape by joining with each other in the construction phase. The reason why sandwich design was selected was its greater stiffness and inclusion of insulation against a monolithic laminate.[231]

Figure 3. 60. Solid shell structure, California Bay House, San Francisco, Leonard and Walker & Moody Architects (Source: Composites Technology, 2010)

[230] Composites Technology. 2010.
[231] Ibid.

Curvilinear solid systems are also used in high rise buildings where skeletal system becomes the primary structural system. Curvilinear panels that consist the solid surfaces also have structural function, however; their small spans reduce the importance they have as structural members compared to their fabrication and logistical issues.[232] The load-bearing curvilinear panels behave similar to columns in terms of structural behaviour and work for compression. As the exterior load-bearing walls are curved, they resist to horizontal and vertical loads better and reduce the buckling problem through the wall.[233] Der Neue Zollhof by Frank Gehry in Dusseldorf, Germany is an example where three multi-story office towers have concrete solid systems for covering the buildings as facades. The load-bearing curvilinear external wall panels are the secondary bearers of the buildings made of precast concrete.[234] They were casted in styrofoam moulds of sizes approximately 3.0m to 3.5m and assembled with each other on construction site.[235]

Figure 3. 61. Concrete panels, Der Neue Zollhof, Dusseldorf, Germany, Frank Gehry (Source: Shelden, 2002)

3.3. Structural Design in Production and Construction

In digital structural design, there is a direct link of design to production. Digital technologies are being used in manufacturing and construction phases of buildings. The

[232] Bechthold, Martin. 2008.
[233] Sandaker, Bjørn Normann, Arne Petter Eggen, and Mark R. Cruvellier. 2011.
[234] Kolarevic, Branko. 2009. pp. 29-54.
[235] Dhir, Ravindra K., Peter C. Hewlett, and Roderick M. Jones, eds. Creating with Concrete: Opening and Leader Papers of the Proceedings of the International Conference Held at the University of Dundee, Scotland, UK on 6-10 September 1999. London: Thomas Telford, 1999.

availability of a wide range of digital machines that support production and construction of complex forms enable architects to design whatever they desire and think of.

The digital data, which includes detailed information for manufacturing, controls digital machines during manufacturing process. Manufacturing data consists of a set of computational instructions and controls the movement of the machine tools such as determining the operation path. After manufacturing, construction is also supported by digital technologies where robots are used for locating and assembling the structural parts.

3.3.1. Computer Aided Manufacturing (CAM): From Mass Production to Mass Customization

Computer Aided Manufacturing (CAM) is the usage of computational software for controlling production processes. It is in integration with Computer Aided Design (CAD) technology that with the connection of Computer Aided Design (CAD) to Computer Aided Manufacturing (CAM), an effective information transfer is present for realization of digital architectural and structural designs.

When a digital design process ends, final digital model has all detailed information related to production and assembly. Structural details such as material properties, component sizes, and joint types are included in the digital model. Therefore, there is no need to convert the digital information to construction instructions. Architects are in integration with production processes. The design information can be directly used for controlling digital fabrication machines.[236] Therefore, if a design can be computationally described by parameters or numerical information, it can be constructed. Constructability problem is related to computability in digital structural design as Kolarevic states; "the new digitally-enabled processes of production imply that the constructability in building design becomes a direct function of computability."[237]

Computer aided design provides architects to design complex curvilinear forms which are unimaginable beforehand. For corresponding to load calculations of the complex forms, structural design solutions also become complex which comprise of unique elements in size and shape. Therefore, this uniqueness requires mass-

[236] Kolarevic, Branko. 2009. pp. 29-54.
[237] Ibid. p. 33.

customization in production, and production gets beyond the limits of standardization. Steve Hatzellis emphasizes this change in his article of “Formal complexity in digital architecture.” He states that; “if the 20th century is synonymous with the repetitive forms of mass produced Modernist buildings then the 21th century will see the individuality of mass-customization.”[238] Digital architectural and structural design does not necessitate mass production of repetitive elements. Digital construction technology enables the production of a variety of unique elements. In addition, however the fabricated unique elements are complex, cost of fabrication is no longer as expensive as before. Complexity corresponds to economy and efficiency in digital production.[239] For example; complex curvilinear form of the Dynaform Pavilion in Frankfurt by Bernhard Franken and ABB Architekten cost less than the orthogonally designed MINI Pavilion which was also designed for the same client, built next to the Dynaform.[240]

Manufacturing process of digital structural designs takes place in factories. The structural system parts are manufacturable ex situ (in factories) rather than the traditional in situ method in which parts are produced in construction site.[241] After the parts are produced, they are transferred to construction site for assembly.

Complex forms and structural systems were being designed and constructed in the absence of digital technologies, too. Then the problem was buildings’ construction processes. They were lasting too long and this waste of time was causing project’s time and cost to exceed than usual.[242] However with digital technologies, it is both easy and short-time to design, structure, represent and construct buildings without depending on the complexity of the shapes.

3.3.2. Fabrication Technologies

Fabrication technologies transfer the three dimensional model in digital medium into a product. Fabrication machines are used in these translation processes for the production of structural members and their joints. There are various types of fabrication technologies which differ in terms of cutting head’s movement capabilities such as two-

[238] Hatzellis, S. 2006. p. 58.
[239] Kolarevic, Branko. 2009. pp. 29-54.
[240] Franken, Bernhard. 2009. pp. 121-138.
[241] Hatzellis, S. 2006. pp. 51-58.
[242] Terzi, Nilay. “Mimarlıkta Hesaplamalı Teknolojiler ve Geometri.” MS Thesis. Yıldız Teknik Üniversitesi, 2009.

axis movement, three-axis movement and rotation. Another criterion is thickness and scale of material. For example, planar sheet materials can be manufactured by two-dimensional cutting, whereas volumetric blocks can be formed by subtractive fabrication. From the perspective of production techniques, manufacturing processes also differ including water jet cutting, laser cutting, electrical production and mechanical production.[243]

Different fabrication technologies can be collected under different titles based on machines, materials, techniques and strategies. For example, researchers Helmut Pottmann, Andreas Asperl, Michael Hofer, and Axel Kilian make a classification on digital fabrication technologies based on different strategies and material types that can be cut in their book of "Architectural Geometry." According to them, there are three types of fabrication strategies which are cutting-based, additive and subtractive strategies.[244] Researcher Peter Szalapaj classifies the digital fabrication technologies based on complexity of the form that will be produced. For example, simple geometric forms can be produced by subtractive fabrication with CNC (computer numerical control) machines, whereas geometrically more complex forms can be produced by additive fabrication with rapid prototyping technology.[245] In Branko Kolarevic's classification, fabrication strategies are categorized based on the techniques and the strategies used. Kolarevic's classification also includes Pottmann et al.'s classification of two-dimensional cutting, subtractive fabrication and additive fabrication, and adds an additional fourth category which is formative fabrication.[246]

Different approaches to manufacturing are collected under three main categories in this thesis based on the production strategies of structural systems. These main categories are two-dimensional cutting approach, subtractive approach and additive approach. Two-dimensional cutting is used for production of frame, truss and grid systems. If structural member has a hollow section, flat edges of the members can be produced by two-dimensional cutting and then welded together. If structural member is a two-dimensional plane, the member can be cut directly without any additional operation. In two-dimensional cutting, the sheet materials are cut by two-axis movements of the cutting head, the moving bed or both of them. Laser-beam, plasma-

[243] Helmut, Pottmann, Andreas Asperl, Michael Hofer, and Axel Kilian. Architectural Geometry. 1st ed. Exton, Pa.: Bently Institute Press, 2007.
[244] Ibid.
[245] Szalapaj, Peter. 2005.
[246] Kolarevic, Branko. 2009. pp. 29-54.

arc, water-jet and sheet cutter are some of the cutting technologies that differ in terms of the material and the thickness they cut, and the technology they use etc. Laser-cutters cut using infrared light with a jet of highly pressurized gas and are applied to materials which can absorb light energy. The cutting head in laser-cutters moves in x-axis and y-axis and applies the laser vertically to the sheet material for cutting it by burning. With laser-cutters, the thickest material that can be cut cost-effectively is 16mm. Another technology for two-dimensional cutting is plasma-arc technology which applies heat for cutting. It can cut up to several inches of steel and is a preferred technology because of its inexpensiveness. Water-jet is a technology that cuts using highly pressurized water with solid abrasive particles. It can be applied to any kind of material such as steel, plastic and wood. With water-jet cutters, thicker materials can be cut considering laser-cutters, up to a thickness of 38cm. The abrasive materials within the highly pressurized water and the heavy machinery make the usage of this technology expensive. The last technology includes sheet cutters which can cut thin materials such as paper or foils using blades. [247,248]

The BMW exhibition pavilion “Dynaform” for the IAA 2001 by Bernhard Franken and ABB Architekten is an example where CNC plasma cutting was used for the manufacturing of steel frames. The box sectioned steel frames were produced in pieces as planar elements. More than 30.000 fabricated unique pieces were then welded manually by hand and located to their locations based on digital construction information. [249] Kolarevic defines the method of generating a sequence of planar sections from main form and using them as dimensional and locational references for structural system as contouring. He states that the contouring method is a production strategy where structural parts can be manufactured with two-dimensional equipment.[250]

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[247] Helmut, Pottmann, Andreas Asperl, Michael Hofer, and Axel Kilian. 2007.
[248] Kolarevic, Branko. 2009. pp. 29-54.
[249] Franken, Bernhard. 2009. pp. 121-138.
[250] Kolarevic, Branko. 2009. pp. 29-54.

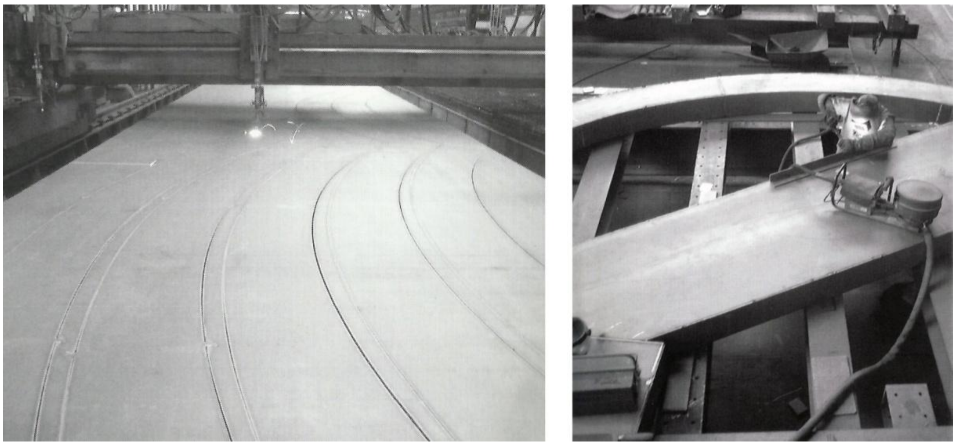

Figure 3. 62. CNC cutting process and assembling of structural frames, “Dynaform,” Bernhard Franken and ABB Architekten (Source: Franken, 2009)

The BMW exhibition pavilion “Bubble” for the IAA 1999 in Frankfurt, Germany was another example by Bernhard Franken and ABB Architekten that the planar frames were manufactured by CNC driven cutters. Water-jet technology was used for cutting approximately 3,500 aluminum sheets. All the construction information for assembly was also recorded on the sheets such as drilling of the holes and the assembly markings. Therefore, the time of on-site construction was reduced to minimum.[251]

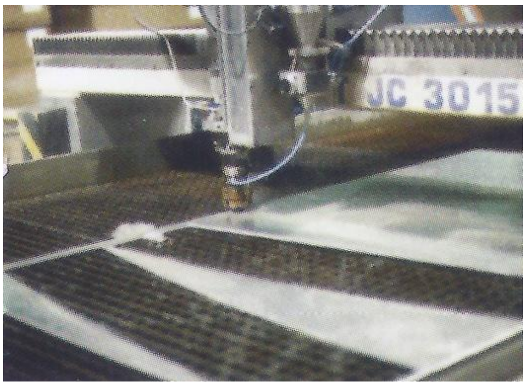

Figure 3. 63. Two-dimensional cutting process, “Bubble,” Bernhard Franken and ABB Architekten (Source: Franken, 2009)

[251] Franken, Bernhard. 2009. pp. 121-138.

In the Experience Music Project by Frank Gehry, curvilinear I-sectioned frames were also manufactured by plasma cutters. Firstly, top and bottom edges of the I-sections were manufactured. The edge plates took their final curvilinear shapes by CNC plate rolling machines. Finally, the rolled edges and the curvilinear middle plates were connected and I-sectioned frames were formed.[252]

Figure 3. 64. Production process of I-sectioned frames, Experience Music Project, Frank Gehry (Source: Shelden, 2002)

In British Museum Great Court by Foster and Partners, the beams and the joints were both manufactured by two-dimensional CNC cutting.[253] Flame cut method was used for cutting the parts from thick steel plates. During manufacturing process, each node was numbered and therefore, the nodes were located their final positions and orientations easily by using this numerical information during construction.[254]

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[252] Shelden, Dennis R. 2002.
[253] Kolarevic, Branko. 2009. pp. 29-54.
[254] Szalapaj, Peter. 2005.

Figure 3. 65. Assembly of members with nodes
(Source: http://www.fosterandpartners.com/projects/great-court-at-the-british-museum/)

In digital structural design, structural systems have generally complex curvilinear forms and thus, two-dimensional fabrication is not enough in some cases. After the members are produced, additional interventions are needed such as formative processes. Formative process involves deformation or reshaping of elastic materials such as steel, using mechanical forces, heat or stream to give the material the desired shape. For example, steel can be reshaped by stressing it to past its limit of elasticity, heating it and then bending it while it is still hot and deformable. Formative fabrication is used in the shaping of curvilinear structural members and claddings including axial or surface constrained deformation.[255]

The Brandscape BMW Pavilion at the 2000 Auto Show in Geneva, Switzerland by Bernhard Franken and ABB Architekten is an example where formative fabrication was used for reshaping the structural members. Aluminum extruded profiles constitute the structure which were manufactured with single curvature and bidirectionally bent to reach their final form. Edge supports were made from steel-pipe elements.[256] As steel elements were stiffer, they could not be manufactured as aluminum elements. Therefore, steel pipes were cut into pieces and every piece was radially bent to take its unique doubly-curved form.[257] The bent pieces were assembled with welding and located to their places.[258]

[255] Kolarevic, Branko. 2009. pp. 29-54.
[256] Franken, Bernhard. 2009. pp. 121-138.
[257] Kloft, Harald. "Engineering of Freeform Architecture." Fabricating Architecture: Selected Readings in Digital Design and Manufacturing. Ed. Robert Corser. New York: Princeton Architectural Press, 2010. 110-127.
[258] Franken, Bernhard. 2009. pp. 121-138.

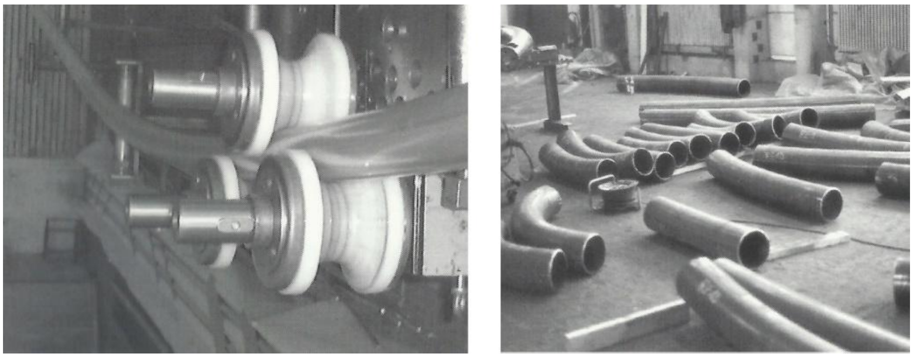

Figure 3. 66. Bidirectionally bent aluminum profiles and radially bent edge supports, “Brandscape,” Switzerland, Bernhard Franken and ABB Architekten (Source: Kolarevic, 2009)

Beijing National Stadium by Herzog and de Meuron in China is another example where formative fabrication was used for giving structural members their final form. Envelope of the building has continuous box profiles that extend along the structure. As profiles follow the outer contour of the building, they curve and twist in order to maintain the complex curvilinear geometry of the structure. The curvilinear members have developable surfaces that meant that the members could be produced by two-dimensional cutting from steel plates and then rolled to give the steel members their curvature. [259]

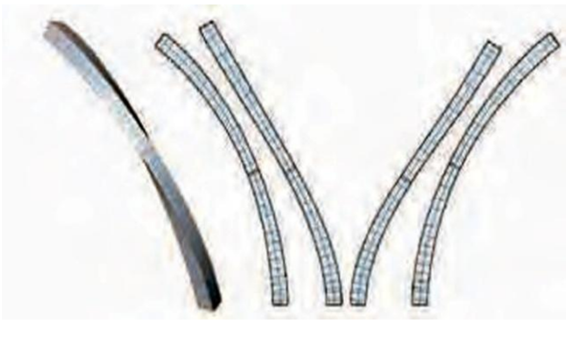

Figure 3. 67. Two dimensional plates that constitute the curvilinear box sections (Source: Burrows, Simpson, 2009)

[259] Burrows, Stephen, and Martin Simpson. 2009. pp. 16-19

Subtractive approach is used for production of structural members, solid shells and formworks where the shells are casted. It includes removal of material from a solid mass using electrical, chemical, or mechanical milling processes. The milling can be in three different ways including axially, surface, or volume constrained processes. The simplest production is the axial production where the milling head moves in only one direction, in the z-axis. Although it is easy to control the machine, the axial movement limits the production of a wide range of geometries. In surface milling process, the head moves in two directions over the surface in the x-axis and y-axis similar to two-dimensional cutting. The volume constrained milling process is different from axial and surface milling processes in its ability to milling in three dimensions. The milling head moves up and down in z-axis in addition to x-axis and y-axis. There are also 4-axis and 5-axis machines where additional rotation axis is added to cutting head or cutting bed for increasing the range of models, and also reachable areas considering 3-axis machines. For example, undercuts can not be produced by 3-axis machines. As the movement and rotation capability of the milling head increases, machines become more expensive and controlling the machines becomes more complex. The advantage of this approach is the possibility of using materials such as wood and stone in their natural forms. [260, 261]

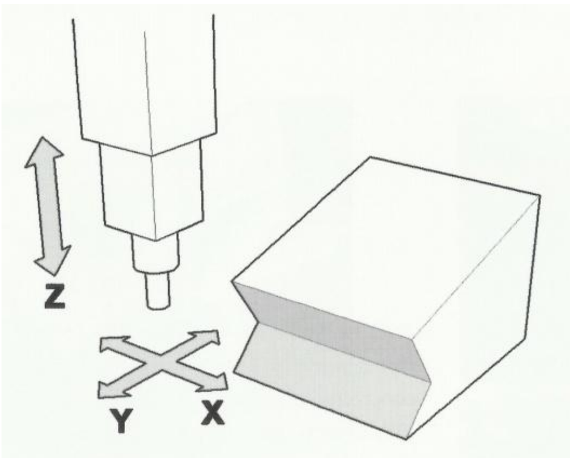

Figure 3. 68. Undercut in a solid
(Source: Kolarevic, 2009)

260 Kolarevic, Branko. 2009. pp. 29-54.
261 Helmut, Pottmann, Andreas Asperl, Michael Hofer, and Axel Kilian. 2007.

Various sizes of drill bits, which are part of the cutting heads, can be used for subtraction. Bigger bits are used for removing big solid parts and smaller bits are for fine work. Rotation speeds of the bits also vary in terms of the material properties such as hardness. [262]

For example in Gehry's Der Neue Zollhof project, load bearing concrete panels of the three office buildings were precast in Styrofoam formworks and assembled on site. [263] 355 different curvilinear Styrofoam blocks were first modeled in CATIA and then CNC (Computer Numerical Control) milled for being the formworks where the reinforced concrete panels would be casted.[264]

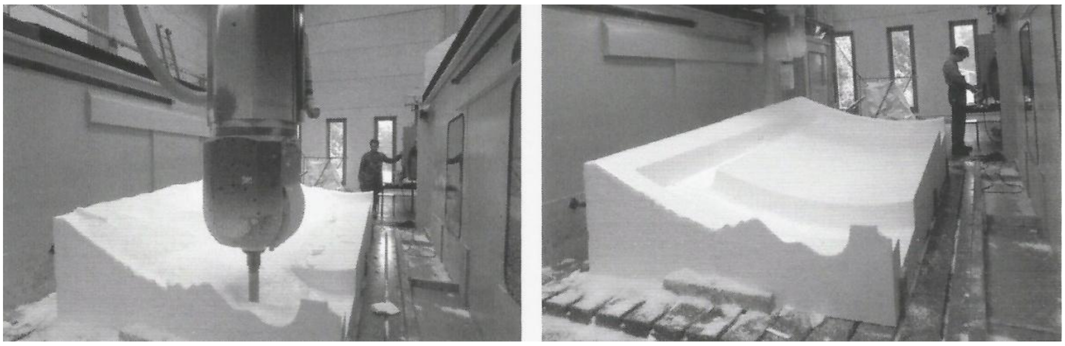

Figure 3. 69. Production of formworks with CNC milling, Der Neue Zollhof, Germany, Frank Gehry (Source: Kolarevic, 2009)

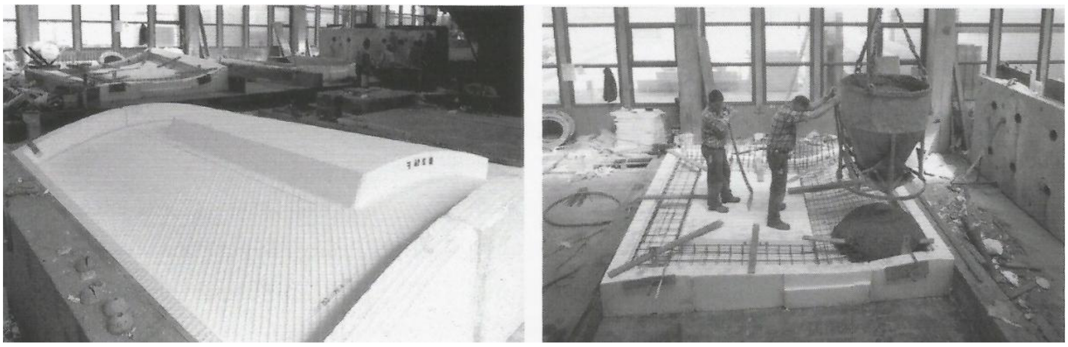

Figure 3. 70. Casting of reinforced concrete panels, Der Neue Zollhof, Germany, Frank Gehry (Source: Kolarevic, 2009)

[262] Kolarevic, Branko. 2009. pp. 29-54.
[263] Dhir, Ravindra K., Peter C. Hewlett, and Roderick M. Jones, eds. 1999.
[264] Kolarevic, Branko. 2009. pp. 29-54.

CNC milling was also used in California Bay House project by Leonard and Walker & Moody Architects to produce expanded polystyrene (EPS) foams where curvilinear composite wall panels would be casted. The building shell consists of 9 segments and for every composite segment, one-off mold was produced.[265]

Figure 3. 71. CNC milling process of composite panels, California Bay House
(Source: Composites Technology, 2010)

Robotic machining is a developing area of digital manufacturing which is used within subtractive processes. Robotic machining is the combination of robotics and machining where robotic arms are used generally for foam millings. Different from the fabrication machines mentioned above, robotic arms can mill larger blocks than the machine itself. There is no need the machine to cover the material to reach all the points. Robotic arms offer a "larger-reach envelope" and movement flexibility that various sizes of volumetric materials bigger than the machine can be milled easily.[266]

Additive fabrication is the third fabrication strategy which is used for fabricating small scale products such as joints and structural system prototypes. In additive approach, shape is produced layer by layer, by adding material on top of another until the shape is completed. Additive fabrication is also named as layered manufacturing, solid freeform fabrication, rapid prototyping, and desktop manufacturing.[267] During fabrication, when a layer is completed, support platform moves downward in the z-axis

[265] Composites Technology. 2010.
[266] Helmut, Pottmann, Andreas Asperl, Michael Hofer, and Axel Kilian. 2007.
[267] Kolarevic, Branko. 2009. pp. 29-54.

to enable following layer to be added. [268] The layers are two dimensional layers which can be liquid polymers, metal powder, ceramic powder, plastic paper etc. For example in Selective Laser Sintering (SLS), metal powder is melted by laser light for becoming solid layers. In Stereolithography (SLA), liquid polymers solidify under laser light. And in the Laminated Object Manufacture (LOM) process, sheets of paper or plastic are used and glued to create the final three dimensional forms.[269]

Additive fabrication is a less chosen method considering other technologies because a limited size of forms can be produced, the fabrication equipment is expensive and the production process is longer. Still, it is seen that additive fabrication is used for the production of structural design models, detail designs and repetitive building components such as joints of the systems. For example rapid prototyping was used for the production of the steel elements in the truss structure of Polshek's Rose Center for Earth and Sciences in New York. [270]

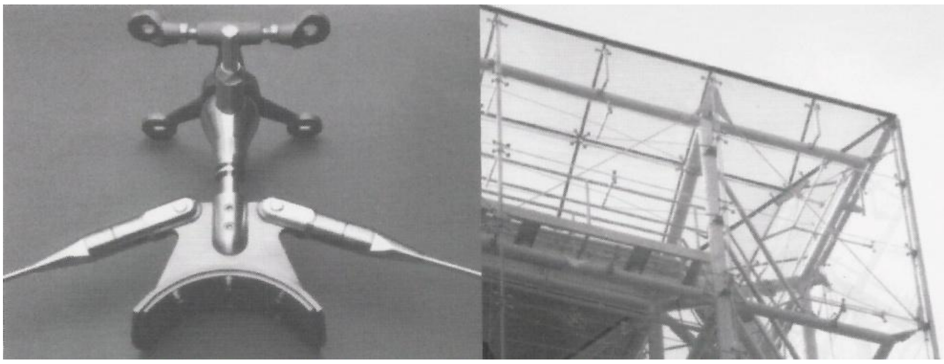

Figure 3. 72. Truss elements, Polshek's Rose Center for Earth and Sciences, New York (Source: Kolarevic, 2009)

Beijing National Stadium by Herzog and de Meuron in China is another example where rapid prototyping was used for creating physical structural models of the project. Physical models proved to design team and client that the project was buildable. Initial models were produced from card, foam-board and 3-D wax printers. In addition

[268] Helmut, Pottmann, Andreas Asperl, Michael Hofer, and Axel Kilian. 2007.
[269] Kolarevic, Branko. 2009. pp. 29-54.
[270] Ibid.

to small scale models, a full scale model was also prototyped from foam-board to comprehend the real scale of the members.[271]

Figure 3. 73. Small scale and full scale protoypes, Beijing National Stadium, China, Herzog and de Meuron (Source: Burrows, Simpson, 2009)

Additive fabrication can be used with subtractive fabrication during a production process at the same time. This integration provides greater accuracy to production process and product where subtraction is used for overcoming the redundancies of the additive fabrication.[272]

3.3.3. Assembly and Construction

Digital technologies are also being used for assembly and construction in addition to design and fabrication processes. By technologies such as electronic surveying and laser positioning, coordinates of every single building component are determined in the construction site. In addition to determining the location, the components are moved to their locations and fixed in their proper place.[273] Frank Gehry's Guggenheim Museum in Bilbao and Experience Music Project in Seattle can be given as examples where digital technologies were used rather than manual measurements for the construction. Annette LeCuyer describes the digital construction processes of Guggenheim Museum in her article of "Building Bilbao;"

[271] Burrows, Stephen, and Martin Simpson. 2009. pp. 16-19.
[272] Szalapaj, Peter. 2005.
[273] Kolarevic, Branko. 2009. pp. 29-54.

Gehry`s office wryly notes that Bilbao was built without any tape measures. During fabrication, each structural component was bar coded and marked with the nodes of intersection with adjacent layers of structure. On site bar codes were swiped to reveal the coordinates of each piece in the CATIA model. Laser surveying equipment linked to CATIA enabled each piece to be precisely placed in its position as defined by the computer model. [274]

Design information, which comes from electronic surveying and laser positioning devices, control construction robots. It determines the location of the components, carry them and assemble them to their locations. For example, Shimizu's Mighty Jack developed in Japan is used to position heavy steel beams. Also developed in Japan, Kajima's Reinforcing Bar Arranging Robot and Obayashi-Gumi's Concrete Placer are used to pour concrete into moulds. [275] SMART system (Shimizu Manufacturing system by Advanced Robotics Technology) is another digitally-driven system that automates a variety of construction phases such as placement and installation of various building parts. For example, it locates steel frames, concrete floor planks and wall panels to their locations and makes their assembly on site. Therefore, SMART system can be used for the construction of a full-scale building. If we go in detail into the SMART system; it has a lifting mechanism and automatic conveying equipment installed on an operating platform. These mechanisms automatically move the steel structural parts, locate them to their locations and do the installation. When construction of ground floor finishes, all the automated equipment is lifted upwards for construction of the upper floor. Therefore, construction continues floor by floor. The digitally controlled SMART system reduces labor force and predicted construction period of the project.[276]

Nagoya Juroku Bank Building in Japan is an example where SMART system was used for construction phase. Steel frame of the building was placed, concrete slabs and walls of the building were located and installed by the SMART system.[277] Welding of columns and beams was also controlled digitally and done automatically by welding robots.[278]

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[274] Le Cuyer, Annette. "Building Bilbao." Architectural Review 202.1210 (1997): 43-45. MutualArt.com. Proquest. 3 May 2013 <http://www.mutualart.com/OpenArticle/Building-Bilbao/1C95F3317E7722B7>

[275] Kolarevic, Branko. 2009. pp. 29-54.

[276] Yamazaki, Yusuke, and Junichiro Maeda. "The SMART System: an Integrated Application of Automation and Information Technology in Production Process." Computers in Industry 35.1 (1998): 87-99.

[277] Kolarevic, Branko. 2009. pp. 29-54.

[278] Yamazaki, Yusuke, and Junichiro Maeda. 1998. pp. 87-99.

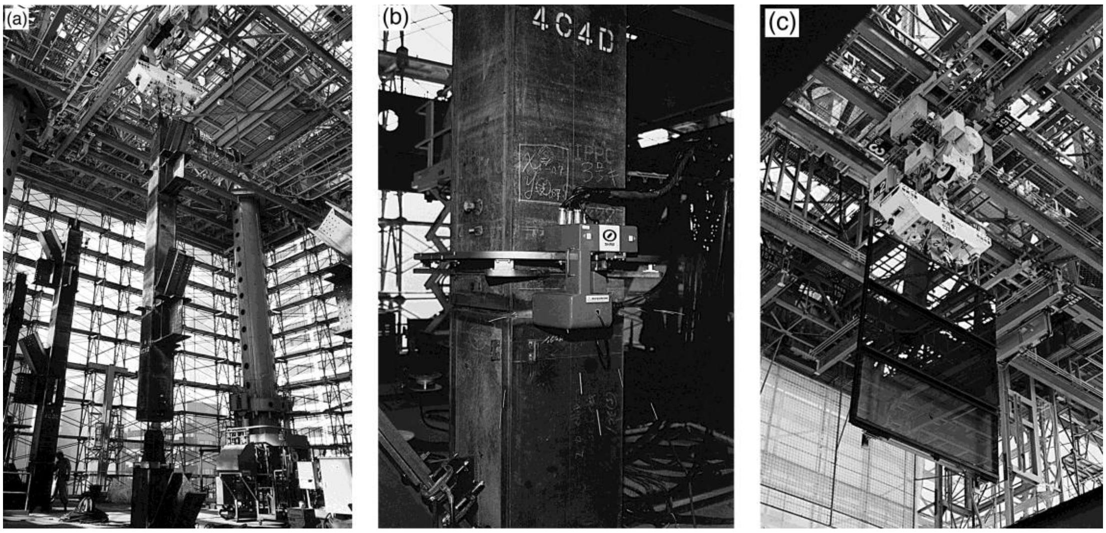

Figure 3. 74. Construction Process of Juroku Bank Building, Nagoya
(Source: Yamazaki, Maeda, 1998)

Software that is being used in computer aided manufacturing and construction is not developed in architecture discipline. Architects inspired from other fields and made use of their technologies. For example, Frank Gehry's buildings whether they were not designed in digital medium were made possible by the use of CATIA which is an aeronautical software used for aircraft design and fabrication.[279] Gehry's design for the large Fish Sculpture in Barcelona, Spain is an example which was developed and constructed digitally using the software CATIA. Structural analyses were realized and construction drawings were derived from the three dimensional model in CATIA.[280]

[279] Imperiale, Alicia. 2000.
[280] Kolarevic, Branko. 2009. pp. 29-54.

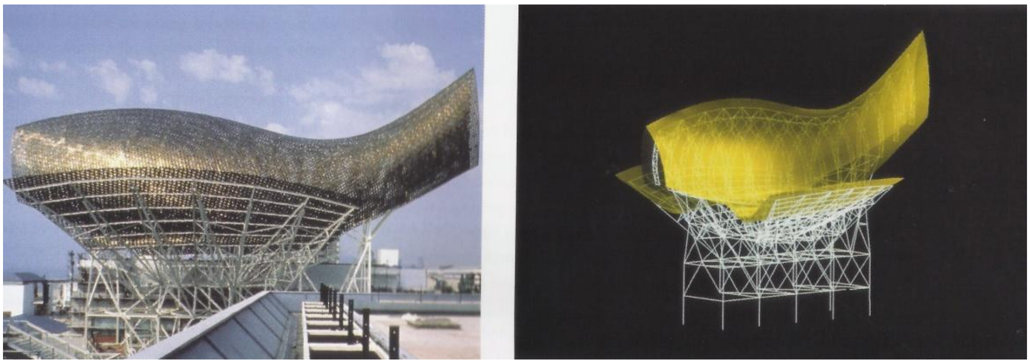

Figure 3. 75. Fish Sculpture, Vila Olimpica, Barcelona, Spain, Frank Gehry
(Source: Glymph, 2009)

Alias, Maya and CNC milling systems are also other examples to software programs which were developed for the manufacturing of different products from the fields of car industry, naval design, aircraft and movie industries. [281] Alicia Imperiale in her book of “New Flatness: Surface Tension in Digital Architecture” emphasizes the importance of this interchange between different fields. She states that; “this kind of cross-fertilizing and borrowing from other media and other disciplines (philosophy, chaos theory, mass media theory, etc.) has enriched the practice of architecture.”[282]

[281] Imperiale, Alicia. 2000.
[282] Ibid. p. 82.

CHAPTER 4

CASE STUDIES: UNDERSTANDING DIGITALLY STRUCTURAL SYSTEM DESIGN

In this chapter, three different form-structure relationships within digital design and construction processes are examined through three cases. Every case is investigated over its general view, design phase, structural system and manufacturing; considering the models and the tools that were used. For composite design process; “Kunsthaus Graz,” for structure based design process; “Channel Tunnel Railway Terminal,” and for linear design process; “BMW Exhibition Pavilion Dynaform” are explained in detail.

All the three cases are digitally designed and constructed buildings. Different types of design models, tools, structural systems, and manufacturing and construction methods are examined over these three cases.

4.1. Composite Design Process: Kunsthaus Graz

The Kunsthaus Graz (1999-2003) of Peter Cook and Colin Fournier is located in Graz, Austria. As Peter Cook was a member of the Archigram group, Kunsthaus was interpreted as an Archigram building which was constructed in real life. Kunsthaus Graz was first designed for a competition. As Graz was named as the European Culture Capital for the year of 2003, Kunsthaus was planned and designed as an art museum for representing the technological developments of the end of the 20st century.[283] In addition to representing technological developments; complex geometry of the site, architects’ desires to create the alien nature of the building and to make the building look cuddly and friendly were the other design criteria that shaped the building.[284]

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[283] Szalapaj, Peter. 2005.
[284] Cook, Peter, and Colin Fournier. A Friendly Alien: Ein Kunsthaus fur Graz. Ostfildern: Hatje Cantz Publishers, 2004.

Figure 4. 1. The Kunsthaus Graz, Austria, Peter Cook and Colin Fournier
(Source: Kolarevic, 2005)

Kunsthaus project has a composite design process where architectural design and structural design processes affected each other. Form and structure were evolved in an interactive process. Structural optimizations were allowed to make changes on the shape of the form during design process. Therefore, final shape emerged based on the integration of structural analyses and optimizations into the architectural design process.

Whether there was a composite process of form and structure, the focus was form creation initially. After form was created, structural system design studies were started and optimized the form in terms of structural analysis results. Architects Cook and Fournier emphasize their focus on form creation using complexity and irregularity. For example, Fournier refers to complexity to define the curvilinear form of the building as he states;

> Although 'biomorphic' architecture, characterized by geometries (often double-curved surfaces) more complex than those manifest in the usual orthogonal typologies of modernism, are currently becoming more common, the Graz Kunsthaus, in its conception and construction, is one of the few built examples within this new kind of design research.[285]

Fournier also refers to irregularity to define the form of the building and indicate his focus on form generation as he states; "because of the complexity and irregularity of

[285] Fournier, Colin, and Peter Cook. "Research Outputs 1 and 2: Kunsthaus Graz." UCL Discovery (2003): 1-59. 30 Apr. 2013 <http://discovery.ucl.ac.uk/13132/1/13132.pdf>.

the overall form of the building, every panel is double curved and has a different geometry."[286]

The structural system of the Kunsthaus was abstracted from the main geometry formally and therefore, what defines form also defines the structural system. The structural system also has a complex character like the form of the building. Kloft defines both the curvilinear form and the structural system of the Kunsthaus geometrically by referring to complexity in his article of "Non-Standard Structural Design for Non-Standard Architecture." He states that; "for the complex roof of the Kunsthaus Graz, the principle task was to design a system of tubular steel members that would support an outer layer of acrylic glass panels with complex shapes."[287]

Architect Jan Edler also refers to Cook and Fournier's focus on form generation in his article of "Communicative Display Skin for Buildings: BIX at the Kunsthaus Graz." He refers to irregularity and define the form of the Kunsthaus irregular as he states; "the irregularly shaped, biomorphic building structure floats as an independent body, balloon-like, above a glass foyer.[288]

4.1.1. Form Generation Process: NURBS within Performance Based Model

During preparation process of the irregular form of Kunsthaus to competition, architects did not utilized CAD-CAM technologies. Form was not designed in digital medium by using computational models based on scripting. Physical model of the project was also handmade. After winning the competition, Cook and Fournier took advantage of digital technologies for realization of the building. Rather than three-dimensional scan of the physical model for creating the digital version, they computationally created a 3D model from scratch relying on design decisions. They started designing from conceptual phase with collaboration of architects and engineers using Rhinoceros program.[289] Non-uniform rational B-splines (NURBS) were used for controlling the geometry of the form and modeling the surface during digital design process. [290] The reason of usage of NURBS was its ability to create various forms from

[286] Fournier, Colin, and Peter Cook. 2003. pp. 1-59.
[287] Kloft, Harald. 2005. p. 143.
[288] Edler, Jan. 2005. p. 153.
[289] Kloft, Harald. 2006. pp. 248-255.
[290] Szalapaj, Peter. 2005.

straight lines to curvilinear surfaces. Therefore by using NURBS, architects maintained the design intentions and created a form which was similar to the proposed form for the competition.

Initially, a sphere was defined by a mesh of gravitation points. By changing the location of these points; curves and thus, form was moulded.[291] Therefore, starting from the shape of a sphere, the irregular final shape of the building was generated by positioning the location of the control points and therefore, deforming the sphere.[292]

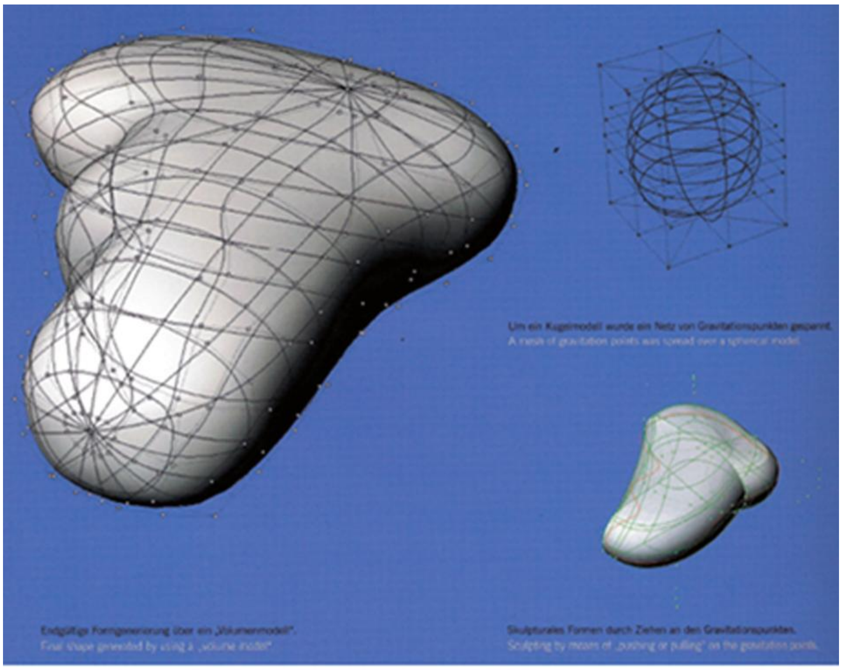

Figure 4. 2. Deformation process (right) and the final 3D digital design model (left) (Source: Fournier, 2013)

The 3D model was then analyzed and optimized within a performance based model based on performance analyses considering surface curvature, stability, internal organization, lighting and aesthetics.[293] Based on the results, structural performances were integrated into the form of the building by modifying the skin where needed. For example, roundness of the roof was increased for improving the structural performance

[291] Fournier, Colin, and Peter Cook. 2003. pp. 1-59.
[292] Szalapaj, Peter. 2005.
[293] Fournier, Colin, and Peter Cook. 2003. pp. 1-59.

of the building.[294] Civil engineer Harald Kloft as the project leader in the office of Bollinger+Grohman emphasizes this integration of form and structure in his article of "Structural Design of Form." He asserts that; "the digital design model of the Kunsthaus was shaped in an iterative process to capture the design intent of the original scheme, optimize the form with regard to structural behavior, such as its geometrical stiffness, and to address manufacturing issues."[295]

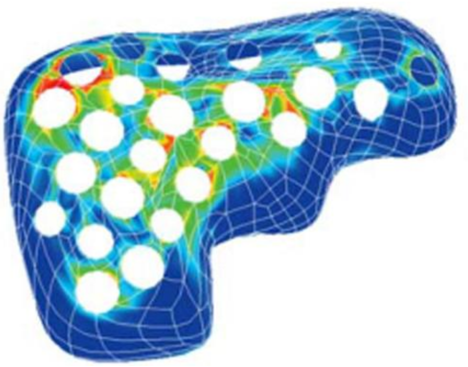

Figure 4. 3. Finite Element Analysis of the shell
(Source: Kolarevic, 2005)

Branko Kolarevic also emphasizes structural system optimization's role on the shaping of form in his book of "Architecture in the digital age – design and manufacturing." He asserts that;

> The original blobby shape of Peter Cook's and Colin Fournier's competition winning entry for the Kunsthaus in Graz, Austria was altered somewhat after the digital structural analysis, by consulting engineers Bollinger + Grohmann from Frankfurt, revealed that its structural performance could be improved with minor adjustments in the overall form.[296]

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[294] Chaszar, André. "Cooperation of Bernhard Franken with Klaus Bollinger and Manfred Grohmann." B+G Ingenieure Bollinger und Grohmann GmbH.
[295] Kloft, Harald. 2006. p. 252.
[296] Kolarevic, Branko. 2009. p. 25.

4.1.2. Complex Behavior of the Surface Structure: Framed and Grid System

Having the width of 60 meters, structural system of the Kunsthaus building was generated in close collaboration with structural engineers. The structural system consists of main load bearing structure and surface structure. As the main load bearing structure, there is post and beam system with two exhibition levels. Lower exhibition level is made of solid steel framework. In addition, there are concrete cores in the building for reinforcement which at the same time serve for access and infrastructure.[297]

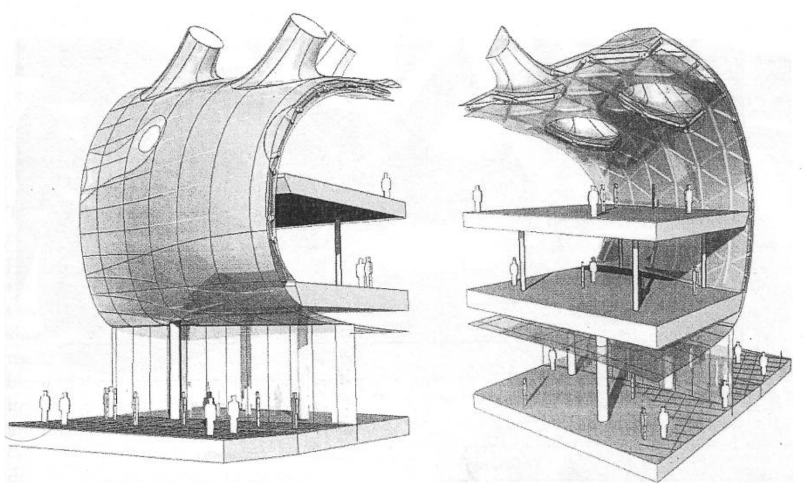

Figure 4. 4. Load bearing structure
(Source: Szalapaj, 2005)

The surface of the building works as a shell which took the shape of the complex irregular form of the building. Form was modeled using subdivision technique, and regular longitudinal and transversal divisions were located over the surface. These longitudinal and transversal grids intersected each other, and this triangular grid that was generated by the intersection became the grid system of the shell structure.[298] The reason of the usage of the triangulated grid structure was the stiffness of a triangulated arrangement structurally.[299]

[297] Szalapaj, Peter. 2005.
[298] Fournier, Colin, and Peter Cook. 2003. pp. 1-59.
[299] Kloft, Harald. 2005. p. 143.

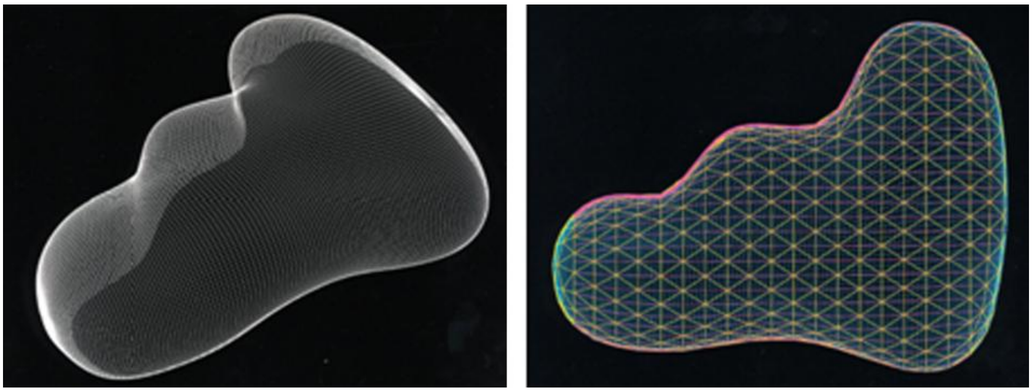

Figure 4. 5. Generation of the structural design by surface divisions
(Source: Fournier, 2013)

The shell structure consists of rectangular steel box girders as primary structural frames and square tubes that cover the spaces between them. Rectangular frames are located parallel to each other at regular intervals and square tubes between them constitute a triangulated pattern.[300] In addition to working as a frame system, the hybrid structural system of the Kunsthaus also works as a shell structure made of triangles.[301]

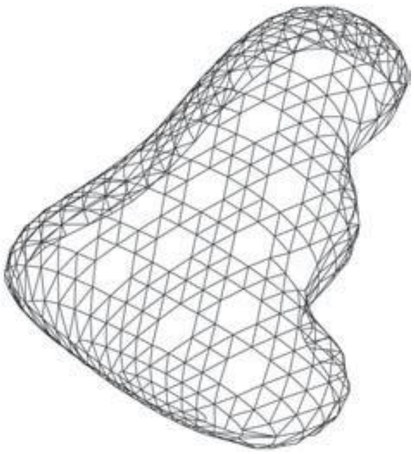

Figure 4. 6. Triangulated shell structure
(Source: Kolarevic, 2005)

The shell structure supports the skin where there are acrylic panels as covering materials. Over the glass skin, there are nozzles which work as skylights. They project

[300] Szalapaj, Peter. 2005.
[301] Kloft, Harald. 2006. pp. 248-255.

outwards from the skin to north to get most efficient daylight. There is also an additional cantilevered glass structure above the building connected to the top level that functions as an exhibition space.[302]

Figure 4. 7. The cantilevered structure and the nozzles
(Source: Kolarevic, 2005)

4.1.3. Manufacturing and Construction Process of the Surface Structure

Manufacturing process for Kunsthaus was an automated and digitally controlled process. Computer aided design environment was linked to computer aided manufacturing. Therefore, all the design and construction information in the 3D model was directly transferred to manufacturing robots.[303] During construction, concrete columns were constructed with in-situ method. Then, the surface structure was constructed from steel bars and perched on the concrete columns.[304]

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[302] Szalapaj, Peter. 2005.
[303] Ibid.
[304] "Kunsthaus Graz." Detail 11 2003. 3 June 2013 <http://detail-online.com/inspiration/kunsthaus-graz-103751.html>.

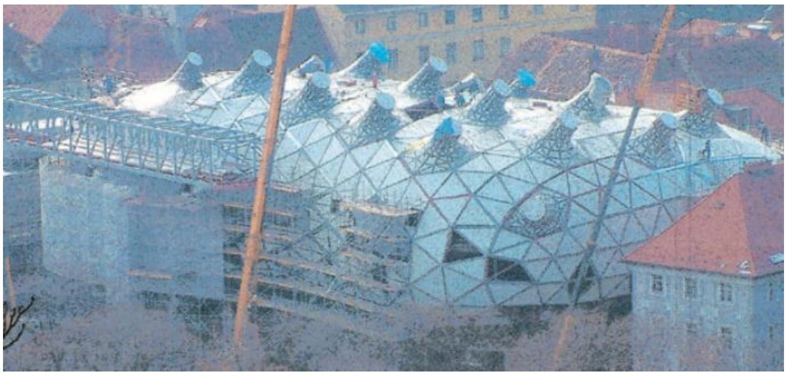

Figure 4. 8. Various sized triangles over the surface during construction
(Source: Project Building Info, 2013)

4.2. Structure Based Design Process: Channel Tunnel Railway Terminal

The Channel Tunnel Railway Terminal of Nicholas Grimshaw and Partners in collaboration with Anthony Hunt Associates is a railway station in Waterloo, London. Nicholas Grimshaw sees the terminal as a 21st century airport because of its full accoutrement.[305] The terminal consists of two parts. First part is below the platform, which includes spaces for arrivals and departures, ticketing and car parking, and has a reinforced-concrete skeletal structure. The second part is above the platform where there is a roof structure that covers the platform and tracks.[306] Site constraints such as changing width of 35m to 48m, narrowness, irregularity, location of tracks and Grimshaw's desire "to create a sense of wonderment" were taken as design criteria that shaped the building.[307]

[305] Moore, Rowan, and Kenneth Powell, eds. 1993.
[306] Macdonald, Angus. 2000.
[307] Moore, Rowan, and Kenneth Powell, eds. 1993.

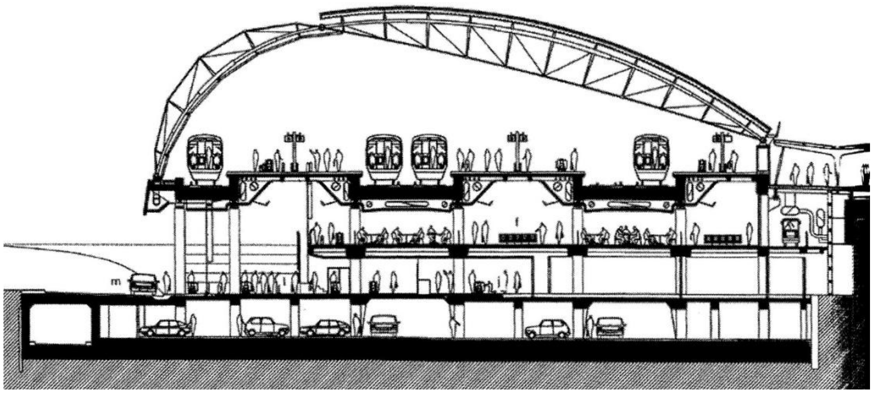

Figure 4. 9. Section view showing underground and above ground levels, Channel Tunnel Railway Terminal, London, Nicholas Grimshaw and Partners (Source: Sandaker, Eggen, Cruvellier, 2011)

The Channel Tunnel Railway Terminal has a structure based design process where main concern is structural design rather than form generation. Structural design controls the whole design process and defines the form of the building. Different from composite design process, initial design idea is to create a structural system. The generated structural system defines the interior and exterior spaces, and covers the building like a shell form.

The structural design process becomes the architectural design process in terminal building. Architects define the form of the structural system and indicate their focus on structural design using complexity and variability. For example, Angus Macdonald defines the structural system geometrically complex and expresses the complexity as; "complex surface,"[308] and "highly complex geometry of the train shed."[309]

Rowan Moore also defines the structural system complex as he states; "the complex geometry of the roof structure was mastered using computer-assisted design"[310] in the book of "Structure, Space and Skin: The Work of Nicholas Grimshaw and Partners."

Michael Phiri is another architect who defines the structural system of the terminal by referring to complexity in his book of "Information Technology in Construction Design." He asserts that; "IT was immensely useful in the roof design, a

[308] Macdonald, Angus. 2000. p.132.
[309] Ibid. p. 134.
[310] Moore, Rowan, and Kenneth Powell, eds. 1993. p. 35.

process driven (both in terms of CAD and structural analysis) by dealing with the complex geometry. The roof of the new train shed involved complex geometry which also altered along its length."[311]

The site constraints had a role in the constitution of the main shape. As the site is curvilinear and has a differentiating span, the structural system also had a differentiating shape. Therefore, architects define the form of the structure and its constituent members also using variability in addition to complexity. For example Angus Macdonald uses variability to indicate the uniqueness of structural members as he states; "variations in the diameters of the sub-elements were limited to two and this meant that only two different patterns were required for each nodal connection." [312] Macdonald uses variability also to define the whole structural system which is the result of the organization of the inner logic and site constraints. He states that; "a significant problem arose in connection with the fabrication of the trusses: that of devising an economical way of coping with the variations in span and height that occurred due to the tapering, curvilinear form of the plan. [313]

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311 Phiri, Michael. Information Technology in Construction Design. London: Thomas Telford Publising, 1999. 91.

312 Macdonald, Angus. "The Aestheticisation of the Steel Framework: The Contribution of Engineering to a Strand of Modern Architecture That Became Known as High Tech." Proceedings of the Second International Congress on Construction History. The Construction History Society. Cambridge, 2006. 2050.

313 Ibid.

Figure 4. 10. Arial view of the terminal building showing the irregular site
(Source: Riley, 1995)

4.2.1. Structure Generation Process: Parameters within Parametric Model

Working as a canopy, design of the irregular roof structure of the Waterloo Railway Terminal was the focal point during design process. In the roof structure, there are 36 different arches with different widths and curvature. Rather than designing every arch separately, a parametric model was created. By changing input parameters such as location, dimension or width, all the other related parameters were resized. Therefore, all the other varieties of arches different in span, position and curvature yet identical in topology were generated automatically based on the equations of the parametric model in a short time. Parametrically designed arches were expanded through the 400m long curvilinear site and constituted the main building. In addition to configuration of the arches, joint details were also designed with parametric model.[314]

[314] Kolarevic, Branko. 2009. pp. 11-28.

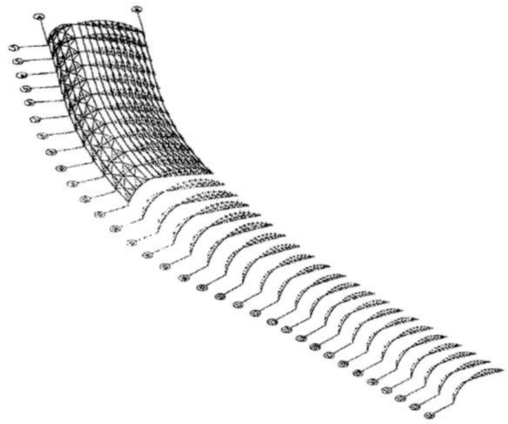

Figure 4. 11. Expanded arches throughout the site
(Source: Kolarevic, 2009)

"hx = ((29152 + (B + C)2)½" is a parametric definition example for the scaling factor of truss geometry where B is the minor truss span and C is the major truss span.[315] Based on this parametric equation, where the spans of the trusses increased, the arches in the structural system became wider. For an arch to be wider, structural elements that constituted that arch also became longer.

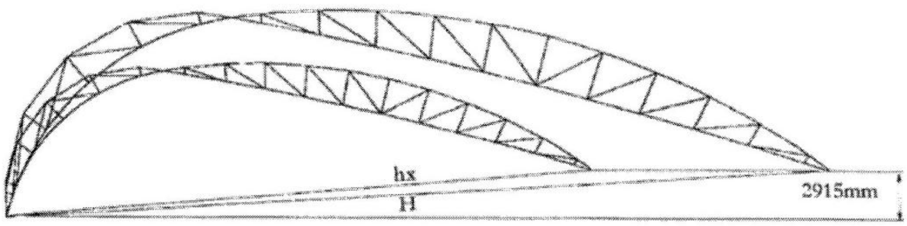

Figure 4. 12. Parametric relations of arches
(Source: Kolarevic, 2009)

The reason of the usage of parametric model in the railway terminal was the need to adjust the building to the variations in span, height etc. Therefore, rather than assigning rigid values to components, parameters were assigned. Parameters enabled architects and engineers to input various dimensions for the creation of the irregular

[315] Ibid.

structure.[316] Kolarevic also defines the logic of parametric model and indicates its importance by stating that; "for the first time in history, architects are designing not the specific shape of the building, but a set of principles encoded as a sequence of parametric equations by which specific instances of the design can be generated and varied in time as needed."[317]

4.2.2. 3D Truss System

Arches in the structural system consist of two bowstring trusses.[318] These trusses are three-dimensional space trusses that have triangular cross-sections. Thus, arches look like lozenges from top view.[319] The reason of the usage of aches is that arches are light and do not require any interior supports for crossing the span.[320]

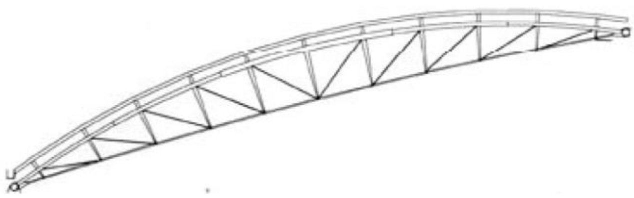

Figure 4. 13. Bow-string arch
(Source: Çıngı, 2007)

Trusses that constitute the arches work for overcoming bending moments and compression forces which are the cause of the asymmetric structure of the arch. Asymmetry of the structure is based on the location of one track. One of the tracks is very close to the western edge of the site. Therefore, roof height became higher at this point for the trains to pass.[321] As the arches are asymmetrical, longer and shorter sides of these arches work differently from each other. Tension and compression functions are reversed in east and west facades. Inside of the longer truss work for tension while

[316] Burrows, Stephen, and Martin Simpson. 2009. p. 19.
[317] Kolarevic, Branko. 2009. p. 18.
[318] Moore, Rowan, and Kenneth Powell, eds. 1993.
[319] Macdonald, Angus. 2000.
[320] Larsen, Olga Popovič, and Andy Tyas. Conceptual Structural Design: Bridging the Gap Between Architects and Engineers. London: Thomas Telford, 2003.
[321] Moore, Rowan, and Kenneth Powell, eds. 1993.

inside of the shorter side work for compression.[322] The circular-hollow sectioned structural elements that constitute the compression booms have a changing diameter from 219 mm to 355mm. The solid rods that constitute the tension booms have a diameter of 75 mm.[323]

Figure 4. 14. Three dimensional space trusses that constitute the arches
(Source: Kolarevic, 2005)

Primary arch elements are connected to each other with secondary structural elements which provide lateral restraint to prevent buckling. The circular-hollow sectioned tubes as secondary structural elements space the distance between the primary arches. They are mounted to the arches with welding from their compression booms which have also circular-hollow sections. Thus, covering material is located on the outside of the longer truss and inside of the shorter truss. The secondary structure is also supported by tie-rods which worked for the resistance against upward and downward acting loads.[324]

Steel trusses that generate the arches have three pin connections on it. Two of them are for the ground connections of the structure and one of them is for the connection of major and minor trusses.[325]

Trains approach to the terminal from the western side of the building and for providing passengers “a public showcase” of Westminister and the River Thames;

[322] Larsen, Olga Popovič, and Andy Tyas. 2003.
[323] Macdonald, Angus. 2006. pp. 2037-2054.
[324] Macdonald, Angus. 2000.
[325] Moore, Rowan, and Kenneth Powell, eds. 1993.

Grimshaw's team decided to make this façade entirely glass. East façade is the inverse of the west façade where structure is covered by solid steel panels.[326]

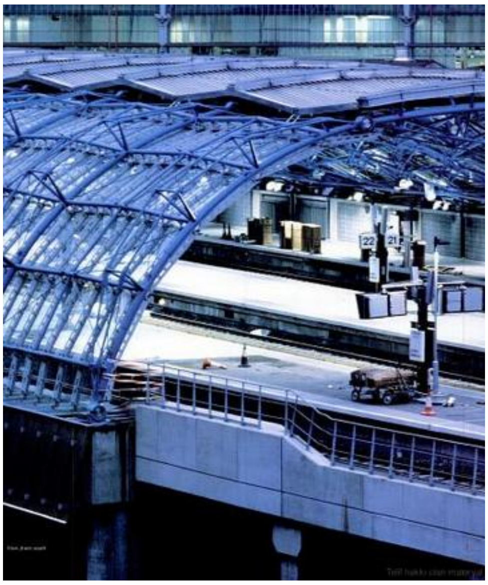

Figure 4. 15. Primary and secondary structural elements
(Source: Riley, 1995)

4.2.3. Manufacturing and Construction Process of the Structural System

Weldable cast steel was used for production of the structural system components where steel could be casted during fabrication and then bended and welded to take its final form. Structural members' sizes through the structure were different in terms of length and diameter; therefore, mass customization became the fabrication approach for the terminal. The different sizes of the tension booms and compression booms caused the connection members between tension and compression booms to become tapered. Therefore, tapered members connected large diameter tubes of the compression side with small diameter tubes of the tension sides. For fabrication of these tapered members, hot-rolled steel was used. Trapezoidal plates were bent in a large brake press and formed into half cone shapes. Then, these half cones were welded together to form

[326] Ibid.

the conically-shaped tapered members. Weldable cast steel was also used for the joint details of two ground connections and one apex connection.[327]

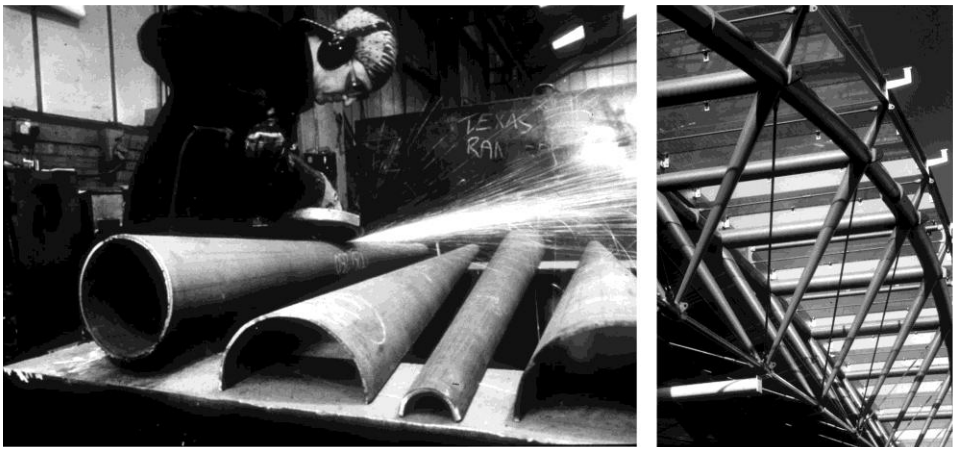

Figure 4. 16. Steel half cones constituting the tapered members with welding (Source: Macdonald, 2006)

Construction process of the roof structure of Waterloo started on concrete decks. After the arch structures were constructed, they were carried to their places one by one by mobile cranes.[328] All the 36 arches that have changing widths of 35 to 50m were located at regular intervals through the site and assembled.[329]

4.3. Linear Design Process: BMW Exhibition Pavilion Dynaform

The BMW exhibition pavilion Dynaform for the IAA 2001 by Bernhard Franken in association with ABB Architekten in Frankfurt, Germany was designed to host a car exhibition. Communication was an important criterion for design of the building. Main concern was to create a new spatial experience. Therefore, Franken and his team embraced an approach where "form follows force." Effects of the forces in the design medium reflected to design. As Franken asserted that; "admittedly we can not grasp

[327] Macdonald, Angus. 2006. pp. 2037-2054.
[328] Çıngı, Tuba. "An Appraisal of Curvilinear Forms in Architecture With an Emphasis on Structural Behaviour: A Case Study on Channel Tunnel Railway Terminal at Waterloo." MS Thesis. The Middle East Technical University, 2007.
[329] Kolarevic, Branko. 2009. pp. 11-28.

forces directly with our senses, but can only infer them through their effects,"[330] visitors could comprehend the forces that affected design process by experiencing the space.[331]

Figure 4. 17. BMW exhibition pavilion Dynaform, Germany, Bernhard Franken with ABB Architekten (Source: Kolarevic, 2005)

The BMW exhibition pavilion Dynaform has a linear design process where form was created firstly, and then structural system was developed. In this project, main concern is the "digitally generated form." Structural design is not allowed to make changes on the shape of the form. Generated form is the master geometry that should be maintained until realization of the building. Therefore, the form was taken as dimensional reference and structural system took the shape of the form as a surface structure.

The form based concern and the focus on architectural design process are expressed in project descriptions of architects. For example, Franken refers to complexity to characterize the building form. [332] Franken and his team also refers to dynamism to characterize the form of the building which was generated in interaction with the dynamic forces in the context. They state that; "The BMW exhibition pavilion

[330] Franken, Bernhard. 2009. p. 125.
[331] Ibid. pp. 121-138.
[332] Ibid. p. 127.

for the IAA 2001 focused attention on the world premiere of the new 7 Series and expressed with its dynamic shape the BMW brand essence: the joy of driving."[333]

The generation process of form was another focal point that Franken worked on. For example, he defines the form creation process and the changes that the form undergoes during design process using deformability. He states that;

> Our experience, however, made us highly sensitive to deformations that correspond to a natural play of forces. This faculty was an evolutionary advantage, when, for example, a tree bent by the wind could be perceived as indicating a potential danger. Our perception is thus conditioned towards forces, and uses them to interpret shapes. Deformed forms carry the information about the forces of their origin. [334]

Kloft also uses deformability to define the formation process of the form as he asserts that; "through a time-based (4D) modeling process, the initial shape was deformed and altered by the software, until an architectural form was found by sampling the generative process.[335]

Kolarevic expresses the form based design process of the Dynaform by using dynamism, in his article of "Digital Morphogenesis." He defines the generation process dynamic by stating that; "It is the dynamics of forces, or, more precisely, force fields, as an initial condition that produces the motion and the particular transformations of form, i.e., the digital morphogenesis. The form and its changes become products of the dynamic action of forces."[336]

4.3.1. Form Generation Process: Force Fields within Motion and Force Based Model

At the beginning of design process, some basic rectangular structures were defined in digital medium. Then, force field simulations were applied on these structures. The field forces caused deformations on form and the changes were realized by a motion and force based model. Computational design process evolved within the software program Maya where forces and information in the design medium were

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[333] Franken\Architekten. "Dynaform." Overview Projects. 26 Apr. 2013 <http://www.franken-architekten.de/index.php?pagetype=projectdetail&lang=en&cat=-1&param=overview&param2=38&param3=0&>.
[334] Franken, Bernhard. 2009. p. 125.
[335] Kloft, Harald. 2005. p. 139.
[336] Kolarevic, Branko. 2009. p. 21.

recorded into the surface of the building computationally. Based on input parameters, the final form emerged. Therefore, every curve and contour on the surface had a meaning and reason, and was not arbitrary.[337]

The forces that were used for shaping the form were not only environmental forces such as wind, sun, gravity, pedestrian movement and car traffic. There were also conceptual forces which did not originate within the context itself.[338] Some of the field forces were created as a result of acceleration of space around vehicles for creating sensation of driving.[339]

Figure 4. 18. Application of force fields during form generation process
(Source: Kolarevic, 2005)

The generated form in Maya, which was a single layer surface without any details such as thickness, was called the master geometry. Master geometry remained its geometry during structural design and optimization processes, because if there was a change; the forces that generated the form would no longer be comprehendible.[340] Master geometry became the "dimensional reference" for the project collaborators such as structural engineers during design and construction.[341]

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[337] Kloft, Harald. 2005. pp. 121-138.
[338] Ibid.
[339] Franken\Architekten. "Dynaform." Overview Projects. 26 Apr. 2013 <http://www.franken-architekten.de/index.php?pagetype=projectdetail&lang=en&cat=-1&param=overview&param2=38&param3=0&>.
[340] Franken, Bernhard. 2009. pp. 121-138.
[341] Kloft, Harald. 2005. pp. 135-148.

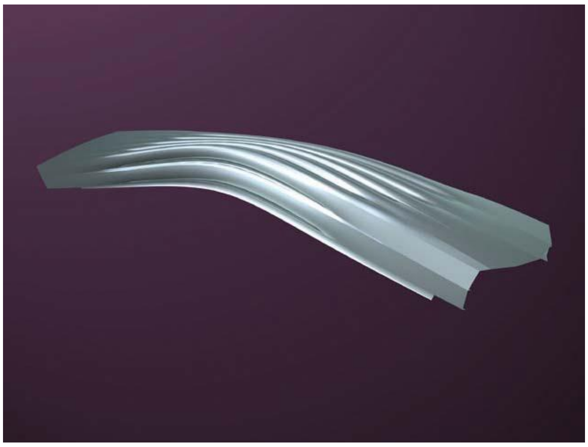

Figure 4. 19. The "master geometry"
(Source: Kolarevic, 2005)

4.3.2. Surface Structure: Framed System

After form design and definition of the master geometry, Franken and his office collaborated with Bollinger + Grohmann Ingenieure for structural system solutions. They used finite element analyses program for analyzing the behavior of the form as a shell structure. Structural design was not allowed to make changes on the geometry of the form, therefore; structural studies and optimizations were continued until an efficient system was found that was compatible with the irregular form of the building.[342] At the beginning of the structural design process, there were two options for the structural system. First one was separation of structure from skin. Second one was integration of structure with skin where skin would be main bearer and there would be no need for an additional skeletal system. These two options were analyzed and because of the extremely short construction period, first option was selected where there is a primary frame system and a secondary skin that is carried by the frame system.[343]

Considering the structural system decision, fifteen cross sections were generated from the main form based on the collaboration of architects and engineers. Structural frames were then inscribed into these sections. Outer layer of the structural frame was the abstraction of the master geometry that tracked the lines of the skin. Inner layer was

[342] Ibid.
[343] Kloft, Harald. 2005. p. 142.

the reverse of the same master geometry.[344] Structural frames, which have hollow box sections, are located at intervals of 8m through the 135m long building. All the planar frames are connected with horizontal beams for lateral stability throughout the building.[345]

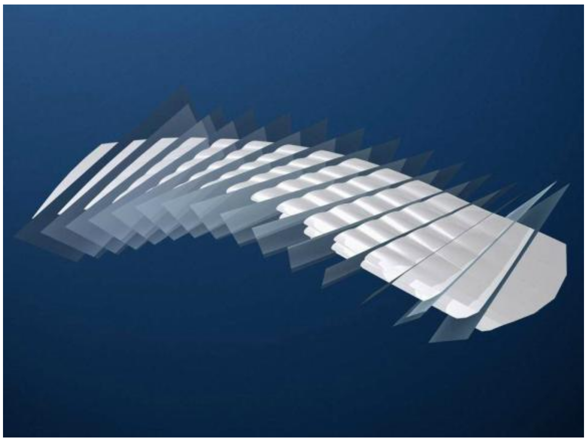

Figure 4. 20. Fifteen cross sections
(Source: http://www.franken-architekten.de/)

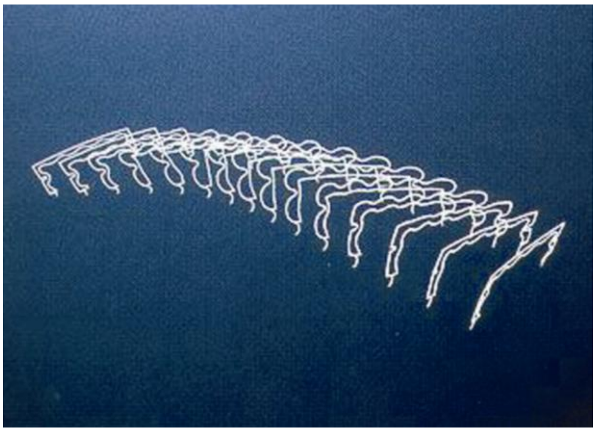

Figure 4. 21. Fifteen structural frames
(Source: © B+G Ingenieure Bollinger und Grohmann GmbH)

[344] Kloft, Harald. 2005. pp. 135-148.
[345] Bollinger und Grohmann Ingenieure. "BMW Dynaform." Projects. 29 Apr. 2013 <http://www.bollinger-grohmann.de/homepage/index.php?page=374&language=EN&bg_project=4CB87842-6B7E-1A06-A47F-417E27B80417>.

Franken and his team's aim in this project was to break down the boundaries between design and production. Therefore, all project participants collaborated from design ideation to construction. They used an interface for exchanging data; "a protocol, with which the special programs can communicate, and a browser, with which everyone can view the data."[346] During design and production processes, all modifications were updated in the browser and all the participants were informed by fax or email about latest updates.[347]

4.3.3. Manufacturing and Construction Process of the Surface Structure

During manufacturing and construction phase, structural members were fabricated by CNC cutters and then assembled to create the curvilinear frames. Initially, fabrication data of hollow box steel members was transferred to construction site from digital model with the help of CAD/CAM. More than 30,000 unique pieces were cut from flat steel plates using two-dimensional CNC plasma cutting.[348] Pieces were then bent to become curvilinear and assembled to each other with welding to constitute the hollow box curvilinear frames.[349] The pieces were so big and a welding machine that would work for such large pieces was not available. Therefore, welding of the structural pieces was done by hand.[350] After the frames having width of 25m and height of 18m[351] were produced in factories, they were carried to construction site. They were located to their locations based on the information that comes from laser surveying device, and then assembled.[352]

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[346] Franken, Bernhard. 2009. p. 132.
[347] Ibid. pp. 121-138.
[348] Ibid.
[349] Kloft, Harald. 2005. pp. 135-148.
[350] Franken, Bernhard. 2009. pp. 121-138.
[351] Bollinger und Grohmann Ingenieure. "BMW Dynaform." Projects. 29 Apr. 2013 <http://www.bollinger-grohmann.de/homepage/index.php?page=374&language=EN&bg_project=4CB87842-6B7E-1A06-A47F-417E27B80417>.
[352] Franken, Bernhard. 2009. pp. 121-138.

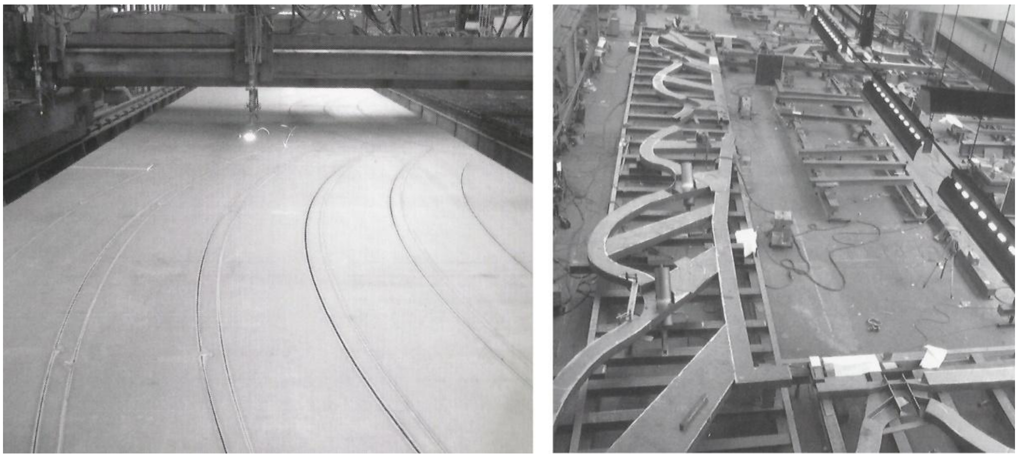

Figure 4. 22. CNC plasma cutting of structural pieces and manual welding operation
(Source: Franken, 2009)

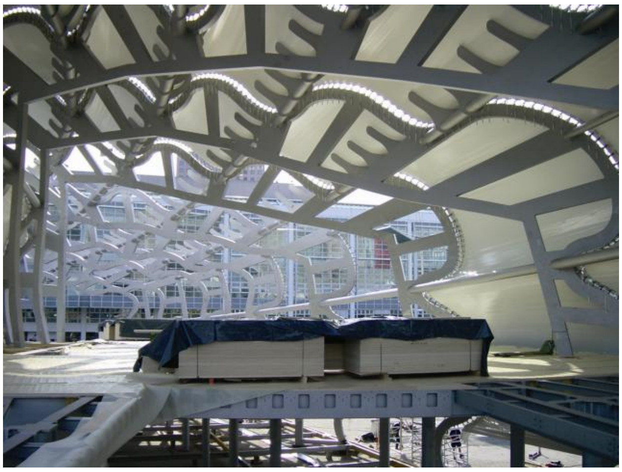

Figure 4. 23. Construction phase
(Source: © B+G Ingenieure Bollinger und Grohmann GmbH)

CHAPTER 5

CONCLUSION

Digital architectural design process initially existed as form creation process in digital medium. From the end of 1990's, it evolved to a process which included evolution from design ideation to construction. Now, complex forms that are produced by digital models and tools are able to be constructed. Structural design that enables the construction of complex forms becomes a part of this production process. Therefore, digital design process should not be viewed as a form generation process. Assessing the architectural design process in this context requires understanding of the realization of unified form-structure production process and also form-structure relationship.

In the context of this thesis, different form-structure relationships during digital design and construction processes are put forward. While the form-structure relationship is being analyzed, models and tools are examined which control and direct the generation processes of form and structure. As a result of the examination, five main design models are put forward which are; biological models, parametric models, motion and force based models, performance based models and evolution based models. These design models evolve in design tools. Architects and engineers use tools in every phase of design, starting from design ideation to manufacturing and construction. The different tools are categorized in the thesis to understand in where and how digital architectural and structural design processes evolve. It is found out that there are three main design tools that are used for the construction of forms and structures. They are; computational geometrical studies, computer programs, physical drawing and model making.

The form-structure relationship during digital design and construction processes are also examined over the existence of structural design within a digital architectural design process. It is found out that there are three different types of existences which are; composite design processes, structure based design processes and linear design processes. In composite design process, there is integrated development of form and structure. In structure based design process, architectural design process is the structural design process where final output is a structural system. In linear design process, structure is designed after form design based on geometry of the form. The second and the third processes which are structure based design processes and linear design processes do not define totally new relationships to form-structure besides being designed in digital medium. The first relationship, which is the composite design process, defines a new type of relationship considering contemporary linear design processes. Hierarchical nature of design where disciplines work separately from each other is demolished. Models and tools that are used for form generation are also used for structural design. All disciplines work in a common design medium in relation with each other.[353]

Structural systems are also examined in the thesis in order to understand the different systems that support the complex forms and their reasons of usage. It is also tried to be found out that if there are any new structural system types different from conventional orthogonal systems. Based on the examination that was made over built examples, different types of systems are found out and collected under four main categories based on the structural systems' working principles. Categorization was made for understanding the systems better with their differentiations. The categories are two-dimensional frame structures, space frames and trusses, grid systems and solid systems. Digitally designed frame structures differ from conventional frame structures in terms of their irregularity. They take the shape of the complex forms by being curvilinear. Space frame and space trusses differ from conventional three dimensional systems in terms of their constituent members' shapes. Members become curvilinear and unique. When they are all connected to each other with also unique joints, they constitute the desired shape. Grid systems are also curvilinear formed systems in digital structural design. They either constitute from curvilinear members or straight members with various joints to create the complexity of the form. Solid systems also differ from conventional concrete shells. The difference is their double curvature and ability to have both concave and convex curves within its structure at the same time.

In case of looking all the digitally designed structural systems that carry complex forms, it is seen that there is a common point in all of them which is curvilinearity. The digital structural systems are not totally different from the conventional systems; however, the difference is their complex curvilinearity or their constituent members' curvilinearity. They take the shape of the complex forms by

[353] Tanyeli, Uğur. 2012. pp. 76-83.

following the outer contours. Therefore, they get additional support from the folds of the form.

As the digital architectural design process becomes a unified process, examining only the design process is not sufficient for understanding form-structure relationships. Therefore, manufacturing and construction processes are examined which are also digitally controlled processes. It is found out that, design information in digital medium generally includes all the detailed information related to construction. The digital data controls manufacturing robots and therefore, by translating the digital data into construction site by the direct link of design to production, all the structural members are manufactured digitally. For understanding the production processes of different structural systems, production strategies are revealed and collected under three categories. These categories are; two-dimensional cutting approach, subtractive approach and additive approach. Digital fabrication and construction machines are advantageous that they enable production of a wide range of complex forms.

Structural design becomes an integral part of the architectural design process with digital technologies. The relationship of structural design and form design processes changes. Form-structure relationship becomes complex, and form and structure evolve in interaction with each other. More unified processes of form and structure are defined. When considered that this unified process will continue to be embraced; this thesis contributes to the understanding of this new process and digitalization of structural design.

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