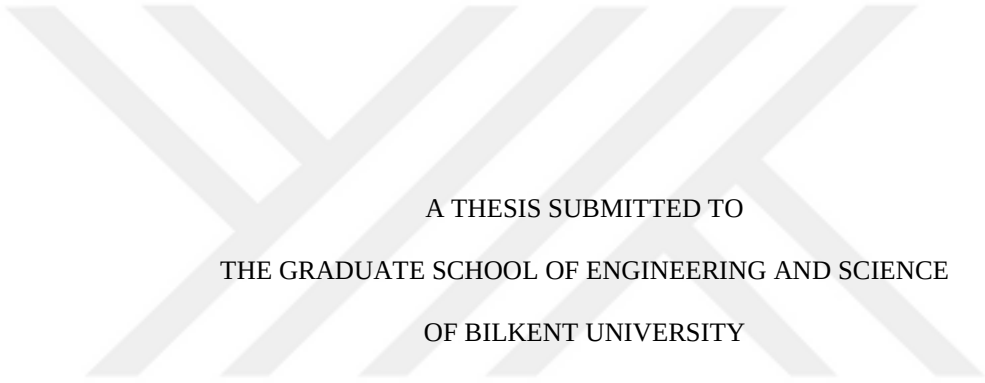


INFLUENCES OF STRUCTURAL SYSTEMS ON FORM AND SPACE INTEGRITY OF FREE-FORM BUILDINGS: AN INVESTIGATION THROUGH CASE STUDIES



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THE GRADUATE SCHOOL OF ENGINEERING AND SCIENCE
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By

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We certify that we have read this thesis and that, in our opinion it is fully adequate, in scope and in quality, as a thesis for the degree of Master of Science.

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ABSTRACT

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Free-form architecture is a contemporary design language that challenges traditional geometric forms in architectural design. It is characterized by its complex and irregular shapes, which are mainly achieved through advanced digital design and fabrication technologies. However, free-form buildings may overly prioritize form over structural rationality and spatial quality because of their irregular nature. Therefore, the potentials and limitations of their flexibility need to be investigated through the architectural components, structure, form, and space.

This thesis investigates the potential of structural systems which are an aesthetic and inventive medium for shaping and experiencing free-form buildings. It is intended to determine and evaluate structural systems' influences on form and space integrity of free-form buildings. With this framework, seventeen selected pioneering free-form buildings are investigated through an in-depth analysis that is resulted in a tabular report which involves specific structural, formal, and spatial analysis with a general assessment part. As a result, it has been determined that the design process for a free-form building needs to be more integrated to ensure the integrity of form and space. Moreover, the findings indicate that contemporary free-form buildings contain overly complex hierarchical structural organization, such as primary and secondary systems. Consequently, designing structural systems that seamlessly integrate with such buildings' form and spatial configurations necessitates a distinct perspective and specialized design knowledge. In line with these findings, this thesis suggests that an integrated design process should be supported by a comprehensive knowledge and understanding of structural systems, their hierarchical organization and how they simultaneously effect formal and spatial configurations.

Keywords; Free-form buildings, Structural Systems, Form, Space, Integrated Design

ÖZET

SERBEST BİÇİMLİ BİNALARIN YAPISAL SİSTEMLERİN BİÇİM VE MEKAN BÜTÜNLÜĞÜ ÜZERİNE ETKİLERİ: VAKA ÇALIŞMALARI YOLUYLA BİR İNCELEME

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Serbest biçimli mimari, mimari tasarımda geleneksel geometrik biçimlere meydan okuyan çağdaş bir tasarım dilidir. Temel olarak gelişmiş dijital tasarım ve üretim teknolojileriyle elde edilen karmaşık ve düzensiz şekilleri ile karakterize edilirler. Bununla birlikte, serbest biçimli binalar, düzensiz doğaları nedeniyle biçime, yapısal rasyonaliteye ve mekânsal kaliteye kıyasla daha fazla öncelik verebilir. Bu nedenle, esnekliklerinin potansiyelleri ve sınırlamaları mimari bileşenler olan yapı, biçim ve alan üzerinden araştırılmalıdır.

Bu tez, serbest biçimli binaları şekillendirmek ve deneyimlemek için estetik ve yaratıcı bir araç olan yapısal sistemlerin potansiyelini araştırmaktadır. Yapısal sistemlerin, serbest biçimli binaların biçim ve mekân bütünlüğü üzerindeki etkilerinin belirlenmesi ve değerlendirilmesi amaçlanmaktadır. Bu çerçevede, seçilen on yedi öncü serbest biçimli bina, genel bir değerlendirme bölümü ile belirli yapısal, biçimsel ve mekânsal analiz içeren bir tablo raporuyla sonuçlanan derinlemesine bir analiz yoluyla araştırılır. Sonuç olarak, serbest biçimli bir yapı için tasarım sürecinin biçim ve mekân bütünlüğünün sağlanması için daha bütünleşik olması gerektiği belirlenmiştir. Dahası, bulgular, çağdaş serbest biçimli binaların, birincil ve ikincil sistemler gibi, aşırı derecede karmaşık hiyerarşik yapısal organizasyonlar içerdiğini göstermektedir. Dolayısıyla, bu tür binaların formu ve mekânsal konfigürasyonlarıyla sorunsuz bir şekilde bütünleşen yapısal sistemlerin tasarlanması, farklı bir bakış açısı ve özel tasarım bilgisi gerektirir. Bu bulgular doğrultusunda bu tez, bütünleşik bir tasarım sürecinin yapısal sistemler, bu sistemlerin hiyerarşik organizasyonları ve yanı sıra biçimsel ve mekânsal konfigürasyonları eş zamanlı olarak nasıl etkiledikleri hakkında kapsamlı bir bilgi ve anlayışla desteklenmesi gerektiğini önermektedir.

Anahtar sözcükler; Serbest biçimli binalar, Yapısal Sistemler, Form, Mekân, Bütünleşik Tasarım

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CHAPTER 1

INTRODUCTION

Throughout the history of architecture, an essential objective has been to create designs that strike a balance between structural efficiency and flexible form. Recent research has shown a growing interest in free-form architectural design, which has led to the exploration of new materials, concepts, surface manipulations, and articulations, all while emphasizing the interplay between mass and space. As a result of their capacity to provide designers with flexibility and versatility throughout the entire design process, from initial concept development to actual construction, free-form architectures have emerged as the prevailing design language of the contemporary era.

Free-form buildings represent a realm of architectural design that offers practitioners the opportunity to explore novel, organic forms unconstrained by conventional geometric shapes. According to Noever (1991), architects who practice free-form architecture held a crucial perspective regarding the modernist-built environment that conveyed an illusion of homogeneity in society through the use of pure forms. Müller (1991) and Liu & Lim (2006) stated that these designers distanced themselves collectively from the limited technological and scientific rationality of simple geometric spatial configuration.

The term "free-form" refers to a style or design that lacks a particular structure or follows an irregular and asymmetrical shape, as defined by the Cambridge and Merriam-Webster dictionaries. However, it is noteworthy that there is no consensus among designers regarding the definition of free-form architecture (Vermeij, P., 2006). In this study, free-form buildings are regarded as intricate surfaces and structures that have an innovative design process and unique construction methods. They have a cutting-edge and visionary approach that challenges conventions and explores novel materials, emphasizing surface manipulation and spatial articulation.

Thus, for the design of such buildings, the integration of form and structure is of utmost importance, requiring a profound understanding of the relationship between mass and space. And this study defends that an effective integration of structural systems is vital to achieve both structural efficiency and meet formal and spatial requirements.

Although free-form architecture has revolutionized the field of structural design, it also has a drawback. The striking appearance of free-form architecture can influence many people without a comprehensive understanding of the various factors involved in designing such buildings (Wong, 2010). This trend can result in neglecting other critical components of architectural design, such as structure and space, by focusing solely on formal expression as the primary objective of free-form design. To prevent the misconception that architectural design is only about creating visually appealing forms, it is essential to have a thorough grasp of structural design. This study aims to investigate free-form buildings and provide data on how to organize structural systems to integrate form and space.

1.1. Problem Statement

Research on free-form architecture often centers on digital design techniques, representation, rationalization, and performance-based design. However, through the literature review, it is observed that these topics primarily stem from mathematical or engineering perspectives which neglect the holistic character of architectural disciplines. Despite recent academic studies on free-form architecture and its practitioners, none of the existing articles seem to focus on the underlying design motives and tactics of this architectural style, as noted by Wong J. F. (2010). The most commonly explored theme adapts to the utilization of digital design and representation techniques, while some articles indirectly touch on topics like simulation and environmental design. This observation highlights the deficiency of research on the design process and assessments of architects who design free-form geometries.

On the other hand, advocates of free-form architecture often argue that free-forms allow greater creativity and expression than rectilinear architecture (Jacobs, 1961). However, some researchers, such as Bagneris (2008), have pointed out that designers

may become overly focused on the malleability of forms and overlook other important parameters. One notable example of this trend is the increasing popularity of free-form buildings after the "Bilbao Effect," which prioritize individualistic identity over functionality or practicality, resulting in visually stunning landmarks (Hertzberger, 2000). Nevertheless, architects and engineers have a task of integrating a wide range of scientific and technological advancements into their work. This challenge involves incorporating structural systems creatively and cost-effectively into the design which is vital to create successful free-form designs(Engel, H., 1967).

In order to explore the influences of structural systems on form and space integrity in free-form buildings, case studies have been investigated. The results are expected to point out how to incorporate structural systems in the conceptual design phase and achieve high form and space integrity.

1.2. Aim and Scope of the Thesis

With the increasing interest in free-form buildings, architects have been exploring new materials, concepts, surface manipulations, and interplays between mass and space. In contemporary era, interest has grown on free-forms because since they allow flexibility and variety throughout the entire design process, from initial concept development to actual construction. The aim is to investigate the influences of structural systems on form and space integrity of free-form buildings. Furthermore, it is intended to understand the role of structural systems while incorporating them in the design phase of a building. At the same time, structure, form, and space are simultaneously analyzed.

The hypothesis of this study can be stated as such: Having an integrated design process for a free-form building provides a stronger integrity of form and space. This study provides a perspective on structural systems and a research methodology to evaluate their influences on form and space in free-form buildings. In order to study this, a collection of selected pioneering free-form buildings has been analyzed. To conduct a thorough examination of these cases, specific parameters that influence the interplay between the structure, form, and space are considered. Consequently, a design and explanation guide through an analytical method is developed with five

parts: general information and graphics, form analysis, structural analysis, space analysis, and general assessment. Finally, the results and discussions provide data on how to achieve a free-form building that has high form and space integrity by incorporating structural systems decisions.

For this study, the research questions are:

1. What are the common structural systems for free-form buildings and what is their role on the formal and spatial configurations?
2. How does the inclusion of structural systems in the design process impact on form and space integrity in free-form buildings?
3. What are the key factors that influence the form reasoning process of a free-form building and how is the interplay between structure and form?
4. How is the spatial organization arranged in a free-form building and how is the interplay between structure and space?

1.3. Thesis Outline

This thesis comprises of seven chapters. The chapters are organized respectively as follows:

The first chapter introduces the problem, aim, scope and structure of the thesis.

The second chapter first, defines how the free-form term emerged and became a concept that is a significant language of the contemporary era by focusing on relevant movements, terminologies, and discussions then, provides a historical overview on free-form architectures by giving references to both theoretical and objective references.

The third chapter begins with a discussion of structural design in free-form architectures, followed by an overview of Engel's (1967) definitions and categorizations of structural systems, which directly relate the methodology of the thesis. The chapter then introduces the role of structure in the design process.

The fourth chapter presents the methodology of this study, including how the data is gathered and how the analysis is conducted. The steps of the methodology are explained through the analysis table which is the primary tool for this thesis. Lastly, the list of cases is presented.

The fifth chapter includes the analysis tables and brief explanations for each case study building. It focuses on the examination of seventeen pioneering free-form buildings, utilizing an analysis table. Each case study begins with an overview of general information, followed by an explanatory and descriptive paragraphs on their structure-form and structure-space relationships.

The sixth chapter focuses on the analysis results that are obtained from the case studies. It includes a comprehensive discussion on the findings which are compared and contrasted.

The seventh chapter is the final chapter which includes conclusions on the findings of the analysis and provides recommendations for future studies. The chapter is followed by a list of references and appendices.

CHAPTER 2

FREE FORM ARCHITECTURE

Throughout the history of architecture, one of the main priorities has been to create designs that have both structural efficiency and a flexible form. The growing research interest in free-form architectural design has prompted the exploration of novel materials, concepts, surface manipulations and articulations while emphasizing the interplay between mass and space. Free-form architecture, due to their ability to offer designers flexibility and variety throughout the design process from initial concept development to actual construction, became the prevalent design language of the contemporary era.

The term ‘‘form’’ is inclusive and contains various definitions. Form references both internal structure and external outline by giving a sense of three-dimensional volume or mass. (Ching, 2007). This study uses form for ‘‘The shape or appearance of something’’ (Cambridge Dictionary, n.d).

As for the term ‘‘free-form’’, relevant explanations are ‘‘Not having or following a particular style or structure’’ (Cambridge Dictionary, n.d) or ‘‘Having or being irregular or asymmetrical shape or design’’ (Merriam Webster Dictionary, n.d). Nevertheless, it is critical to point out that there is currently no strict definition of free-form architecture that designers agree upon (Vermeij, P. 2006).

Free-form architecture is multifaceted thus, it encompasses digital design, performance-based design, rationalization, and manufacturing, thereby allows designers the freedom to diversify and customize their design process, from conception to realization. These designs are characterized by their intricate surfaces and structures which showcase their innovative design process and construction methods. There is no doubt that they have made a change in the world of structural design, however, overemphasizing formal expression as the primary goal of free-

form design can result in bringing other vital elements of architectural design, namely structure and space, into the background. For these reasons, constructing a background on free-forms is a prerequisite to understand their architectural and structural relationships.

This chapter has two main parts: The first part defines how the free-form term emerged and became a concept that is a significant language of the contemporary era by focusing on relevant movements, terminologies, and discussions. Then, second part provides a historical overview on free-form architectures by giving references to both theoretical and objective references.

2.1 Defining Free-Form Architecture

The exhibition at the Museum of Modern Art (MOMA) in New York in 1998 titled 'Deconstructivist Architecture' is mentioned in the following section, indicating that in the past twenty years, a significant change in architecture had set strict rules for design and organization free while providing diversity in expression. This approach, known as "free-form architecture," embraced the varied cultural and societal influences on a project and sought to incorporate them into the design rather than adhering to modernist formalism (Wong, J. F., 2010). However, there is no clear-cut definition of free-form architecture throughout the literature.

In "The Text of Free-Form Architecture," Wong presented Free Form Architecture as a method of creating forms that utilize a combination of distinct shapes and a fluid design style. This approach aimed to express the effects of various influences on architectural design, such as separation, fragmentation, and distortion. Wong further adds that it pushes beyond traditional architectural conventions rather than being limited by conventional building techniques and materials (Wong, J. F., 2010). This explanation highlights the freedom in creating and reasoning forms, moving away from traditional orthogonal forms. However, other interpretations focus on the visual and aesthetical qualities of the designs. Vermeij, P. (2006) indicate that free-form geometries may feature "random curves and tilts" and give the impression of buildings in a state of explosion or collapse, in contrast to the typical vertical walls and right angles of conventional architecture.

Veltkamp, M.(2007) mentioned free-forms as load-bearing structures of double-curved and irregular building shapes stand out from others by their amorphous shapes, complex geometries, and smooth surfaces. Furthermore, it had been observed that architectural forms were often categorized into "regular" and "irregular" forms according to their geometric properties, and this method of classification was commonly used (Ching, 2007). As stated by Ching, regular forms are cohesive and related, frequently displaying symmetry along one or multiple axes. Examples of common forms include the sphere, cylinder, cone, cube, and pyramid. On the contrary, irregular forms are characterized by their lack of consistency among parts. They can be created by removing irregular elements from traditional forms or by irregularly combining traditional forms. (Ching, 2007)

Despite utilizing different approaches, architects who design free-forms held a significant viewpoint regarding the fallacy of a uniform society presented by the modernist architecture that relied solely on pure forms (Noever, 1991). Together, these designers aimed to distance themselves from the constrained technological and scientific rationality by purposefully avoiding common geometries and straying from classical construction techniques and the simplistic geometric language of modernist spatial arrangements (Müller, A. M., 1991, Liu & Lim, 2006).

Consequently, they employed clashing forms, distorted grids, and conflicting geometries as representations of the diversity found in the society and the opposing forces - including technical, political, cultural, social, economic, environmental aspects, among others - that contribute to its constant state of flux. Thus, free-form architecture served as a tangible manifestation of these architects' novel worldview (Wong, J. F., 2010). In Jodidio's explanation of Hadid's Vitra Fire Station in Weil am Rhein, Germany (Figure 1), it is described as an instance of "transforming her unconventional vision of a fragmented and unstable society into concrete, steel, and glass" (Jodidio, P., 2001: 10). Architects aimed to break free from conventional forms and meanings by embracing an approach that allowed forms to continuously shift and evolve through ever-changing affiliations and alliances (Kipnis, J., 1993: 44).



Figure 1. Vitra Fire Station by Zaha Hadid. (<https://www.archdaily.com/785760/ad-classics-vitra-fire-station-zaha-hadid-weil-am-rhein-germany>)

Even though free-forms existed pre-digital tools, a vast majority of studies mention them as emerging within the developments of digital technologies. Mosoarca, M., Anthimos A., and Kampouris A. (2014) mention that architects depended on simple geometries and rectilinear forms; however, this situation changed with the new advantages of form generation. Furthermore, Wong, J. F. (2010) stated that a new approach to form-making in architecture emerged within the liberation of formal expression and organization. Eekhout et al. (2015) argue in their book that the rise of Free Form Architecture can be attributed to the interplay between technological advancements in architectural tools and the creative drive of architects and engineers. They propose that the development of this architectural style is a direct consequence of the innovative opportunities afforded by cutting-edge 3D design computer programs. These evolving software platforms empower designers to conceive elaborate virtual structures with intricate geometries, marked by distinctive forms that typically incorporate unique components.

Additionally, a significant amount of study refers to free-form architecture as “curvilinear”. The curved form was a prevalent feature in nature and had been inspiring humans since the earliest times when they built structures for shelter. As civilizations evolved, curved forms continued to be developed in addition to linear forms. Over the centuries, the curved form has been used for structural enhancements, aesthetics, and as a symbol of religious or symbolic meanings. The need for more extensive, uninterrupted spaces in buildings such as churches, mosques, halls, and auditoriums has led designers to explore curvilinear forms to achieve longer spans. (Çiingi, 2007). Besides, the term ‘curvilinear’ does not directly

refer to the shape or form; thus, it is observed that the buildings they refer to as ‘curvilinear’ do not always have smooth finishings (Figure 2).



Figure 2. The metropol parasol. (Photo by: jurgen Mayer <https://www.arkitektuel.com/metropol-parasol/#jp-carousel-2215>)

That is to say, these intricate shapes were also found in pre-digital times. Kara, N. (2021) stated that still, it is possible to say that with the advent of digital technology, which makes it easier to create these forms, designers became independent from certain constraints, so, they experimented with more diverse shapes. This situation led to a departure from traditional, straight-lined shapes and architectural styles to ones that are computer-generated and feature non-standard, non-Euclidean geometric shapes. (Kolarevic, B., 2003).

Greg Lynn, an influential figure in the digitalization of architecture, suggested that conventional architecture was composed of stiff, rectilinear shapes only affected by gravity. He advocated for the use of curvilinear forms in order to create architecture that can adapt to various environmental factors, resulting in more dynamic and smooth designs similar to the ones used in different industries. In his essay “Architectural Curvilinearity”, featured in AD Profile 102, “Folding in Architecture”, marks the beginning of an era characterized by the use of curved shapes and intricate, smooth surfaces in architecture, which became popular during the latter half of the 1990s. (Lynn, G., 2013).

Lynn described the new “smooth transformations” style as the natural outcome of the dialectical tension between Post-modernism, which emphasizes classical composition, unity, and order, or contextualism, and Deconstructivism, which highlights angularity, disconnections, conflict, and oppositions. (Carpo, M., 2013). Before, architects who initially focused on the internal discontinuities within

buildings and sites are now using urban strategies that exploit them by connecting them through continuous and flexible systems. Overall, the approach was shifting towards incorporating external influences and curvilinear developments. (Lynn, G., 2013). Lynn focused on creating forms in digital mediums, utilizing concepts like complexity, smoothness, pliancy, and curvilinearity. He held the belief that the interconnection between a building and its environment, along with the integration of variations and contextual influences, are essential factors in the design process. (Altıntaş, Y. D., & İnceköse, Ü., 2021).

In other words, architects had a long-standing interest in free-forms for creating large open spaces like religious institutions and performance halls. In the 19th century, the emergence of new metallurgical materials led to forms that utilized intricate surfaces. More recently, with the advent of modern materials and engineering advancements, designers have been able to create mathematically precise and structurally optimal free-forms (Çıngı, 2007). Eekhout (et al., 2015) referred to these architectural designs as “blob”, “free-form”, “liquid” and “fluid” designs and mentioned that they were characterized by their sculptural and irregular shapes, which are created using advanced computer technology and mathematical calculations.

A common argument favoring free-form architecture is that it allows for greater expression and creativity than rectilinear architecture. (Jacobs, J. 1961) Bagneris, M., Motro, R., Maurin, B., & Pauli, N. (2008) stated that designers could get drawn into the flexibility of forms, regardless of whether or not they maintain the intended connections between form and other parameters. Furthermore, mention that a new style of double-curved systems emerged with the so-called "Bilbao effect," and free-forms characterize them that they refer as flexible forms. Furthermore, these free-forms usually are eye-catching forms that stand out and establish a unique identity rather than being focused on functional and practical factors (Hertzberger, H., 2000).

Bagneris et al. (2008) categorized non-standard architectures into three groups: Analytical Forms (such as arches, vaults, and domes), Mechanical Forms (which emerged in the latter portion of the 20th century, exemplified by Frei Otto's "Form-Finding" techniques for funicular shapes, and so on), and Flexible Forms (which have double-curved surfaces). Subsequently noted that these flexible forms presented

a challenge in connecting the supporting structure and skin, and there was a disagreement between their respective partners.

This situation may result from a conventional view of architectural design that assumes a logical, step-by-step design process and a creator-like role for the architect, but this does not reflect reality. This approach prioritizes creating a desired visual appearance rather than letting the natural processes guide the form-finding process. In contrast, natural systems arise from interactions between initially disordered components, and a successful form-finding approach in architecture should prioritize understanding and harnessing these types of processes. (Goldsmith, N. S., 2014).

To discuss the form and shape of an architectural object, it is necessary to understand the logic behind their terminology. Ching (2007) defines shape as the unique outline or form of a 2D figure or 3D object used to recognize, identify, and classify figures and forms. The perception of shape is influenced by the contrast between the object and its background or surroundings (Figure 3). On the other hand, it highlights the role of form in creating space, as it establishes the limits of that space through the interaction of planes and surfaces. Therefore, form encompasses not only the three-dimensional mass or volume, but also the arrangement of lines that outline the architectural space, encompassing both its internal structure and external shape(Ching, 2007). By understanding the relationship between form and shape, one can better grasp the essence and significance of free-form architecture in breaking conventional geometric constraints and embracing a boundless and creative expression in architectural design.

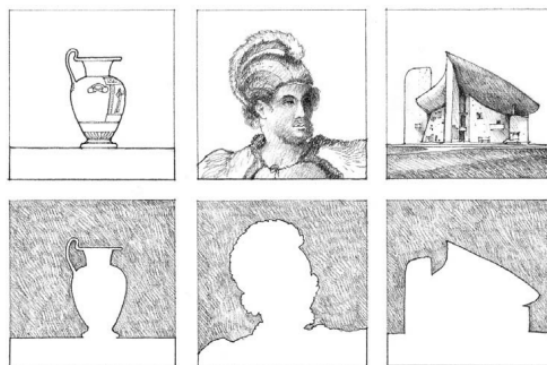


Figure 3. 'Image to describe a shape. Ching, Francis D. K. 2014. (Architecture: Form, space, and order. John Wiley & Sons, p.36)

Related the concept of form and shape, Goldsmith, N. S. (2014) introduced two distinct approaches, namely shape-finding and form-finding, and provided a comparison between two images (Figure 4, Figure 5) as examples. One image depicted a soap film model created by Frei Otto, which was utilized to create a conoid form for a tensile structure. The soap film model exhibited a minimal surface with uniform tension, resulting in a tensile structure that avoided fabric wrinkling and maintained equal stresses throughout. On the other hand, the other image showcased John Utzon's initial drawing of the Sydney Opera House, which represented an organic shape requiring substantial engineering manipulation to transform it into a physical built form (Goldsmith, N. S., 2014).

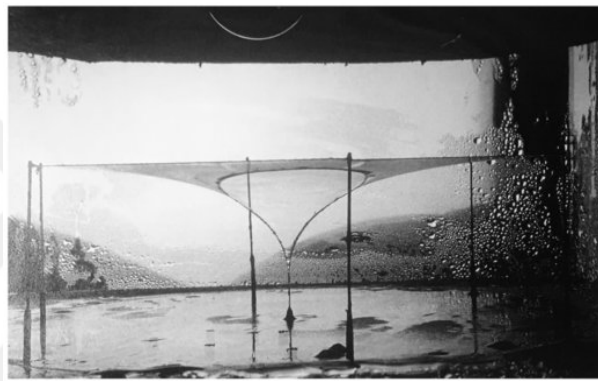


Figure 4. Frei Otto employed a soap film model to advance the development of the column in the shape of a chalice., Stuttgart 21, 1997. (Gta Archives, Eth Zürich)



Figure 5. Concept sketch of the Shells, 1958, Jørn Utzon. (Red Book, Mitchell Library)

Goldsmith, N. S. (2014) stated that while the form-finding approach is often preferred for free-form buildings, a good design can also come from a more deliberate approach to shape-finding. They added that form-finding in architecture involves looking to natural processes to organize buildings better. It focuses on discovering optimal form and dynamic adaptability and uncovering unique relationships not typically relevant to traditional architectural approaches. Rather than being deliberately designed, the beauty of the form emerges from natural

systems. This approach provides aesthetic benefits and allows forms to develop organically, without a preconceived plan, across various scales and materials. (Goldsmith, N. S., 2014)

Although architects used to conduct empirical analyses on their own using prototypes before the advent of computer-based analysis programs, Penttilä, H. (2006) mentioned that they used various methods, such as curved plastic aids, clay models, compasses, and pens-tied-to-ropes to create prototypes of complex and irregular forms. The expertise of skilled builders and their collaboration with the architect was also crucial in the construction process. Additionally, construction involved a trial-and-error approach, where buildings were often demolished and rebuilt until the desired form was achieved. Bechthold, M. (2008) pointed out that architects now have access to computational software, allowing them to analyze their designs more easily, quickly, and accurately. The Finite Element Method (FEM) is one example of software that can analyze a design's structural performance, material properties, and energy and fluid dynamics.

Furthermore, structural optimization methods for these free-form surfaces have been advanced and these techniques also involve improving the "Form follows Force" structures with an emphasis on considering the entire life cycle of the structure (Goldsmith, N. S., 2014, 1-10). Their approach to form-finding involves creating optimal free-form geometries that achieve stable force equilibrium and aesthetic factors. These geometries are derived from sources like nature, modified from existing structures, or explored through a range of options using physical or computational models. The determination of the "optimal" shape is guided by one or more objectives, such as reducing material usage, minimizing deformations, or maximizing structural rigidity (Adriaenssens et al. 2014).

Given these, Marcos, C. (2011) argues that when the aim of a design is to create visually striking buildings, it can lead to a shallow form of design that is disconnected from architecture's traditional values. Furthermore, designing is finding and translating the right idea for a project into a physical space. A good design concept should be open to interpretation by minimizing the emphasis on specific forms and focusing more on the use of space (Hertzberger, H., 2000).

Research on free-form, intricate architectural designs has increased through pushing limits, challenging traditional ideas, and exploring new materials and concepts related to architectural shape and structure (Schittich, C., 2012). Introducing new possibilities has enhanced the importance of previously overlooked aspects of architecture, such as surface manipulation and articulation (Picon, A., 2004). However, architecture is about understanding how mass and space are related, and form is the medium that connects them. The quality of architectural forms is determined by a designer's ability to integrate the interior and the surrounding outdoor spaces of buildings (Bacon, E. N., 1967). Therefore, architects should consider both the inside and the outside when making design decisions on form and space (Venturi, R., 1992).

Briefly, free-form architecture is a groundbreaking and inventive approach to architectural design that liberates architects from the confines of traditional rectilinear forms, encouraging them to embrace a limitless and diverse expression. This visionary style combines distinct shapes and fluid design elements, often incorporating captivating irregular curves and tilts, with the purpose of showcasing the profound impact of various influences on the design process, such as separation, fragmentation, and distortion. Departing from conventional building norms, free-form architecture empowers architects to explore unconventional geometries and expand the boundaries of form and expression, resulting in structures characterized by organic and amorphous shapes, intricate geometries, and polished surfaces. These dynamic and visually alluring designs seamlessly adapt to their environmental context. Furthermore, free-form architecture provides the creative freedom to respond to specific site conditions and cultural influences, giving rise to highly personalized and context-sensitive designs. However, this innovative style may pose challenges in terms of construction complexity, elevated costs, and the integration of building systems and structural integrity. Nevertheless, free-form architecture continues to be an enticing realm for architects to express their creativity and craft structures that stand out distinctly in the urban landscape.

As it is obtained from the literature, free form architecture has several study topics, including digital design, performance-based design, rationalization, and manufacturing. Further studies on these topics are crucial for this new, innovative

design style of the contemporary age that is characterized via the development of intriguing, free-flowing buildings that represent the expressiveness of design together with the originality of structure and construction methods (Hameed, A., Al-Alwan, H., & Oukaili, N., 2020). Free-forms became an inseparable component of architectural design since they provide flexibility and diversity for designers, from concept development to realization. (Adriaenssens, S., Block, P., Veenendaal, D., & Williams, C., 2014). To construct a background on their origins and current state, the following section includes a historical overview on them.

2.2 Historical Overview

Throughout architecture's history, achieving forms with formal flexibility and high structural efficiency was a primary concern. The use of curved surfaces in construction dates back to the Stone Age with the creation of dome-like roofing using stacked stones (Figure 6). The first domes were built in ancient Rome in the 1st century BC. Until the 18th century natural fibers, wood, brick, and stone were mainly used for constructing arches and domes (Heinle, E., & Schlaich, J., 1996). Thus, the constant search for construction materials and methods resulted in the emergence of concrete material in the 2nd century BC. The advances that concrete material brought in construction engineering can be traced to the remains of Imperial Rome, including the Pantheon, a still-standing concrete shell finished in 125 AD (Figure 7).

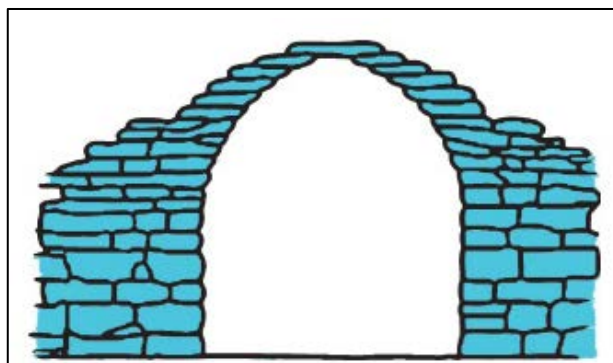


Figure 6. Schematic Drawing of A False Vault.



Figure 7. Pannini, G.P. Interior Of The Pantheon, One of the first concrete buildings., Rome [Painting].
(Encyclopædia Britannica, <https://www.britannica.com/topic/Pantheon-Building-Rome-Italy> 02.01.23)

Even though concrete was invented years before, reinforced concrete accelerated the utilization of curved organic forms while raw concrete became more appropriate as a façade finish. Concrete's sculptural formality mainly works in compression and provides structural efficiency through a unified form and structure (Schlaich, J., 1985). Also, the emphasis on concrete material reduced the dependence on form and altered the shapes of the buildings, thanks to its viscosity. In addition, CAD/CAM manufacturing allows the generation of suitable formworks for organic forms. The concrete's liquid state allowed it to be poured into molds that later cured and solidified into load-bearing, futuristic forms. (Tang, G., 2012).

With the emphasis on concrete shell forms in the 1930s, designers experimented with the freedom of achieving wider spans with maximum efficiency (Huijben, F., Van Herwijnen, F., & Nijse, R., 2011). Thereby, architectures of the International Style, characterized by orthogonal lines, perfect circles, cylinders, or symmetrical layouts, started to diminish with the introduction of these systematized, lightweight, flexible structures. Concrete or thin shell structures have strength and stiffness provided by their curved surfaces, which have relatively small thicknesses compared to their span (Asmaljee, Z., 2013).

To better understand the design of shell structures, it is necessary to mention different methods and calculations involving structure, mathematics, and aesthetics. Because of their aesthetic discernment, which complements their engineering skills

they exploit the material's formal possibilities fully. (Chilton, J., & Chuang, C. C., 2017). There were several methods used to define shells. Between 1930 and 1950, mathematically defined geometries remained at the forefront (Huijben, F., Van Herwijnen, F., & Nijse, R., 2011). In the early 20th century, structural engineers such as Eduardo Torroja (1899-1961 and Pier Luigi Nervi (1891-1979) designed concrete shell structures and at that time, when no other alternatives were accessible, the calculation could only be performed manually. (Figure 8, Figure 9).



Figure 8. Torroja, E. The Zarzuela Hippodrome [Photo]. (<https://Divisare.Com/Authors/2144735691-Eduardo-Torroja> 05.01.23)



Figure 9. Nervi, P.L. The Palazzetto Dello Sport [Photo]. (<https://Divisare.Com/Projects/384547-Pier-Luigi-Nervi-Mi-Chenxing-Palazzetto-Dello-Sport> 05.01.23)

In contrast, the Spanish architect Felix Candela (1910-1997) employed thin shells which were referenced to hyperbolic paraboloid surfaces (Figure 10) (Chilton, J., & Chuang, C. C., 2017). Colin Faber characterizes Candela's Cuernavaca Chapel (Figure 10) as a structure where the free edges serve as the epitome of shell design refinement, potentially due to the indication of the shell's thinness or thickness, leading to a more elegant aesthetic (Faber, C., 1963). These architects and engineers constructed a range of notable shells featuring double curvatures, including hyperbolic and elliptical paraboloids (Meyer, C., & Sheer, M., 2005).



Figure 10: Candela, F., *Los Manantiales* [Photo]. (<https://www.archdaily.com/496202/ad-classics-los-manantiales-felix-candela> 06.01.23)



Figure 11. Candela, F., *Cuernavaca Chapel* [Photo]. (<https://architectuul.com/architecture/chapel-lomas-de-cuernavaca>)

In contrast to the aforementioned shell designers, Heinz Isler, a Swiss engineer (1926-2009), achieved a harmonious balance between the aesthetic appeal and structural efficiency of his shell structures, earning him the reputation of a "structural artist." (Billington, 2003). Moreover, he followed a different approach based on a physical model similar to A. Gaudi's hanging chain models (Figure 12). Hanging models allowed him to discover elegant forms while creating pure compression shells under self-weight (Figure 13) (Chilton, J., 2012). That was, in a way, undertaking the three-dimensional parametric design using physical models. Designers, like Isler, demanded greater flexibility in forms and did not confine their creativity to the constrained set of analytic shapes (Bagneris et al., 2008).



Figure 12. Gaudi, A., *Hanging Chain Model* [Photo]. (<http://dataphys.org/list/gaudis-hanging-chain-models/>
06.01.23)

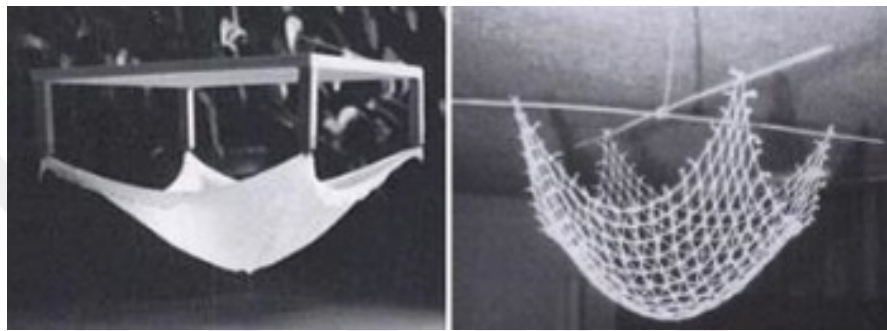


Figure 13. Isler, H. *Hanging Models* [Photo]. (Fernandes, M. J., Kirkegaard, P. H., & Branco, J. M. (2016).
Tectonic design elastic timber grid shells. 06.01.23)

Isler's renowned shell structures, including tennis courts and sports halls, exemplify how he derived the forms through experimentation, as noted in the works of Chilton and Chuang (2017) and Kotnik and Schwartz (2011). In Isler's approach, the primary focus of the design was not solely on engineering factors, as he sought to balance aesthetics with structural functionality. Consequently, these shells should not be regarded purely as industrial buildings but rather as demonstrations of Isler's artistic approach to structural design. Holy Spirit Church, located in Lommiswil, Switzerland and built in 1967 (Figure 14), is an example of Isler's work. Roland Hanselmann played a prominent architectural role in the design of this shell structure. The proposed church form takes the shape of a rising spiral, featuring a free-form cut-out roof obtained from an uneven hypersurface." (Chilton, J., 2011).



Figure 14. Isler, H., *Holy Spirit Church* [Photo]. (Chilton, J. (2011). Heinz Isler: shells for two churches. *Journal of the International Association for Shell and Spatial Structures*, 52(3), 173-183. 06.01.23)

However, shell forms may cause difficulties in spatial design due to their morphology. Their organic properties make them structurally efficient; thus, the spaces within them may need to be more practical for not-so-flexible programs (Chilton, J., & Isler, H., 2000). These impracticalities could be seen in the furniture organization Balz House designed by Heinz Isler and Michael Balz (Figure 15, Figure 16, Figure 17). The space is furnished with handmade custom-carved furniture produced by Balz to fit the curvilinear form.



Figure 15. The original plan of the house shows the clover-shaped layout. [Drawing, by Michael Balz]

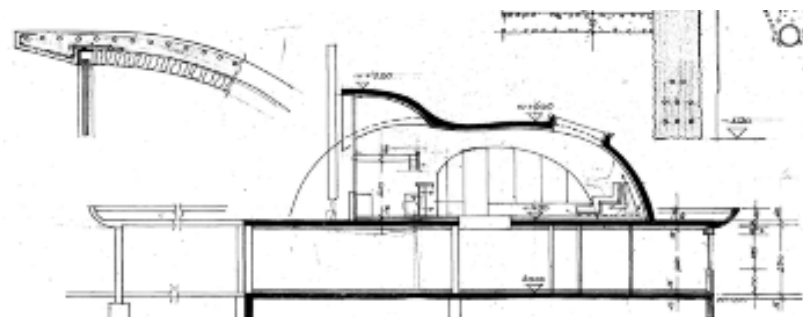


Figure 16. The cross-section of the Balz House reveals the presence of rectangular rooms on the lower level and a curved space on the upper level. [Drawing, by Michael Balz]



Figure 17. The curved purple and white interior of the upper living space, [Photo] of the Balz House.

As observed, in the latter part of the 20th century, shells were three-dimensional, “structure-based building skins” developed by engineers rather than architects (Chilton, J., & Chuang, C. C., 2017). Due to several reasons, towards the end of the 1950s, concrete shells lost favor in the architectural scene (Meyer, C., & Sheer, M., 2005). Ricardo Bitella, a structural engineer working for Arup, pointed out that concrete shells lack flexibility, so architects face difficulties developing their geometries. They mention more freedom in design systems, such as conventional reinforced concrete or structural steel. Furthermore, the appeal of concrete shells has decreased due to advances in other building systems, like lightweight steel, membrane, and cable nets. In addition, the revolutions in material engineering brought up new aesthetic concerns that shifted the opaque monolith shells to high-tech transparent designs. (Tang, G., 2012). Contemporary shells can have larger spans and are thinner than their historical counterparts.

On the other hand, in the late 1960s, we see timber shell structures emerge with architect Frei Otto. He had worked with Gaudi-like form-finding methods, such as Heinz Isler, to obtain efficient free-forms. He designed significant timber grid shells like Mannheim Multihalle (Figure 18). During its realization process, the architectural firm needed to switch engineering teams due to the complexity of the design. The main driving force for the choice of a grid shell was the structural scheme that made it possible to achieve the initial shape proposed by the architect (Paoli, C. C. A., 2007)



Figure 18. Otto, F., Mannheim Multihalle [Photo, by Daniel Lukac]. (<https://mannheim-multihalle.de/en/architecture/> 10.01.23)

Eekhout, M., Wichers. S. (2015) pointed out that free-forms are closely related to shell structures because they became prominent after the innovations introduced to the construction industry. Furthermore, they mention shells as pre-historic or early free-form designs built without the assistance of computers. Asmaljee, Z. (2013) said mentioned their similarities in terms of tectonics, as they both contain continuous surfaces that transmit the forces in different directions. Likewise, Corrao and Pastore (2010) explained the relationship between Free Form Architecture and Shell Structures, stating that the shell typology was one of the early structural systems employed in free-form buildings. The technology for shells, initially developed to a limited extent in the 1930s by Franz Dischinger, gained significant prominence through the works of architects like Heinz Isler, Eero Saarinen, Pier Luigi Nervi, and Felix Candela. Shell structures possess the ability to bear and transfer loads with minimal thickness, relying on their three-dimensional curved geometry and proper positioning and orientation of supports for optimal performance. Typically, shell structures are supported at their perimeters, and while additional elements like ribs may enhance their strength, they do not significantly encroach upon the interior space. Consequently, these structural systems enable the creation of dynamic and expressive buildings and find applications in organizing internal functions, often leading to the formation of innovative and impressive spaces. This versatile system is widely used in various contexts, including flowing interior spaces such as auditoriums, sports facilities, and public infrastructures.

Despite all, these challenging geometries were still popular because they could cover longer spans with maximum structural resistance and minimum load-bearing elements. (Kara, N., 2021). And before digital tools, free-form geometries were

based on physical models or mathematical calculations where the design and realization process were separate. Alongside advancements in the design and construction industry, a fresh perspective on the concept of shells emerged. These were referred to as “sculptural forms” since their formal and aesthetical character got ahead of their structural efficiency (Huijben, F., Van Herwijnen, F., & Nijse, R., 2011).

Following these it is important to mention the Sydney Opera House building, constructed among 1957 and 1973, since it is often cited as the starting point for unconventional designs and free-forms. However, this building also exemplifies the challenges of balancing artistic expression with technical and structural factors. This is evident in the prolonged development process, building shape changes, and the overrunning budget (Baldassini, N., Pottmann, H., Raynaud, J., & Schiftner, A., 2010). Furthermore, it is considered a significant architectural achievement that exemplifies the use of advanced technology, and the integration of aesthetics started a new era by demonstrating the possibility of achieving innovative free-form designs (Mosoarca, M., Anthimos A., and Kampouris A., 2014).

Even though the architect of the Sydney Opera House, Jorn Utzon’s original sketches was composed of shells that vary in size and shape; it was not possible to construct this initial form because of the structural analysis problems, the extensive need for labor power, and the lack of computer-controlled fabrication machinery (Figure 19). Eventually, the engineering team, Ove Arup, solved these problems by rationalizing the design. Overall, the building process was time-consuming and expensive, and the “shell” forms were heavy and bulky instead of the intended lightweight and floating designs (Figure 20) (Mitchell, W. J., 1998). These challenges and difficulties in rationalizing and constructing free-form architecture indicate that there may be future challenges in constructing such structures.

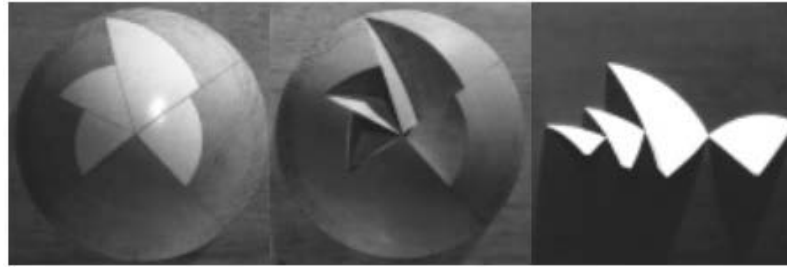


Figure 19: The model to simulate the ribs of the shell roof, and pre-fabricated segments of the shell ribs, 1965.
(photos: 'Zodiac No. 14', Mitchell Library, State Library of NSW)

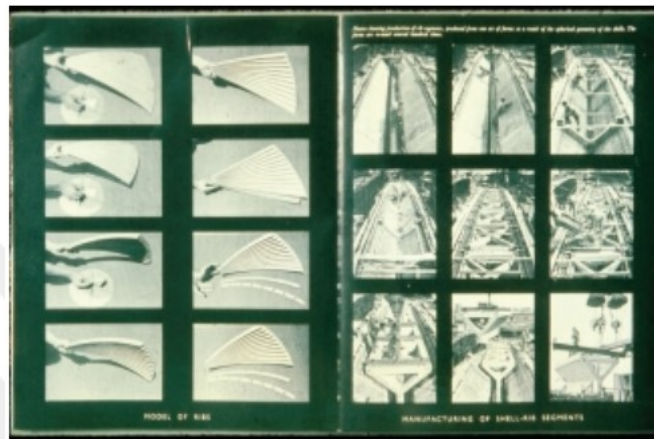


Figure 20: The model of the spherical solution: Dennis Wolanski. (Archive of the SOH, Sydney Opera House Trust)

Another significant characteristic of the Sydney Opera House was its 'iconic value,' which encompasses fame, symbolism, and aesthetic quality (Sklair, L., 2012). Unsurprisingly, the Sydney Opera House became an iconic structure, given its combination of innovation and design. It became a notable landmark after its construction and symbolized Sydney and Australia (Colbert, F., 2003). Given that the most crucial aspect of architecture in the 21st century is to be one-of-a-kind, and icon and the Sydney Opera House is one pioneering example of this signature architectural understanding.

According to Noever (1991), the new approach to architectural building forms deviated significantly from pure and linear forms. Jencks (2006) and Jodidio (2001) defined this approach as a dynamic arrangement of volumes that expressed distortion, fragmentation, and separation. This architectural style can be traced back to the influential exhibition titled "Deconstructivist Architecture" at the Museum of Modern Art (MOMA) in New York, which took place in June 1988 (Glusberg, 1991; Jodidio, 2001; Puglisi, 2008). The term "Deconstructivist" is used to mention the

works of architects such as Coop Himmelblau, Bernard Tschumi, Daniel Libeskind, Rem Koolhaas, Frank O. Gehry, Zaha Hadid, and Peter Eisenman who had distinct architectural styles that differed from one another (Wong, J. F., 2010). The usage of this term arose because of its resemblance to Russian Constructivism and its philosophical association with Derrida's deconstruction theory in the realm of literary criticism (Glusberg, 1991; Wigley, 1993). Furthermore, these architects not only made an impact within the field of architecture but also gained recognition and influence in the broader realms of art and culture (Horn, Bradley, n.d.).

Architects associated themselves with the label of Deconstructivist Architecture because they shared a common belief in opposing the dominance of pure forms. Their objective was to liberate architectural form from the constraints imposed by pure form (Johnson, P., & Wigley, M., 1988). As Johnson and Wigley (1988) stated, each architect pursued a unique approach to subvert form by challenging different inhibitions. In essence, free-form architecture encompasses both the physical shape of a building and the idea of breaking free from traditional architectural limitations. It encompasses the structural geometry as well as the concept of architectural design freedom (Wong, J.F., 2010).

In 1997, the Guggenheim Museum in Bilbao, designed by Frank O. Gehry, was completed. It was another milestone in the field of free-form architectures (Figure 21). Even though many architecture critics had predicted that Gehry would design this type of building, the museum's unusual shape and unique location significantly impacted the world of architecture (Eekhout et al., 2015), furthermore, it was also referred to as one of the initial examples of "Blob" architecture due to its lack of straight lines and angles (Bagneris et al., 2008). It showcased the potential of free-form buildings and brought it to the general public's attention (Terzidis, K., 2004). Furthermore, the building's significance gained global recognition and it influenced the creation of a term known as the 'Bilbao effect' within architectural literature.



Figure 21: Guggenheim Museum. (<https://www.archdaily.com/422470/ad-classics-the-guggenheim-museum-bilbao-frank-gehry>)

Like Gehry's Guggenheim, contemporary buildings could create large and intricate free-form structures at an affordable cost and within a reasonable timeframe with the help of CAD/CAM software, structural analysis tools, computer-controlled fabrication machinery, and advanced surveying methods that aid in the designing, documenting, and constructing of these types of buildings (Mitchell, W. J., 1998). Thus, architects began to examine the concept of boundaries, focusing on these free-form geometries.

To summarize, the change from modernist design principles that utilized transparent materials to create spatial depth to current efforts to compress interior depth into building surfaces is influenced by a combination of changes in philosophical perspectives on binary oppositions and advancements in architectural design and construction technologies (Islami, Y. S., n.d.) However, one negative impact of this trend is that the striking appearance of free-form architecture heavily influences many young architects and architecture students without fully understanding the various factors that went into designing these buildings. (Wong, J.F., 2010) To prevent the misconception that architectural design is simply about creating visually striking forms, it is crucial to have a thorough understanding of structural design.

CHAPTER 3

STRUCTURAL DESIGN

Architects, structural engineers, and designers may have their own individual interpretations however, their definitions of 'structure' generally derive from similar underlying principles. Onouye (2002) describes structure as a composition of interconnected components arranged in a specific pattern of organization. It is the interrelation of these parts, guided by the overall character of the whole, that defines the structure. Furthermore, highlights the importance of structure, particularly in nature, as a mechanism for achieving maximum strength while utilizing minimal materials by arranging elements within a form that aligns with its intended function.

The main purpose of a building's structure is to offer support and effectively distribute forces and loads to the foundation in a safe manner. Structures are designed to withstand various external forces, including wind, gravity, vibrations, and earthquakes. Hence, similar to any physical entity, buildings rely on a structural framework to ensure their physical integrity (Onouye, B., 2002). A well-designed structure must possess stability and durability, serving its intended purposes and offering cost-effectiveness. The aim of structural systems is to achieve the highest possible performance while utilizing the least amount of material to support the specified load or enclose a specific volume. The challenge lies in finding the right balance between structural performance and the associated cost (Addis, B., 1994).

While using the terms "form" and "structure" interchangeably is often acceptable, it is crucial to make a clear distinction between the two in certain contexts. According to Billington, D. P. (1983), "form" is more appropriate when referring to the entirety of an entity, while "structure" is used to analyze the individual parts that constitute the entity. When discussing architectural works, it becomes essential to clarify the difference between these terms. "Architectural form" can encompass an entire building or a component with a certain level of independence, such as a Greek

temple, column, or capital. On the other hand, "structure" indicates the elements that support the building, such as load-bearing walls, beams, and columns.

Mainstone, R. J. (1975) emphasized that there is no fixed relationship among form and structure if we only consider the geometric organization of the structure as the element that defines the form. A specific geometry may be associated with structural characteristics like strength and stiffness. However, he noted that while the geometric configuration of a structure is important, it is just one aspect of its overall form. Nevertheless, it can be regarded as the most critical factor since it determines whether the structure can achieve equilibrium and which structural actions are feasible while excluding others. The materials used, internal details, and construction techniques can create or restrict various possibilities within these parameters (Mainstone, R. J., 1975).

On the contrary, free-forms have various levels of structural integrity when compared to traditional structural design which consists of columns and beams. As observed from the earlier examples of surface structures, such as shells, we realize they did not have several structural systems since the surfaces were designed to function as the primary structural system. However, the contemporary free-form approaches show that these two components, form, and structure, can also perform separately.

Related to this subject, it is necessary to mention a key aspect which is the hierarchical organization among structural systems. This hierarchical organization refers to the division of structural elements based on their function and significance in supporting the overall load of the building. In the literature, these are referred to as primary, secondary, and tertiary structural systems. The primary structure comprises the essential load-bearing components that ensure overall stability and support. These elements transfer the building's weight to the foundation and are vital for its resistance against external forces. The secondary structural system supports the primary elements and has a critical role in distributing the load evenly throughout the building. This system enhances the overall structural integrity by providing additional support and reinforcement to the primary components. The tertiary system, on the other hand, is responsible for maintaining the building's shape, providing lateral stability, and incorporating elements such as cladding, roofing, and

facades. These components not only enhance the appearance of the building but also contribute to its weather resistance and insulation.

Today, due to the continuous growth of the scope and complexity of architectural design, architects are confronted with the overwhelming challenge of incorporating numerous scientific and technological advancements into architecture. This issue mainly involves integrating innovative, imaginative, and cost-effective structural elements into the design process. This challenge is more critical than ever in history (Engel, H., 1967). Consequently, these innovations in form generation required further research on this topic. The following chapter is organized as two sections. The discussion begins with the structural design in free-form architectures, followed by structural systems and their categorizations.

3.1 Structural Systems

In the literature, structural systems are categorized according to different aspects such as their behavior and response to external loads (Engel, H., 1967), active internal forces in the system (Hurol, Y. 2016), structural material types used (Macdonald, 1997), and different combinations of these characteristics such as geometry and material aspects (Veltkamp, M., 2007), the relationship between form and efficiency (Macdonald, A. J., 2001).

Different studies have examined various approaches to categorizing structural systems. In this specific study, Engel's classification is utilized due to its emphasis on the primary objective of these systems, which is to create architectural form and space. By employing visual representations to clarify the functioning of architectural structures and accentuating their significant potential for architectural design, architects gain access to and understanding of a crucial aspect among many that shape the built environment. Briefly, according to the categorization, the behavior of a structure when it is subjected to loads, including how those loads are received, transferred, and transmitted, is referred to as structural action. The materials used to construct the structure and the arrangement of its components are the primary factors that affect its behavior (Macdonald, A. J., 2001).

Engel grouped structural action into four "families" with subdivisions into "types" and "structure singles"(Engel, H., 1967, p.42). While the highest level remains purely theoretical, the second and third levels pertain to structures commonly observed in traditional designs featuring straight lines. Hence, for the purposes of this study, these levels are disregarded. A table shows the four structure systems and their corresponding types to avoid confusion. (Figure 22, Figure 23)

Structure Systems	Types
Form-Active	Cable Structures
	Tent Structures
	Pneumatic Structures
	Arch Structures
Vector-Active	Flat Trusses
	Transmitted Flat Trusses
	Curved Trusses
	Space Trusses
Section Active	Beam Systems
	Frame Structures
	Beam Grid Systems
	Slab Structures
Surface Active	Plate Structures
	Folded Plate Systems
	Shell Structures

Figure 22. Structure Systems And Structure Types, Engel H. (1967)

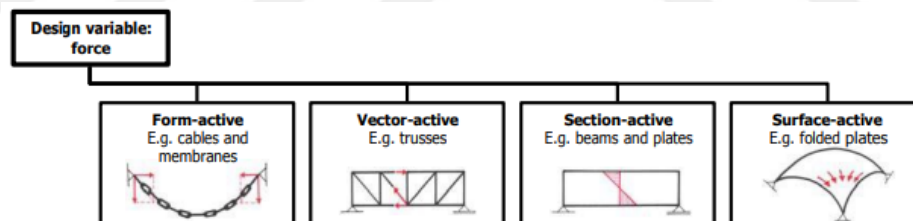


Figure 23. Four mechanisms of structural actions, introduced by Engel H(1967), (Veltkamp, M., 2007)

The four main load transfer mechanisms rarely occur in isolation in actual structures. In most cases, multiple mechanisms act simultaneously within the same element, either at the same or different scales. When mechanisms act on the same scale, they interact and depend on each other, providing benefits such as compensating for critical stresses, increased rigidity (Engel, H., 1967), and versatility for multiple loading conditions. When different mechanisms have different hierarchies, the lower positioned system transfers the loads to the system positioned higher in the hierarchy (Macdonald, A. J., 2001).

In the following sections, Engel's structural systems categorizations will be further explained.

3.1.1 Form-Active Systems

Form-active structure systems are systems composed of flexible materials and they use specific design features and stabilization methods to redirect forces. They are systems in single-stress conditions. Through a careful design process, these systems can work efficiently and economically in both pure tension and compression, which makes them ideal for spanning longer distances (Engel, H., 1967).

Forces' natural flow governs form-active structure systems and depend on loading conditions. This means that they cannot be associated with arbitrary free-form designs, resulting in architectural form and space being shaped by this mechanism. The structural elements of these systems can be concentrated on to create surface structures. However, even though they have a single stress condition that distinguishes them as form-active structure systems, they still have to follow the principles of the funicular pressure line and tension line (Engel, H., 1967).

Moreover, structures that employ the form-active structural systems derive their shape from a particular loading condition, which means they cannot be regarded as free-form shapes designed independently of this loading factor. The materialization process can only control quantitative deformations, while the qualitative aspects have limited controllability. In pneumatic structures, the presence of pressure requirements prevents the adjacency of convex and concave areas, and achieving varying curvatures within an object necessitates patterned inflation or the application of external restraints. When designing a free-form geometry using a form-active system, these factors become the primary focus (Macdonald, A. J., 2001).

Engel, H. (1967) further explained the names of cabled systems, membrane-tent structures, pneumatic systems, and arch as the systems of form-active structures (Figure 24).

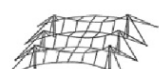
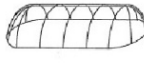
Cable Structures	 Parallel Span Systems	 Radial Span Systems	 Biaxial Span Systems	 Cable Trusses
Tent Structures	 Peak Tent Systems	 Undulating Tent Systems	 Indirect Peak Tents	
Pneumatic Structures	 Air-Controlled Indoor Systems	 Air Cushion Systems	 Air Tube Systems	
Arch Structures	 Linear Systems	 Vault Systems	 Vaulted Lattice Systems	

Figure 24. Form-active systems and some subsystems (derived from Engel, 1967)

- Cable System:** Cables and suspension structures are regarded as the most cost-effective and lightweight systems operating under tension and between 50 to 200 meters. These systems can take on different shapes, such as simple hanging, crisscrossing networks, radiating, biaxial, or trussed. They can be combined with structural elements such as beams, columns, arches, or truss systems. They are utilized for various purposes that require vast column-free spaces, such as bridges, stadiums, and concert halls (Hurol, Y.,2016).
- Tent/Membrane:** The membrane is a tensile structure that can stretch over a distance of 80 meters and serves as a structure and cladding. When designed for covering vast areas, membrane structures operate on the same principles as cable structures. Tents are the most basic membrane structures, including three essential components: fabric under tension, compression struts, and tension or compression side supports. In larger membrane structures, cables and pre-tensioned cables are utilized to divide the membrane into smaller sections, which increases the system's stability against wind. (Hurol, Y.,2016).
- Pneumatics:** Pneumatic structures rely on hydrostatic forces to maintain their shape, and they are essentially air-inflated membrane structures (Silver, P., Evans, P., & McLean, W., 2014). There are two types of pneumatic systems: single-layer systems that rely on continuously pumped air and double-layer

systems that have two layers of material filled with air in between. Pneumatic systems have various applications, such as being used as a roof, a dome filled with air, or a series of linear pneumatic units. Steel or aluminum secondary structures are used to span longer distances of up to 200 meters and prevent wind-related instability issues (Hurol, Y.,2016).

- **Arch:** The arch is the primary element of vaults and domes and is designed to span longer distances through internal compression. The optimal shape for a funicular arch is a parabola, representing the moment diagram form under applied loading (Hurol, Y.,2016).

3.1.2 Vector-Active Systems

Vector-active structural systems consist of linear members that redirect forces while distributing them into vectors along tensile and compressive elements in multiple directions. The relationship between the members' geometry governs the redirection of forces, and the optimal angle between members is typically between 45 and 60 degrees. Vector-active structures operate as "systems in coactive compression and tension," meaning that the system members experience both compression and tension forces without bending (Engel, H., 1967, p. 135). The efficiency of vector-active structures relies heavily on axial tension and compression rather than bending or shear forces. This feature enables them to span longer distances without the need for intermediate vertical structural members (Silver P., et al., 2014; Hurol, Y., 2016)

Utilizing straight members within vector-active structural systems implies that achieving free-form curved shapes is possible only through the approximation of polygons. The level of deviation between the desired curved shape and its polygonal approximation is determined by the size of the members employed. Since bending, torque, or shear forces are absent in this mechanism, the material stresses within the cross sections of the members are evenly distributed, resulting in efficient utilization of the structural material. However, it is necessary for the members to possess some resistance to section action to prevent instability and local bending. While the use of straight members imposes limitations on formal freedom, the structural efficiency can still be maintained and employed if other elements of the structure are designed to resist bending through an alternative system (Macdonald, A. J., 2001).

Engel, H. (1967) further explained under the names flat, transmitted flat, curved, and space trusses as the systems of vector-active structures (see Figure 25).

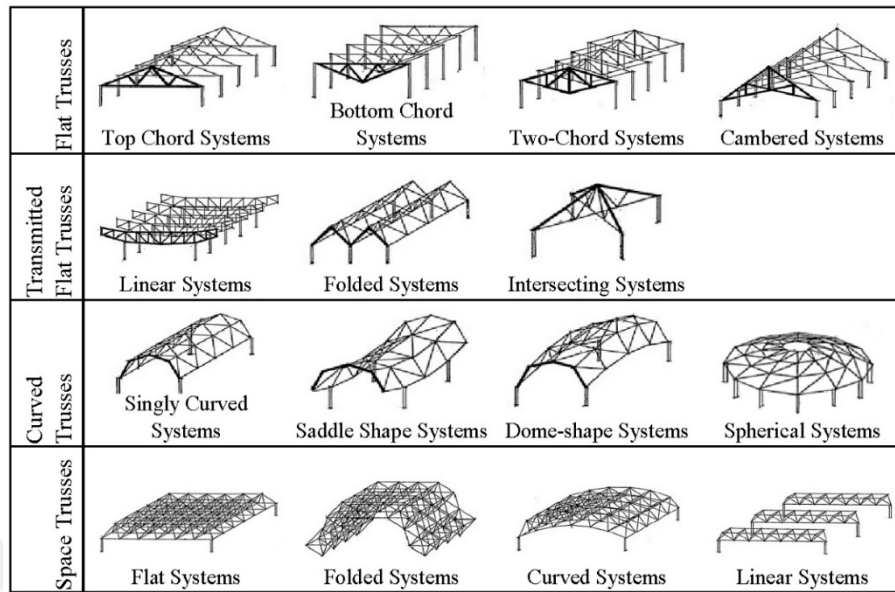


Figure 25. Vector-active systems and some subsystems (derived from Engel, 1967)

- Flat (2D) Truss:** Trusses are a fundamental part of vector-active structures and consist of beams arranged in a triangular pattern using small bars. The inherent stability of triangles makes trusses an effective structural system because their shape cannot be altered without changing the length of a side. Furthermore, they can be incorporated into a structure in various configurations depending on the building's geometry (Ambrose & Tripeny, 2011; Hurol, Y.,2016).
- Transmitted Flat Truss:** The term "transmitted flat trusses" refers to trusses with a flat upper chord and an angled lower chord, which help transfer loads to the supports. These trusses can be used in different applications, including single-layer and double-layer systems, and can be made from different materials, such as steel or timber. (Maier, G., & Schlaich, M., 1996).
- Curved Truss:** Engel, H. (1967) defined a curved truss as a structure composed of straight members that are connected by joints and are organized according to the form of the truss is curved. The curved shape of the truss allows it to resist external loads in a particular manner, with the curved geometry distributing the forces along the members and reducing the bending

stress in each member. Curved trusses useful in many applications requiring strength and stability, such as roofs.

- **Space Truss:** Space frames are truss systems that operate in three dimensions (3D) and have a higher capacity to span longer distances of up to 200 meters. These systems extend over the entire space in horizontal (x and y) dimensions, eliminating the need for vertical supports. They are cost-effective and commonly used because they are lightweight, prefabricated, and easily assembled on-site (Hurol, Y.,2016).

3.1.3 Section-Active Systems

Section-active structural systems comprise solid, rigid, linear elements (also their compact form as slab) that redirect force through the mobilization of sectional forces. This system's members mainly depend on bending (Engel, H., 1967). In the building industry, the most frequent types of systems used are comprised of elements that can withstand various forces such as axial tension and compression, bending, shear, and torsion (Silver, P. et al.) The efficiency of these systems is influenced by the shape of their components, the particular properties of the materials used, and the uninterrupted nature of the members. Furthermore, they operate on the principle of continuity to create large open spaces without the need for columns, allowing for long spans.

Macdonald, A. J. (2001) suggests that among the four mechanisms, the section-active mechanism is the most adaptable. In contrast to Engel's definition, this mechanism does not require members to be solid or linear but allows for the use of rigid materials in various compositions. The diverse range of stresses generated by this mechanism facilitates the transfer of different types of loads. However, the deficiency of this diversity is the uneven distribution of stress inside a single member, which may result in unused capacity. Free-form building designs often possess unpredictable geometries and varying load-bearing conditions. In such cases, the versatility of the section-active mechanism, while not highly efficient, proves to be suitable (Macdonald, A. J., 2001).

Engel, H. (1967) further explained beam, frame, beam grid, and slab as section-active systems. (see Figure 26)

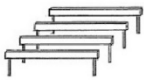
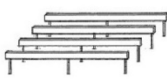
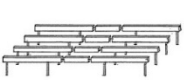
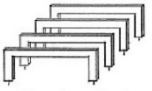
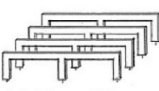
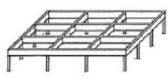
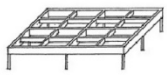
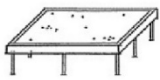
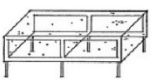
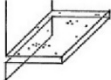
Beam Systems				
Frame Structures				
Beam Grid Systems				
Slab Systems				

Figure 26. Section-active systems and some subsystems (derived from Engel, 1967)

- **Beam System:** Beams play a crucial role in section-active systems as fundamental components. They are structural elements designed to withstand bending forces aligned with their axis and to transfer forces perpendicular to their axis. By utilizing sectional stresses, beams effectively distribute these lateral forces along their axis, ultimately transmitting them to edges(Engel, H., 1967, p. 179). Pre-stressed members and composite materials provide efficient cross-sections that are crucial for the overall effectiveness of beam systems (Engel, 1967)
- **Frame System:** In frame systems, the vertical and horizontal components are linked with solid joints that resist lateral loads (Engel, H., 1967).
- **Beam grid System:** The Beam Grid system is a modular construction method involving a standardized grid of beams intersecting at right angles to form a structural framework. This system allows for a high degree of flexibility and adaptability in design, as well as efficient use of materials and easy construction (Engel, H., 1967).
- **Slab System:** Various slabs exist, including uniform slabs, slabs with column capitals and drop-panels, ribbed slabs, waffle slabs, and cantilever slabs

(Engel, 1967; Hurol, 2016). Uniform slabs may be upheld by beams at both ends in both directions or upheld by columns strengthened with capitals and drop panels. If the longer span is at least twice as long as the shorter span, one-way slabs are favored, with beams placed only on the longer span. For slabs where the thickness needs to exceed 20 cm, and the shorter span is greater than 7 meters, ribbed or waffle slabs are used in the design to decrease dead load (Hurol, Y., 2016)

3.1.4 Surface--Active Systems

Surface-active structural systems consist of rigid surfaces that can resist compression, tension, and shear, and forces are redirected through surface resistance and particular surface forms. To optimize performance, surfaces in surface-active systems are designed to redirect forces. They are best suited to resist forces parallel to the surface rather than point loads that cause local bending stresses. Continuity of surfaces is essential, as proper form allows the system to distribute loads evenly into small units across the surface (Engel, H., 1967).

Since surfaces define architectural space, the design of surface-active systems determines the character of their space. The efficiency of form in surface-active systems defines space and allows for material efficiency. Deviating from the correct form can result in wasteful use of materials and economic problems. Also, it is noted that all structural systems can incorporate surface-active elements and potentially become superstructures for surface-active systems(Engel, H., 1967).

Also, surface-active structures consist of a surface, they are similar to form-active structures. The difference among the two structural systems is the material the surface is made of. The material can resist shear, tension, and compression in surface-active structures, while form-active structures cannot. As free-form building designs often use rigid materials for surfaces, load transfer through surface action is a suitable mechanism to utilize the enclosure structurally (Macdonald, A. J., 2001).

Engel, H. (1967) further explained under the names, plate, folded plate, and shells as the systems of surface-active systems (see Figure 27).

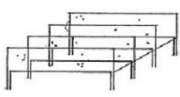
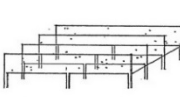
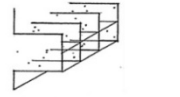
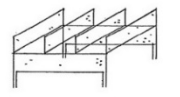
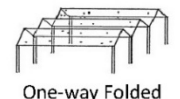
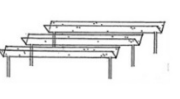
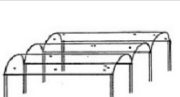
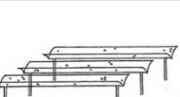
Plate Structures				
Folded Plate Systems				
Shell Structures				

Figure 27. Section-active systems and some subsystems (derived from Engel, 1967)

- Plate Structures:** Engel, H. (1967) explained that plate structures are a vital feature of surface-active systems because they can span large distances and support loads primarily through flexural stress. These structures can be constructed using various materials like steel, concrete or timber and can be designed in different shapes and thicknesses to enhance their strength and stability. Furthermore, it added that plate structures are essential to architectural design, providing both functional and aesthetic benefits.
- Folded Plate:** Folded plates offer a variety of form possibilities due to the numerous folding types that can be employed. Each section acts as a beam in folded plates and resists bending stress. With the appropriate depth achieved through folding, they can span up to 150 meters (Engel, 1967).
- Shell:** Engel, H. (1967) described shells as capable of supporting loads by distributing them across their curved surfaces. They are typically made from concrete or metal and are often reinforced with steel or other materials to increase their strength. They are characterized by their ability to span long distances without needing internal support, making them an efficient and cost-effective choice for constructing roofs, domes, and other curved structures. Moreover, shells can be designed to have various thicknesses, curvatures, and forms, and their shapes can be optimized to achieve maximum strength and stability. Furthermore, it highlights their ability to combine functionality and aesthetic appeal in architectural design.

3.2 Free-Form Structural Design

In the 21st century, free form architecture, prevalent in both architectural practice and education, had become a prominent characteristic of modern architecture. Free-form buildings exhibit unique characteristics and properties in their structural systems. These structures, often characterized by complex and irregular shapes, require innovative approaches to achieve stability and structural integrity. One of the key characteristics is the absence of traditional orthogonal grid-based structural systems commonly found in conventional buildings. Instead, these structures rely on unconventional structural configurations that follow the organic and fluid nature of the architectural form. Even though the properties of free-form structural systems include adaptability and flexibility, this departure from regularity poses challenges in terms of load distribution and structural analysis.

Majowiecki, M. (2008) criticized that contemporary architecture often prioritizes aesthetics over structural rationality and seeks to achieve original solutions through structural efficiency. This results in using design languages, such as the structure as a sculpture, the incorporation of natural elements, and the repetition of architectural motifs. Nevertheless, these contemporary styles can still be appreciated for their ability to adapt the physical environment to accommodate social needs and achieve a level of artistic and sculptural excellence in architecture.

Regarding these, analysis on architecture and structure relationship became even more substantial for these structures. (Wong, J. F., 2010, Pottmann, H. et al., 2008). Mitchell, W. J. (1998) defended that conventional structural design methods rely heavily on assumptions of regularity, symmetry, and the duplication of identical components. However, when it comes to free-form designs, traditional structural models may not serve as effective starting points, particularly if the established typologies are rigidly defined and lack flexibility. Thus, a sensible and adaptable typology must adapt to this new context.

Veltkamp, M. (2007) raised concerns about specific free-form buildings that lack alignment between their structure and shape, leading to complexities in connections and the requirement for diverse systems. Moreover, highlighted the significance of identifying the most suitable structural schemes, systems, and designs, along with

free-form buildings that exhibit high levels of systematization, formal freedom, and material efficiency. Although it is acknowledged that using curvature to improve structural efficiency is still applicable with modern materials, the primary purpose of structures remains to support the free-form design of architecture. (Majowiecki, M., 2008, Çingil, T., 2007).

Following these, specialized structural systems are necessary to support the unique form of the building. These systems typically take on the shape of the building's surface and become an integral part of its overall structure. Oxman, R., & Oxman, R. (2010) stated that if the building has irregular or twisting forms, the structural system must also bend and twist to maintain the geometry and support the weight of the building. As a result, the shapes of these structural systems may deviate from traditional engineering methods, posing a challenge to engineers.

In order to solve this discrepancy in handling highly intricate shapes, digital tools have been developed to address the issue of production. With this, CAD/CAM technologies emerged to create new possibilities for producing and constructing intricate shapes (Balinski, G., Januszkiewicz, K., 2016). With digital technology advancements, it has become simpler and more cost-effective to construct free-form buildings. This is because digital design and manufacturing expertise helps to reduce the duration and cost of the production and construction phases. Several fabrication technologies, such as CNC cutting, subtractive, additive, and formative methods, are now available. (Kolarevic, B., 2003).

The growth of computer technologies, including the creation of virtual space, has enabled architects to explore intricate shapes and the creation of more flexible computer-generated surfaces (Marcos, C., 2011). However, for Islami, S. Y. (2007), many of these designs were not based on constructability due to the faster development of digital tools compared to the necessary construction techniques. This has caused a conflict between the conception and production of freeform designs (Eekhout et al., 2015). Moreover, the advent of digital tools and focus on production and materiality has shifted the paradigm to a design process that prioritizes construction awareness over materiality (Marcos, C., 2011).

Despite the availability of these digital tools and cost-effective construction methods, curved beams and panels are still commonly used in free-form architecture, even

though straight members and flat panels are more economical and easier to handle. The preference for curved elements can be attributed to artistic factors and the desire to achieve a high-quality final surface (Pottmann H. et al., 2008). However, the manufacturing cost of curved elements remains significantly higher due to limitations in mass production. Consequently, finding the right balance between surface quality, shape complexity, and budget poses a challenge. Similarly, in the case of steel-glass constructions for free-form designs, the use of straight members and flat panels is prevalent due to the high cost associated with curved elements (see Figure 28). Flat panels offer advantages such as reduced member count per node, per unit of surface area, and overall construction weight (Pottmann H. et al., 2008). Despite the availability of digital tools, the choice between curved and straight elements in free-form architecture involves careful consideration of factors such as aesthetics, cost, and project requirements.

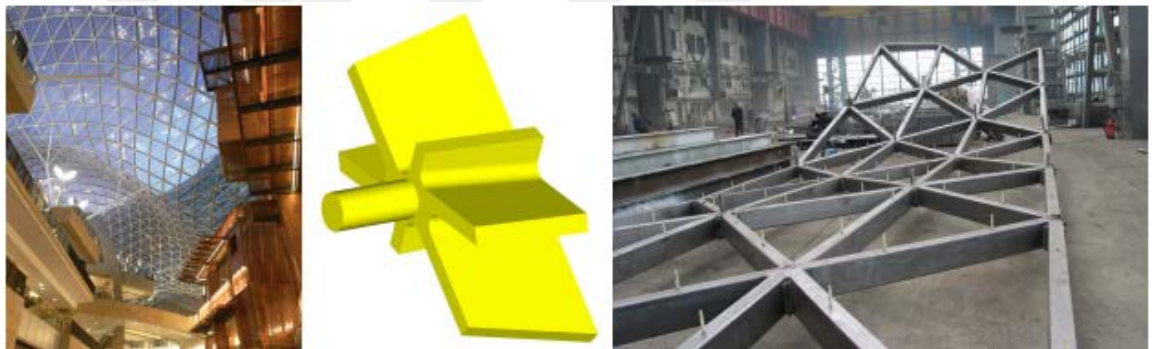


Figure 28. Steel-glass constructions following a triangle mesh. (Images courtesy Waagner-Biro Stahlbau)

Due to critical measurements and prefabrication processes, free-form design and construction present significant challenges to engineers and contractors. To ensure that the building components fit precisely during construction, a considerable amount of intellectual effort is required during the engineering stage to define the shape and dimensions of each building element (Eekhout et al., 2015). Furthermore, poor construction details can cause irregular grids and roughness, negatively affecting the design's structural stability and aesthetics. The separation between architects and engineers often causes this discrepancy between the design and implementation. This technical disparity makes communicating effectively challenging for structural and aesthetic design. (Knippers, J., & Helbig, T., 2009).

Hence, the rise in the significance of structure and materials has led to the growth of 'digital tectonics,' which merges architecture and structural engineering. (Balinski, G., et. al, 2016). Leach, N., Turnbull, D., & Williams, C. (Eds.). (2004) introduced the term as a new way of thinking in architecture, partially enabled by digital technology but not wholly reliant on it. They discuss this shift which involves an emphasis on the structural integrity and increased collaboration among engineers and architects. The editors even mention a new type of practitioner, an architect-engineer hybrid for the digital age.

In other words, technological advancements and digital tools are utilized to conceptualization and realization of architectural creations. Wong (2010) categorizes digital architects into two groups: those who utilize computers to generate forms and those who use computers to rationalize forms. Hence, to produce high-quality free-form structures, it is critical to have a well-coordinated design approach that extends from form-finding to site assembly.

Consequently, as architectural practice continues to grow in scope and intricacy, architects are confronted with the challenge of incorporating numerous scientific and technological advancements into the realm of architectural art. One significant aspect of this challenge involves integrating creative, imaginative, and cost-effective elements within the design process.

CHAPTER 4

METHODOLOGY

Aim of this study is to understand and explain the influences of structural systems on the form and space integrity of free-form buildings. Thus, a systematic approach was developed to understand the interrelations of structure, form, and space. With this aim, a set of pioneering examples of free-form architectures has been analyzed.

As Chapter two explains, contemporary free-form architecture studies mainly focus on digital design, performance-based design, rationalization, and manufacturing. Unlike those, this thesis provides a guideline on how to read free-form buildings' structural, formal, and spatial aspects while constructing a background on achieving integrity among these design parameters. Therefore, case study research principles are utilized to cultivate a specific viewpoint on the matter.

In general, case study research is employed to address questions pertaining to "how" or "why" (Yin, R. K. 2003). In this specific study, the focus is on understanding how structural systems influence the form and space of free-form buildings. And the methodology comprised of a case study which investigates the contemporary phenomenon within a real-life context. It enables the creation of a framework that demonstrates the connection between the observed situation and its practical manifestations in real-life scenarios. Additionally, cases provide descriptive insights, making them valuable for evaluating specific topics. Therefore, this study adopts the principles of case study research to assess contemporary free-form architecture by examining contemporary works.

In this study, the case study research methodology features a critical analysis based on a total of seventeen cases, primarily selected from the 21st century. They are analyzed based on research factors explained in the following section.

To thoroughly examine the cases, it is essential to consider specific parameters that affect the relationship between the structure, form, and space of a free-form building. This study provides guidelines for design with an analysis table (Table 4.1). The cases are examined by five analysis steps, shown in the aforementioned table including both data collection and analysis: 1. General information and graphics, 2. Form analysis, 3. Structural analysis, 4. Space analysis, and 5. General Assessment.

Table 4.1 Analysis Table

NAME, Year			GENERAL INFORMATION & GRAPHICS	
Architecture			EXTERIOR IMAGE (1)	INTERIOR IMAGE (2)
Structural Eng.				
Program				
GFA				
FORM ANALYSIS				
FORM REASONING PROCESS	VISUAL PROPERTIES			
	STANDARDIZATION IN CONSTRUCTION			
	SUSTAINABILITY			
STRUCTURAL ANALYSIS (F: Form Generation, S: Space Generation)				
STRUCTURAL SYSTEM	FORM ACTIVE	CABLED	F	S
		TENT/ MEMBRANE		
		PNEUMATICS		
		ARCH		
	VECTOR ACTIVE	2D TRUSS		
		3D TRUSS / SPACE FRAME		
		GEODESIC DOME		
	SECTION ACTIVE	BEAM GRID		
		FRAME		
		SLAB		
	SURFACE ACTIVE	LOAD - BEARING WALL		
		FOLDED PLATE		
		SHELL / GRID SHELL		
STRUCTURE IN THE DESIGN PROCESS	INTEGRATED DESIGN PROCESS			
	STRUCTURE-BASED DESIGN PROCESS			
	LINEAR DESIGN PROCESS			
GENERAL ASSESMENT				
Structure and Form Relation		1	Secondary structure(s) generates the form.	
		2	Primary structure(s) generates the form.	
Form Reasoning Process		1	One Topic	
		2	Two Topics	
		3	Three Topics	
Structural Systems in Design Process		1	Linear Design Process	
		2	Structure-Based Design Process	
		3	Integrated Design Process	
Space and Form Compatibility		1	Spatial configurations are not compatible with the form.	
		2	Spatial configurations are partially compatible with the form.	
		3	Spatial configurations are compatible with the form.	
REFERENCES:				

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5

PLAN(S)

SECTIONS(S)

Horizontal spatial organisation

Clustered Spaces

Form-defining spaces

Flexible spaces

Vertical spatial organisation

Set-back spaces

Conjunct spaces

Sole spaces

Attic spaces

The first part of the analysis table, general information, and graphics, contains data that is gathered from the literature, such as official building websites, and information disclosed by the architects and engineers. In the following sections, other parts of the analysis table are explained.

4.1 Structural Analysis

The third part of the analysis table refers to the concepts introduced in Chapter 3, and it is comprised of two components: structural system analysis and structure in the design process which will be explained in the following sections.

4.1.1 Structural Systems Analysis

For the structural analysis part, the work of Engel (1967) is taken as the base for the categorization of structural system types. Therefore, thirteen fundamental structural system types are determined and categorized under four main categories: form-active, vector-active, section-active, and surface-active. The relevant terminologies are explained under the “3.1 Structural Systems” section. Here, configurations of different structural systems with similar working principles have been investigated.

In addition to these, structural analysis part indicates the structural systems and their role on form and space generation with “F” for “Form Generation” and “S” for “Space Generation”. Here, the term “Form” is used for “The shape or appearance of something” (Cambridge Dictionary, n.d) because here, the aim is to indicate the direct relationships between structure/form and structure/space. However, form references both internal structure and external outline by giving a sense of three-dimensional mass or volume (Ching, 2007), so these letters are interpretations on the structural system types which can be marked both “F” and “S” or marked by only one.

Furthermore, structure in the design process section provides information on the buildings’ design process, including Linear Design Process, Structure-Based Design Process, and Integrated Design Process. These are explained in the following section.

4.1.2 Structure in the design process

The emergence of free-form architecture has made it crucial to examine how structural design exists within their complex design process. Because, with digital architectural design, architects and engineers have started to utilize different relationships between form and structure. For instance, Macdonald, A. J. (2001) defended that the relationship between structure and architecture could vary significantly, with a range of possibilities between the structure completely dominating the architecture and the aesthetic treatment disregarding structural requirements. Subsequently it examined an extensive range of possibilities under six general categories: “structure as an ornament, ornamentation of structure, structure as form generator, structure as architecture, structure accepted, and structure neglected” (p.114).

Similarly, Veltkamp, M.(2007) differentiated structural systems integrity to form as “Structures independent of form” and “structures dependent on the form, including self-supporting and weight-optimized structures. Moreover, Demir, Y. (2013) stated that architects and engineers have two options when it comes to designing the structural system: they can either design the structure simultaneously with the process of generating the form, or they can design it during the construction phase to ensure that the already created form is feasible to construct.

Therefore, in the analysis, these diverse design processes were classified into three primary categories: the linear design process, the structure-based design process, and the composite design process, based on the relationship between structural design and architectural design. The structural system's various roles and conditions play a critical role in architectural design. Structural Systems in the Design Process are further explained in the following sections.

4.1.2.1 Linear Design Process

Linear design processes follow a particular sequence where the form is created first, followed by the design of the structural system based on the form's geometric limitations, and lastly, material choices are made. The structural design cannot alter the form during these processes through analyses or optimizations. Architects

typically create the form of a building with less concerns of how it will be structured or whether an efficient structural system is necessary to achieve the desired form. Consequently, during the form generation phase, there is often a lack of information regarding its construction aspects. For this, architects and engineers subsequently work on designing a suitable structural system, selecting suitable cladding materials, and incorporating an outer layer of adequate thickness to the building (Kloft, H., 2006).

Macdonald (2001, p.109) examined the tendency to overlook structures in the process of creating forms, where they do not contribute to the aesthetic objectives. The introduction of steel and reinforced concrete as structural materials brought about a revolutionary shift in architectural design. Since then, it has been possible to conceive building designs without immediate concern for their support or construction. The strength of these materials made it feasible to construct buildings in virtually any shape unless they are huge, and financial constraints do not present a limiting factor. This freedom in design had a remarkable impact. It has emancipated architects from the limitations imposed by the necessity of supporting buildings with conventional materials such as masonry and timber.

In the realm of free-form design, the integration of the structural system with amorphous forms presents challenges, not only during the design process but also in the execution and construction of the structure. The form-based design process can lead to the disintegration of formal and structural aspects. Pottmann, H. et al. (2008) emphasized that contemporary free-forms often adhere to the principle of "Form follows force," where the structural schemes best suited for them are those that exhibit a high level of systematization, formal freedom, and material efficiency.

4.1.2.2 Structure-Based Design Process

The design approach based on structure emphasizes the significance of structural design in guiding the entire design process, from the initial idea to the final form. Architects and researchers Rivka and Robert Oxman discussed a shift towards a material-oriented practice that embraces ecological potential and moves away from formalism. They explain that this approach to architectural design is rooted in pre-

existing material and structural concepts, while structure serves as the design generator (Oxman, R., & Oxman, R., 2010).

Macdonald (2001) delves deeper into the concept of the structure serving as the generator or accepted form of a building. These ideas emphasize the interplay between form and structure, where the structure poses a significant influence on the building's form. And this time, it does not have to be visually exposed. This situation entails embracing the most structurally sensible arrangement of elements, leading to architectural adaptations accordingly. Two distinct scenarios emerge based on the extent of connection between architectural and structural objectives.

In some instances, the relationship is highly favorable, as the form-generating potential of the structure is harnessed to contribute to a specific architectural style. On the other hand, structural requirements may predominantly influence the form while the design concept shifts towards other aspects.

4.1.2.3 Integrated Design Process

The integrated design process involves the simultaneous development of form and structure through architectural and structural design during the design process. In the literature, sometimes, such systems have been called composite; however, for this study, the 'integration' term was found to be more appropriate.

According to the WBDG Aesthetics Subcommittee (2016), the engagement of an integrated design process is crucial for achieving aesthetic objectives in building design. This process involves seamlessly bringing together various disciplines that contribute to the design of the building. It entails a cohesive development of materiality, form, fabrication, construction, and structure, with each aspect informing and influencing the others. Structural analyses and optimizations play a vital role in modifying the building's form during the form generation process, enabling the integration of structure from the initial stages of design to the construction phase. However, while structural design is essential for realizing the building, it typically does not directly impact the initial process of architectural form generation (Kloft, H., 2006).

Mangelsdorf, W. (2010) proposed four design strategies to integrate structure, architecture, and fabrication in the design process. These strategies involved factors of structural behavior from the early stages of the design process, which allows for the engineering and generation of intricate geometries. Also, Lachauer, L., & Kotnik, T. (2010) explored integrating structural behavior and architectural form using the "graphic statics" method. They integrate this method into parametric computer-aided design programs to simultaneously consider architectural geometry and structural constraints. They named this "direct approach," which incorporates structural criteria's such as strength and stability with design decisions.

Given that the relationship between structure and form is essential for the feasibility of construction, it is imperative to adopt new approaches that integrate the structure with the skin, including utilizing the contours and folds of the form for support functions. By doing so, the form can also serve as a support structure (Balmond, C., & Jannuzzi Smith. (2002). Similarly, Bagneris et al. (2008) emphasized that establishing a connection among structural systems and form is crucial in the design. For this, he proposed creating self-sustaining skin. He suggested that new methods should be developed to maintain the coupling between form and structure instead of solely relying on self-sustaining skin.

Building Information Modeling (BIM) is the term used to describe the integrated model utilized in digital architectural design. According to architect Pittman, J. (2009), BIM is a comprehensive model that encompasses elements associated with the construction and functioning of a building, apart from its design factors. BIM is a comprehensive system that collects valuable data throughout the entire design, construction, and maintenance processes, allowing for the necessary information to be presented appropriately. This provides that any alterations made to the model by one participant will automatically notify all other participants through program updates. Consequently, all project participants are connected and integrated into the earliest generative stages of the design process. Furthermore, an integrated computational process allows for the simultaneous consideration of form, structure, and material within a single model where all project participants work together within their specific roles using the same software. (Tanyeli, U., 2012).

In conclusion, architects, structural engineers, and designers share a common understanding of 'structure' based on fundamental principles. The purpose of a structural system is to provide support and withstand various external forces while maintaining stability, durability, and cost-effectiveness. Moreover, the hierarchical organization among structural systems, such as primary, secondary, and tertiary structures, further contributes to the overall stability, function, and appearance of a building. As architectural design becomes increasingly complex, as in free-form designs, incorporating scientific and technological advancements into structures poses a significant challenge for architects. Therefore, the following chapter presents the methodology for exploring structural design in free-form architectures.

4.2 Form Analysis

In the realm of architecture, form holds immense significance and complexity as it forms the essence of architectural design and expression. Essentially, it encompasses both the internal arrangement and structural composition of a building, as well as its external appearance and silhouette, evoking a palpable three-dimensional feel. It's important to note that form goes beyond just the floor plan, encompassing the overall impact and impression it leaves on both observers and users of the structure.

The significance of form is further emphasized by its role in shaping the visual impact of buildings. When form is creatively utilized, it possesses the power to inspire awe, evoke emotions, and create a sense of harmony among those who experience the building. The arrangement of volumes, juxtaposition of voids and solids, and interplay of light and shadow all contribute to this architectural expression.

As described by Ching F. D. (2007), form embodies two integral aspects of architectural design. First, it encompasses the intrinsic arrangement, referring to the way elements, spaces, and functions are interwoven within the building. This includes considerations of spatial relationships and the optimal placement of various elements to achieve functionality and usability. Second, form is the outward manifestation of the structure, encompassing its visual aesthetics, style, and overall appearance. It is this external aspect of form that communicates with the surrounding environment and engages with the sensory perceptions of individuals. The interplay

of architectural elements such as facades, roofs, windows, and ornamentation define the external form and its connection to the built environment.

In the context of this study, form is defined as "the shape or appearance of something," as per the definition provided by the Cambridge Dictionary (n.d). This all-encompassing definition reinforces the idea that form is not limited to a singular dimension but embraces both the internal spatial arrangement and the external aesthetics. By considering form in this holistic manner, architects can achieve a cohesive and compelling architectural expression that resonates with the users and the broader community.

Following this, the second part in the analysis table, form analysis, is explained.

4.2.1 Visual Properties

The first aspect, visual properties, refers to form reasoning that prioritizes the design's visual appearance and overall aesthetic appeal. This involves considering various design elements such as shape, size, proportion, texture, color, and materials to create a visually pleasing and harmonious building. The primary goal is to design a building that not only fulfills its practical needs for users but also enriches the built environment and offers a sense of visual satisfaction to those who encounter it. Visual properties are given high importance in this process, emphasizing the significance of creating an aesthetically appealing building that enhances its surroundings.

4.2.2 Standardization in Construction

The second aspect, standardization in construction, is marked when the building has a rationalization process, which translates a complex and non-repetitive design into manageable parts that can be efficiently constructed. This process involves breaking down the complex geometry into smaller components using standard construction techniques and materials while still preserving the essential qualities of the building, such as its form, aesthetics, and functionality. Due to the unique shapes and structures of free-form buildings, rationalization is essential for their successful construction. These structures can pose significant challenges in terms of time, effort,

cost and waste during initial design, manufacturing, and construction phases. Wallner, J., & Pottmann, H. (2011) highlights that free-form geometries often require unique structural solutions resulting in custom systems that match the design, which can increase expenses and waste. When dealing with a singular project involving non-repetitive and arbitrary curved forms, these challenges increase. And this emphasizes the importance of rationalization in effectively achieving the construction of free-form buildings.

4.2.3 Sustainability

The third aspect, sustainability, comes into play when a building integrates considerations that prioritize performance, aiming to minimize negative environmental impacts and enhance energy efficiency in the constructed environment. However, it is essential to understand that sustainability do not always address issues present in pre-existing design proposals. Here, the main objective is to utilize a reasoning process grounded in performative strategies. Moreover, the current emphasis on building performance as a design approach in response to sustainability is part of a comprehensive framework that encompasses technical factors, as well as financial, spatial, social, and cultural factors.

4.3 Space Analysis

The fourth part in the analysis table, space analysis, includes an examination of the spatial relationships of the buildings. For the space analysis, this thesis adopts the methodology in Yilmaz S.'s (2019) work which the focus is on the relationship between the interior spaces and the building skin; however, this study focuses on structural systems influences on form and space integrity. In other words, here the space analysis part provides data on how the spatial configurations get affected by structural system decisions or how the integrity among space and form changes.

Yilmaz (2019) draws upon the insights of Ching F. (2007) to some extent, where Ching asserted that the enclosure and form of individual spaces within a building can both have an impact on and be influenced by the surrounding spaces. Ching defined three categories of spatial forms, represented diagrammatically based on the plan

drawings of Alvar Aalto's Theater in Seinäjoki (Figure 29). In the first category, there are spaces with similar functions that require specific formal articulation. These spaces can be organized into linear, singular, and clustered forms, offering flexibility through their organization. The second category includes spaces with distinct technical and functional requirements, like auditoriums. They directly influence the forms of the surrounding spaces. Moreover, the third category includes adaptable spaces such as foyers, which have the ability to adjust to their surroundings. The forms of these spaces can be freely shaped by the building envelope or adjacent spaces, allowing for flexibility in their design.

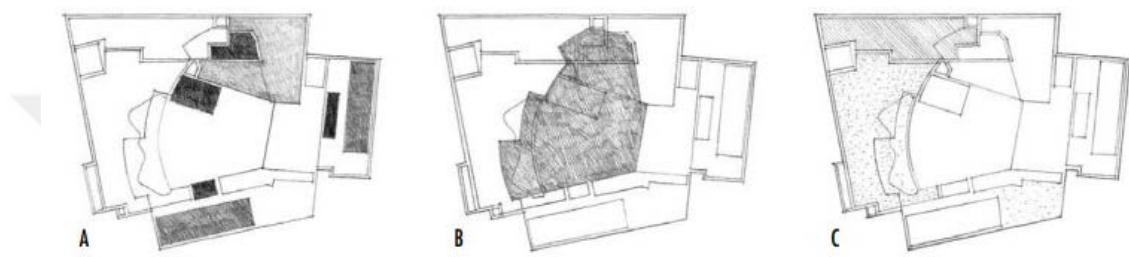


Figure 29. Illustrations of Ching explaining the types of spatial forms.(Ching, F. (2007). *Architecture: Form, space, and order*. John Wiley & Sons., (p.101))

In this study, space analysis is conducted using architectural drawings. Unwin (2014) highlights the significance of architectural drawings in expressing ideas and explains this as plans and sections clearly manifest spatial ideas. In relation to this, the analysis comprises two groups of categories: those derived from horizontal spatial organization and those derived from vertical spatial organization. However, it is important to note that the definitions of these categories are not rigid since they coexist within the building (Yılmaz, S., 2019). Following, Figure 30 illustrates these categories along with the corresponding color code utilized in the drawing examinations.

Categories obtained from horizontal spatial organization

	Clustered Spaces
	Form-defining spaces
	Flexible spaces

Categories obtained from vertical spatial organization

	Set-back spaces
	Conjoint spaces
	Solo spaces
	Attic spaces

Figure 30. Two groups of categories in the spatial analysis

4.3.1 Horizontal Spatial Organization

First, the plan drawings are analyzed according to the categories obtained from horizontal spatial organization: clustered, form defining, and flexible spaces (Ching, F., 2007). Clustered spaces include spaces arranged as clusters and may function flexibly when combined. They are usually compact spaces with distinct yet comparable purposes, like office modules, and they can be arranged into clusters. Form-defining spaces include spaces with special functional and technological needs influencing the building's form. These are spaces that require precise technical and functional requirements, and they determine spatial forms, like conference rooms, auditoriums, and theaters. Also, they can directly influence the design of adjacent areas, and in certain situations, they can even influence the overall appearance of the building envelope. Flexible spaces include naturally flexible spaces, and they can be determined by the expression of the building envelope. These spaces are characterized by their flexibility, which allows them to be defined by neighboring spaces or groups of spaces (Yilmaz S., 2019). Moreover, Yilmaz S. (2019) mentioned that these spaces share some similarities with Venturi's (1992) concept of residual space, meaning they can function as leftover areas between the building envelope and the spaces that give shape to the building.

4.3.2 Vertical Spatial Organization

Second, the section drawings are analyzed according to the categories obtained from vertical spatial organization: set-back, conjoint, solo, attic. Set-back spaces create spatial or visual continuity by distancing themselves from the building envelope, allowing for a wider perspective of the exterior. The design of these spaces is directly influenced by the form and structure of the envelope, determining their overall appearance. Conjoint spaces refer to spaces that are situated on distinct levels, entirely isolated from one another, and adjacent to the building envelope. The form dictates the appearance of the small segment of these spaces that are visible. Solo spaces refer to singular spaces that totally interact with most of the building envelope. This can lead to either the building envelopes form being directly influenced by the solo spaces, or the form of them being determined by the form of the envelope. Attic spaces refer to areas situated at the upmost levels of a building that have a significant connection with the building's envelope. These spaces form is primarily determined by the envelopes form (Yilmaz S., 2019).

4.4 General Assessment

The analysis tables included a part named general assessment which contains general expositions of the table. In this part, the information that is gathered from all of the categories are organized. A scoring system has been made for each case, a numbers are used to evaluate and compare different conditions among the buildings. This section has detailed explanations on how this assessment was conducted (see Figure 31).

GENERAL ASSESMENT		
Structure and Form Relation	1	Secondary structure(s) generates the form.
	2	Primary structure(s) generates the form.
Form Reasoning Process	1	One Topic
	2	Two Topics
	3	Three Topics
Structural Systems in Design Process	1	Linear Design Process
	2	Structure-Based Design Process
	3	Integrated Design Process
Space and Form Compatibility	1	Spatial configurations are not compatible with the form.
	2	Spatial configurations are partially compatible with the form.
	3	Spatial configurations are compatible with the form.

Figure 31. General Assessment Part In The Analysis Table

The first aspect of the general assessment part is the "Structure and Form Relation". It is based on hierarchical categorizations of structural systems, as it is explained in section 4.1, namely primary and secondary structures. This categorization divides structural elements according to their function and importance in supporting the overall load of a building. The primary structure comprises load-bearing components that provide stability, transfer the building's weight to the foundation, and resist external forces. On the other hand, the secondary structure supports the primary elements and evenly distributes the load throughout the building to enhance structural integrity. In this study, it is argued that if a building's form is generated primarily by the primary structural system, the relationship between structure and form will be stronger. This condition is assigned a higher score of two. Conversely, if a building's form is predominantly influenced by the secondary structural systems, the relationship between structure and form will be weaker, as the structural systems share roles. This condition is assigned a lower score of one.

The second aspect is the "Form Reasoning Process" which there are three sub-categories that are: visual properties, standardization in construction, and sustainability. These categories are further mentioned under section 4.2. Each building can address multiple categories and briefly, a building with form reasoning process that addresses multiple categories receives a higher score.

The third aspect is the "Structural Systems in Design Process" consist of linear design process, structure-based design process and integrated design process. These are further explained under section 4.1.2. An integrated design process involves the simultaneous development of form and structure through architectural and structural design during the design process. Thus, if a building had an integrated design process, it receives a higher score. Moreover, a linear design process follows a particular sequence where the form is created first, followed by the design of the structural system based on the form's geometric limitations, and lastly, material choices are made. The structural design cannot alter the form during these processes through analyses or optimizations. Consequently, if a building had a linear design process, it receives the lowest score. Lastly, the structure-based design process involves accepting the most structurally sensible configuration of elements and the architecture adapting accordingly. So, if a building had a structure-based design process, it would receive the mid-score.

The fourth aspect is the "Space and Form Compatibility" which is based on a visual examination that is regarding to the plan and section drawings of each case. These are related to the space analysis part and detailed explanations on this topic are mentioned in section 4.3.

Briefly, the general analysis sections of the tables are responsible for examining and rating various scenarios. Despite the diverse parameters associated with structure, form, and space relationships, the scoring system provides data for the comparisons regarding the integration of structural systems, form, and spaces within the buildings. Furthermore, the cases are analyzed using a timeline, which allows for observing changes over the years.

The utilization of a timeline not only helps track the development of architectural designs but also enables a retrospective assessment of how design choices have influenced a building's performance and functionality throughout its lifespan. This historical perspective aids architects and urban planners in refining their future designs and understanding the lasting impact of their work. Additionally, by considering the evolution of different architectural features, it becomes possible to identify patterns and trends that could further improve the design and construction processes in the future.

CHAPTER 5

CASE STUDIES

This chapter focuses on the examination of seventeen pioneering free-form buildings, utilizing an analysis table that was constructed and explained in Chapter 4. Each case study begins with an overview of general information, followed by an explanatory and descriptive paragraph on their structure-form and structure-space relationships.

As outlined in Chapter 2, the emergence of free-form architectures dates to the late 19th and early 20th centuries, when designers experimented with new forms and shapes that departed from traditional geometries. After the 1960s, free-form architecture became increasingly popular, as architects began to explore new technologies and materials that enabled them to create more complex and innovative forms. The computer-aided design (CAD) software and digital fabrication techniques has further accelerated the growth of free-form architecture in contemporary era, enabling architects to create structures that challenge the limitations of construction techniques and materials, push the boundaries of what is considered structurally efficient.

To analyze the results of the significant change in architectural language mentioned in the previous paragraph, this study focuses on seventeen cases of free-form buildings that were realized in the time period between 1959 and 2019. Each case presents a distinct example of free-form architecture, highlighting the diverse range of approaches, materials, and construction techniques employed in their realization. They are selected according to the following criteria:

First, the buildings are required to be realized projects that contain data throughout their design and realization processes. This criterion ensured that the study would have access to comprehensive information on the buildings' design and construction process and provide for the thorough analysis of their structural, formal, and spatial configurations.

Second, the buildings' international reputation was a critical factor. This means that they are among the pioneering examples which have innovative structural systems, form generation processes or other critical design features. This criterion ensured that the study focused on buildings that have had a considerable impact on the field of free-form building design and construction, and that have attracted attention from architects, engineers, and the wider public due to their technical, aesthetic, or social value.

Moreover, case selection is not constrained by a specific building program, scale, or location. For this, to ensure objectivity, the same case selections remained consistent throughout the analysis. In other words, new building selections were not influenced by the structural systems or other parameters of the buildings. As a result, the hypothesis of the study, which states that "Having an integrated design process for a free-form building provides a stronger integrity of form and space," was objectively examined using the chosen case buildings.

The full list of the cases:

- | | |
|---|---|
| 1) Solomon R. Guggenheim Museum, 1959, Frank Lloyd Wright | 2) Cristo Obrero Church, 1960, Eladio Dieste |
| 3) TWA Flight Center, 1962, Eero Saarinen and Assoc. | 4) Sydney Opera House, 1973, Jørn Utzon |
| 5) Guggenheim Museum Bilbao, 1997, Frank O. Gehry | 6) Selfridges Building, 2003, Future Systems Studio |
| 7) Kuntshaus Graz, 2003, CRAB Studio | 8) Sage Gateshead, 2004, Foster+ Partners. |
| 9) Seattle Central Library, 2004, OMA+ LMN | 10) Denver Art Museum - The Frederic C. Hamilton Building, 2006, Studio Libeskind |
| 11) Mercedes Benz Museum, 2006, UN Studio | 12) Beijing National Aquatics Center (Water cube), 2007, PTW Architects, Ove Arup |
| 13) Beijing National Stadium (Birds Nest), 2008, Herzog & de Meuron | 14) Centre Pompidou-Metz, 2010, Shigeru Ban Architects |
| 15) Heydar Aliyev Cultural Center, 2013, Zaha Hadid Architects | 16) Phoenix International Media Center, 2014, BIAD UoF |
| 17) National Museum of Qatar, 2019, Ateliers Jean Nouvel | |

5.1 Solomon R. Guggenheim Museum, 1959, Frank Lloyd Wright

The architect, Frank Lloyd Wright envisioned the Solomon R. Guggenheim Museum (see Table 5.1) as an inverted ziggurat, drawing inspiration from ancient Mesopotamian architecture. The buildings' structure lies between sculpture and

architecture, leading engineers to find solutions that integrated structure, form, and space.

Briefly, the central concrete ramp, supported by curved columns, acts as the main structural element with web walls serving as shear walls. The cantilevered galleries are supported by radial steel beams anchored to the outer circular wall. Moreover, the dome is supported by ribs connected to web walls. On the other hand, the construction of the building posed a challenge because the building lacked right angles or parallel surfaces. Consequently, the project had an integrated design process which was created by a physical model to provide a precise and easily understandable representation of the building's design to all stakeholders involved. Structural system decisions evolved simultaneously with the formal and spatial configurations.

When the structure-form relationship is analyzed, it is important to state that the building's design was guided by the principle of "form follows function." The museum's form stands out with its iconic spiral shape, deviating from the conventional rectangular or linear designs commonly seen in museums. At the same time, the structure of the building supports and reinforces this distinctive form. The primary structural element is the central concrete ramp, which features a double-curved surface and follows the spiral path. Moreover, the curved concrete columns that support the ramp not only provide structural stability but also enhance the overall sculptural quality of the form.

In terms of the structure-space relationship, there is an intricate and close association among them because structure, form and space are all united. Despite the challenges of achieving integration between form and function, the design offers a distinct spatial experience. The cantilevered galleries contribute to an intriguing visual composition, highlighting the interplay between light, space, and structure. The central concrete ramp, with its double-curved surface and spiral path, serves both as a circulation route and a guiding element for the visitors to get through the museum in a continuous path. As visitors ascend the ramp, they are led through a seamless sequence of interconnected exhibition spaces. The spatial layout is mainly composed of flexible spaces which are in direct visual and spatial relation, and they are solo spaces, through the central atrium. The open and free-flowing spaces, characterized

by curvilinear walls and ramps, create a dynamic and immersive journey through the museum's collection.

Table 5.1 Assessment of Solomon R. Guggenheim Museum

NAME, Year				SOLOMON R. GUGGENHEIM MUSEUM, 1959		GENERAL INFORMATION & GRAPHICS	
Architecture		Frank Lloyd Wright				EXTERIOR IMAGE (1)	
Structural Eng.		Euclid Construction Company				INTERIOR IMAGE (2)	
Program		Museum					
GFA		4,740 m ²					
FORM ANALYSIS							
FORM REASONING PROCESS	VISUAL PROPERTIES		The concept of "form follows function" served as the initial inspiration for the design. Wright referred to the shape as an "inverted ziggurat," drawing a comparison to the stepped pyramids of ancient Mesopotamia in the eastern Mediterranean. While the interior space of the building is large and the building itself is impressive, it did not achieve complete success in usage. (6)				 
	STANDARDIZATION IN CONSTRUCTION		Gaussian analysis is conducted during the design of the museum. However, the building is at the border line between sculpture and art since the form does not comply with the structural requirements. This is the reason why engineers had to seek solutions that didn't rely on a connection between the form and structural elements.(6)				
	SUSTAINABILITY						
STRUCTURAL ANALYSIS (F: Form Generation, S: Space Generation)							
			F	S			
STRUCTURAL SYSTEM	FORM ACTIVE	CABLED		Section Active - Frame : The cantilevered galleries that surround the central ramp are supported by a series of radial steel beams that extend from the central ramp and they are anchored to the outer circular wall of the building. The beams and galleries work together to distribute loads throughout the building and create a continuous and smooth transition of loads. Furthermore, the dome is supported by 12 ribs which transfer into the web walls.			
		TENT/ MEMBRANE					
		PNEUMATICS					
		ARCH					
	VECTOR ACTIVE	2D TRUSS		Surface Active - Load Bearing Wall: The main structural element is the central concrete ramp, is a double-curved surface that is supported with a series of curved concrete columns that follow the same spiral path, creating a continuous surface. The spiral ramp consists of interconnected walls that serve as shear walls, effectively distributing forces both horizontally and vertically, thereby assisting in resisting bending moments.			
		3D TRUSS / SPACE FRAME					
		GEODESIC DOME					
	SECTION ACTIVE	BEAM GRID					
		FRAME					
	SURFACE ACTIVE	SLAB SYSTEM					
LOAD - BEARING WALL							
FOLDED PLATE							
STRUCTURE IN THE DESIGN PROCESS	SHELL / GRID SHELL						
	INTEGRATED DESIGN PROCESS						
	STRUCTURE-BASED DESIGN PROCESS						
LINEAR DESIGN PROCESS							
GENERAL ASSESMENT							
Structure and Form Relation			Secondary structure(s) generates the form.				
			2 Primary structure(s) generates the form.				
Form Reasoning Process			One Topic				
			2 Two Topics				
			Three Topics				
Structural Systems in Design Process			Linear Design Process				
			Structure-Based Design Process				
			3 Integrated Design Process				
Space and Form Compatibility			Spatial configurations are not compatible with the form.				
			Spatial configurations are partially compatible with the form.				
			3 Spatial configurations are compatible with the form.				
REFERENCES: (1) https://www.archdaily.com/tag/guggenheim-museum , (2,3,4,5) https://www.guggenheim.org/ , (6) Bagneris, M., Motro, R., Maurin, B., & Pauli, N. (2008). Structural morphology issues in conceptual design of double curved systems. International Journal of Space Structures, 23(2), 79-87.							

5.2 Cristo Obrero Church, 1960, Eladio Dieste

The architect, Eladio Dieste approached the design of Cristo Obrero Church (see Table 5.2) by considering structure, geometry, and material as interconnected elements, aiming to achieve a synthesis of form. By utilizing the flexibility of the surface, Dieste employed material logic to combine structural efficiency to other design parameters.

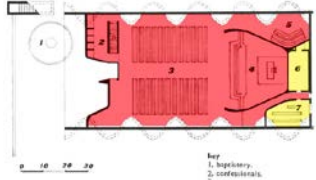
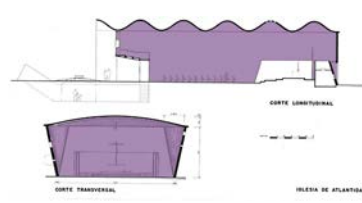
In the rectangular hall, the walls and roof exhibit undulating forms created by reinforced brick Gaussian vaults. These double-curved vaults efficiently withstand deflection using a minimal amount of material. To enhance stability, the vertical surfaces are curved, reducing the overall profile height. Furthermore, the ceramic masonry system, utilizes thin brick shells reinforced with steel bars and concrete, resists both tensile and compressive stresses. Throughout the integrated design process, close collaboration between the architect and the individuals involved in the structural design was maintained.

As it is observed, the building has a strong relationship between structure-form. Dieste used reinforced brick vaults and thin shells to create the distinctive forms, highlighting the structural capabilities of the material. The form emerges as a direct consequence of the structural decisions, resulting in a harmonious integration between the two. The shells are designed to curve and intersect, creating a series of vaulted spaces that define the form of the church. The form emerges directly from the structural logic, as the shape of the brick shells determines the overall appearance of the building. The structural elements of the church not only provide support and stability but also give rise to the unique and sculptural form.

On the other hand, there is an intricate and close association among structure-space because structure, form and space are all united. The reason for this is that the reinforced brick vaults and thin shells create an expansive solo space that is defined by their unique curvilinear shapes. The combination of vaulted ceilings and curved walls are freely organized even though the program has specific requirements since it is a church. The structural elements also contribute to the distribution of natural light and add on to the spiritual atmosphere of the church. Through the skylights and

clerestory windows along the curved surfaces of the vaults, daylight is allowed. This interplay of light and shadow adds depth and atmosphere to the spatial experience.

Table 5.2 Assessment of Cristo Obrero Church

NAME, YEAR		CRISTO OBRERO CHURCH, 1960		GENERAL INFORMATION & GRAPHICS					
Architecture		Eladio Dieste		EXTERIOR IMAGE (1)	INTERIOR IMAGE (2)				
Structural Eng.		Eladio Dieste							
Program		Church							
GFA		550 m ²							
FORM ANALYSIS									
FORM REASONING PROCESS	VISUAL PROPERTIES		To the architect, Dieste, the structure, geometry, and material were all integral parts of a connected entity, viewing form as a matter of synthesis. The utilization of reinforced bricks enables the structure and form to function cohesively, resulting in an aesthetically pleasing outcome with optimal efficiency. (5)						
	STANDARDIZATION IN CONSTRUCTION		By harnessing the flexibility of the surface, the architect employed the principles of material logic to articulate the structural performance, geometry, and form. The design exemplifies a commitment to maximizing resource utilization and promoting sustainability.						
	SUSTAINABILITY								
STRUCTURAL ANALYSIS (F: Form Generation, S: Space Generation)									
		F	S						
STRUCTURAL SYSTEM	FORM ACTIVE	CABLED		Surface Active - Shell/Grid Shell: The rectangular hall features undulating walls and a similarly undulating roof composed of reinforced brick Gaussian vaults. The roof's double-curved vaults efficiently resist deflection with a minimal amount of material. The vertical surfaces are curved to reduce profile height and increase rigidity. The ceramic masonry system uses thin brick shells reinforced with steel bars and concrete to resist tensile and compressive stresses.(5)					
		TENT/ MEMBRANE							
		PNEUMATICS							
		ARCH							
	VECTOR ACTIVE	2D TRUSS							
		3D TRUSS / SPACE FRAME							
		GEODESIC DOME							
	SECTION ACTIVE	BEAM GRID							
		FRAME							
		SLAB SYSTEM							
	SURFACE ACTIVE	LOAD - BEARING WALL							
		FOLDED PLATE							
		SHELL / GRID SHELL							
STRUCTURE IN THE DESIGN PROCESS	INTEGRATED DESIGN PROCESS		The people who worked with Dieste during the structural design and overall concept of the architectural ensemble were in close collaboration during the design process.						
	STRUCTURE-BASED DESIGN PROCESS								
	LINEAR DESIGN PROCESS								
SPACE ANALYSIS									
		PLANS(S)							
		 Key: 1. baptistry, 2. confessional, 3. nave, 4. chapel, 5. altar, 6. sacristy, 7. sacristy, 8. bell-tower. Horizontal spatial organisation - Clustered spaces - Form-defining spaces - Flexible spaces							
		SECTION(S)							
		 CORTE LONGITUDINAL CORTE TRANSVERSAL ISLETA DE ATILANZA Vertical spatial organisation - Set-back spaces - Congruent spaces - Solo spaces - Artic spaces							
GENERAL ASSESMENT									
Structure and Form Relation			Secondary structure(s) generates the form.						
		2	Primary structure(s) generates the form.						
Form Reasoning Process			One Topic						
		2	Two Topics						
			Three Topics						
Structural Systems in Design Process			Linear Design Process						
			Structure-Based Design Process						
		3	Integrated Design Process						
Space and Form Compatibility			Spatial configurations are not compatible with the form.						
			Spatial configurations are partially compatible with the form.						
		3	Spatial configurations are compatible with the form.						
REFERENCES: (1,2,3) https://www.getty.edu/news/the-revolutionary-brick-church-that-changed-a-village/ , (4) Archivo Dieste & Montañez, c. January 1959, (5) Silva-Contreras, M. (2018). New experiences with reinforced tile for Eladio Dieste when building the Cristo Obrero Church. In Building Knowledge, Constructing Histories (pp. 1203-1210). CRC Press.									

5.3 TWA Flight Center, 1962, Eero Saarinen and Assoc.

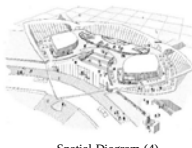
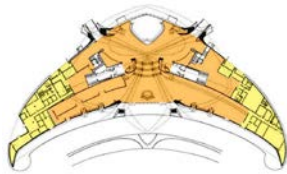
The design concept of TWA Flight Center (see Table 5.3) was developed based on a family of forms, so that all the all the spaces, design elements, and curvatures follow a consistent character. The building is an example of expressionistic approach which the aim was to develop a monumental public structure.

The concrete exterior is reinforced by a concealed steel network which provides support for the roof. The primary supports for the roof are Y-shaped columns which are flexible and work in conjunction with additional beams to support the four sections of the roof. The building had a linear design process which the structural decisions were forced to follow the necessities to approach the particular formal expression. The designers overlooked structural principles and adopted a sequential design approach where the roof form was determined primarily by visual factors rather than structural design factors. This approach led to challenges in the structural implementation, which were addressed by adjusting the design to reinforce the shell in areas experiencing the highest internal forces. Consequently, the structure exhibited inefficiencies, but construction was feasible due to the relatively small spans involved.

When the structure-form relationship is analyzed, it is observed that the structure and form are united due to their approach to concrete material. The roof form evolved as models were created at different scales to test its ability to adjust to the necessary support elements. Briefly, the curved concrete ribs and columns provide the necessary structural support while also contributing to the sculptural form of the terminal.

Furthermore, the relationship between structure and space is carefully organized and the building exemplifies the notion of form following function, as the structural choices directly influence the spatial qualities and user experience. The structural elements play a crucial role in defining the spatial qualities of the terminal. Thanks to this, long spans for expansive interior spaces with minimal obstructions were possible. The curvilinear forms of the structural elements, such as the ribs and columns, contribute to the fluidity of the space, blurring the boundaries between structure and enclosure.

Table 5.3 Assessment of TWA Flight Center

NAME, YEAR		TWA FLIGHT CENTER, 1962		GENERAL INFORMATION & GRAPHICS				
Architecture		Eero Saarinen and Associates		EXTERIOR IMAGE (1)	INTERIOR IMAGE (2)			
Structural Eng.		Ove Arup & Partners						
Program		Terminal						
GFA		5.100 m ²						
FORM ANALYSIS								
FORM REASONING PROCESS	VISUAL PROPERTIES		The design concept permeated every aspect of the building, incorporating a cohesive "family of forms" that gave a consistent character to all the curvatures, spaces, and elements. It is an example of expressionistic style which the aim was to achieve monumentalism though this public structure. (5)					
	STANDARDIZATION IN CONSTRUCTION		The overall form was relying on materialistic and structural aspects. As the design for the TWA Terminal's roof evolved, models were created at different scales to test its ability to adjust to the necessary support elements.					
	SUSTAINABILITY							
STRUCTURAL ANALYSIS (F: Form Generation, S: Space Generation)								
			F	S				
STRUCTURAL SYSTEM	FORM ACTIVE	CABLED			Section Active - Slab: The concrete exterior is reinforced by a concealed steel network, resembling an "invisible steel hammock," that provides support for the roof. The primary support for the roof comes from a Y-shaped column that is flexible and works in conjunction with additional beams to support the four sections of the roof.(6)			
		TENT/ MEMBRANE						
		PNEUMATICS						
		ARCH						
	VECTOR ACTIVE	2D TRUSS				 Spatial Diagram (4)		
		3D TRUSS / SPACE FRAME						
		GEODESIC DOME						
	SECTION ACTIVE	BEAM GRID					 Construction Photos, Y-shaped Column (3)	
		FRAME						
		SLAB						
	SURFACE ACTIVE	LOAD - BEARING WALL						 Main Floor Plan
		FOLDED PLATE						
		SHELL / GRID SHELL						
STRUCTURE IN THE DESIGN PROCESS	INTEGRATED DESIGN PROCESS		The designers disregarded structural logic, with the roof's form being determined based on visual rather than structural considerations. As a result, structural difficulties arose but were resolved by changing the design to reinforce the shell at the locations with the highest internal forces. As a result, the structure lacked efficiency, although construction was feasible owing to the relatively small spans. (7)					
	STRUCTURE-BASED DESIGN PROCESS							
	LINEAR DESIGN PROCESS							
GENERAL ASSESMENT								
Structure and Form Relation			Secondary structure(s) generates the form.					
			2 Primary structure(s) generates the form.					
Form Reasoning Process			One Topic					
			2 Two Topics					
			Three Topics					
Structural Systems in Design Process			1 Linear Design Process					
			Structure-Based Design Process					
			Integrated Design Process					
Space and Form Compatibility			Spatial configurations are not compatible with the form.					
			Spatial configurations are partially compatible with the form.					
			3 Spatial configurations are compatible with the form.					
REFERENCES: (1,2,3,4) https://www.atlasofplaces.com/architecture/twa-flight-center/ , (5) Landmarks Preservation Commission. (1994, July 19). Trans World Airlines Flight Center at New York International Airport (Designation List 259, LP-1916)., (6) https://en.wikiarquitectura.com/building/twa-terminal-at-jfk-airport/ , (7) Macdonald, A. J. (2001). Structure and architecture. Oxford, UK: Architectural Press.								

Additionally, the structural configuration influences the distribution and organization of spaces within the terminal. The placement of columns and the arrangement of load-bearing elements impact the layout and flow of the interior. They are positioned to create clear sightlines, promote intuitive circulation paths, and define functional zones. The clustered spaces are located at the corners while the building mainly housing flexible spaces that are arranged as setbacks.

5.4 Sydney Opera House, 1973, Jørn Utzon

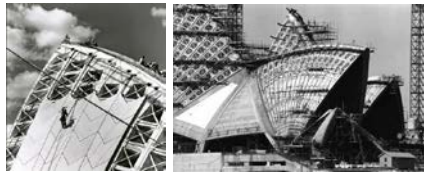
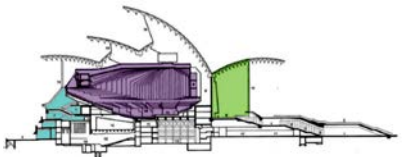
The Sydney Opera House (see Table 5.4) is an important building of the late 20th century, and it became a remarkable global structure due to its pioneering design approach, which underlies its striking appearance. In terms of innovation, the concept of was unique however the construction period was fraught with conflicts and excessive costs. Baldassini et al. (2010) highlighted the importance and complexities of the building and noted that it was a starting point for the popularity of free-form architectures in contemporary era. They further emphasized the challenges involved in reconciling architectural expression with structural and technological limitations. These challenges encountered during rationalization and construction serve as indicators of the future issues associated with constructing free-form architecture.

While commonly referred to as "shells," the roof structure is not strictly shells in a structural sense. Instead, it consists of precast concrete panels which are supported by precast concrete ribs. This approach allowed the achievement of the original design's integrity, with self-supporting shell roofs that did not require additional reinforcements. The podium is made entirely of reinforced concrete and incorporates load-bearing walls. It adopts a cellular structure rather than a framed one. The reinforced concrete columns are used to support the concrete shells and can be easily observed. Although the building was one of the pioneers in employing computers during its construction, it followed a linear design process.

When we analyze the structure-form relation, the design aimed to create a visually striking and iconic architectural form. The "shells" that compose the roof structure are the defining feature of the building's form. Initially, the form of the shells was not mathematically defined, but through the translation of Utzon's drawings by the engineering team, a series of vaults formed by parabolas were realized. This translation process involved the use of precise mathematical descriptions and computer-generated calculations to determine the structural form of the shells. The form is the result of a balance between aesthetic factors and structural requirements.

Table 5.4 Assessment of Sydney Opera House

NAME, YEAR		SYDNEY OPERA HOUSE, 1973		GENERAL INFORMATION & GRAPHICS	
Architecture		Jørn Utzon		EXTERIOR IMAGE (1)	
Structural Eng		Ove Arup & Partners		INTERIOR IMAGE (2)	
Program		Opera House			
GFA		45,000 m ² (approx.)			
FORM ANALYSIS					
FORM REASONING PROCESS	VISUAL PROPERTIES		The objective was to derive inspiration from nature for both the form and structure, ultimately creating a grand urban sculpture. Initially, the "shells" lacked geometric definition; however, the engineering team interpreted the architects' drawings and transformed them into a sequence of vaults composed of parabolic forms. (5)		
	STANDARDIZATION IN CONSTRUCTION		The examination required an exact mathematical representation of the shape of the shells, generated by a computer, to conduct more accurate calculations related to forces, deflections, bending moments, and stresses. The construction of this building marked an early instance of incorporating computer technology into the construction process, making it pioneering in its use of computers.(5)		
	SUSTAINABILITY				
STRUCTURAL ANALYSIS (F: Form Generation, S: Space Generation)					
			F	S	
STRUCTURAL SYSTEM	FORM ACTIVE	CABLED			Section Active - Frame: The roof design is commonly known as "shells," but they do not function as traditional structural shells. Instead, they are precast concrete panels that are supported by precast concrete ribs. This innovative approach allowed for the preservation of the original design concept of self-supporting shell roofs, without the need for additional reinforcements.(5)
		TENT/ MEMBRANE			
		PNEUMATICS			
		ARCH			
	VECTOR ACTIVE	2D TRUSS			Surface Active - Load Bearing Wall: The entire Podium is built using reinforced concrete, which was composed of load-bearing walls instead of columns. The construction follows a cellular approach rather than a framed structure. Additionally, reinforced concrete columns are primarily utilized to carry the shells or the lower stage structure. Also, they are visually distinct from the Podium structure.(5)
		3D TRUSS / SPACE FRAME			
		GEODESIC DOME			
	SECTION ACTIVE	BEAM GRID			
		FRAME			
	SURFACE ACTIVE	SLAB SYSTEM			
LOAD - BEARING WALL					
FOLDED PLATE					
STRUCTURE IN THE DESIGN PROCESS	SHELL / GRID SHELL				
	INTEGRATED DESIGN PROCESS		Utzon's design concepts had developed over the years since his departure from the project, while technology had advanced rapidly. For this reason, even though the design team had altered solutions for the structural design and manufacturing, the initial design of the architect had a form-oriented design process.(6)		
	STRUCTURE-BASED DESIGN PROCESS				
LINEAR DESIGN PROCESS					
GENERAL ASSESMENT					
Structure and Form Relation		Secondary structure(s) generates the form.			
		2 Primary structure(s) generates the form.			
Form Reasoning Process		One Topic			
		2 Two Topics			
		Three Topics			
Structural Systems in Design Process		1 Linear Design Process			
		Structure-Based Design Process			
		Integrated Design Process			
Space and Form Compatibility		1 Spatial configurations are not compatible with the form.			
		Spatial configurations are partially compatible with the form.			
		Spatial configurations are compatible with the form.			
REFERENCES: (1,2,4,5) Croker, A. (2017). Respecting the vision: Sydney Opera House-a conservation management plan. Sydney Opera House, (3) https://en.wikiarquitectura.com/building/sydney-opera-house/ (6) Macdonald, A. J. (2001). Structure and architecture. Oxford, UK: Architectural Press.					

	
Construction Photos(3)	
	
Utzon's spherical model (1962) (4)	
	
Sectional model, 1964 (4)	
SPACE ANALYSIS	
PLAN(S)	
	Ground Floor Plan
Horizontal spatial organisation Yellow Clustered Spaces Orange Form-defining spaces Pink Flexible spaces	
SECTION(S)	
	Longitudinal Section
Vertical spatial organisation Green Set-back spaces Teal Coujozt spaces Purple Solo spaces Pink Attic spaces	

Regarding the structure-space relation, it is observed that the distinct shell-shaped roof structure and the interior spaces are not compatible. The roof structure, with its curved forms and varying heights, exists independently from the spaces. However, the shells' geometry influences the acoustics, lighting, and spatial qualities of the

interior spaces, enhancing the overall experience. Although the building has a free-form structure, it does not have flexible spaces at all. Furthermore, the form-defining spaces do not have connection to the shell-like form.

5.5 Guggenheim Museum Bilbao, 1997, Frank O. Gehry

For the Guggenheim Museum in Bilbao (see Table 5.5), Gehry's intention was to create a visually unified appearance by incorporating twisted and curved shapes that spanned multiple directions. While this design the boundary between sculpture and architecture, it is observed that design team did not initially consider the structural requirements. To transform the design concept into a viable structure, a rationalization process was undertaken. This process involved computer aided design (CAD) technology to generate intricate 3D models of the building's complex curves and shapes. These models were then analyzed and refined to ensure their structural integrity.

The structural system of the building incorporates braced frames, which supported the curved exterior surfaces and enable the construction of the envisioned forms. A contouring method was employed, where wire-frame cross sections of the building form served as a guide for the structural framework. Additionally, the museum features post-tensioned concrete beams spanning the central atrium, forming part of the primary structural system. Steel trusses, serving as the secondary structural system, provide bracing and lateral support while also supporting the roof and floor slabs. The design of the building was achieved through a highly integrated process that fostered close collaboration between architects and engineers. This involved a continuous exchange of ideas and revisions between the design and engineering teams, ensuring that the intricate and artistic forms could be executed in a practical and safe manner. The utilization of computer-aided design (CAD) technology played a crucial role in facilitating this integrated design process.

Table 5.5 Assessment of Guggenheim Museum Bilbao

NAME, YEAR		GUGGENHEIM MUSEUM BILBAO, 1997		GENERAL INFORMATION & GRAPHICS	
Architecture		Frank O. Gehry		EXTERIOR IMAGE (1)	INTERIOR IMAGE (2)
Structural Eng.					
Program		Museum			
GFA		GFA: 24,000 m²(approx.)			
FORM ANALYSIS					
FORM REASONING PROCESS	VISUAL PROPERTIES		Gehry aimed to achieve a sense of unity in the appearance so he utilized shapes that twisted and curved in multiple directions. Although these designs exist on the borderline between sculpture and architecture, they did not consider the structural requirements. As a result, engineers were required to develop solutions that lacked a connection between the form and the structural aspects of the designs.(5)		
	STANDARDIZATION IN CONSTRUCTION		The design concept was transformed into a feasible structure through a rationalization process. This process employed computer-aided design (CAD) technology to generate intricate 3D models of the building's complex curves and shapes, which were subsequently analyzed and perfected to ensure their structural integrity. (6)		
	SUSTAINABILITY				
STRUCTURAL ANALYSIS (F: Form Generation, S: Space Generation)					
			F	S	
STRUCTURAL SYSTEM	FORM ACTIVE	CABLED			Vector Active - 2D Truss: The secondary structural system consists of steel trusses that brace and provide lateral support to the primary structural system. These trusses are also utilized to support the building's roof and floor slabs.(6)
		TENT/ MEMBRANE			
		PNEUMATICS			
		ARCH			
	VECTOR ACTIVE	2D TRUSS			Section Active - Frame: The braced frames in its structural system because they make it possible to construct the designed forms by supporting the curved exterior surfaces. For this, they used a contouring method in which wire-frame cross sections of the building form were used as a guide for the building's structural framework. Also, the building features a series of post-tensioned concrete beams that span the museum's central atrium.(6,7,8)
		3D TRUSS / SPACE FRAME			
		GEODESIC DOME			
	SECTION ACTIVE	BEAM GRID			
		FRAME			
	SURFACE ACTIVE	SLAB SYSTEM			
		LOAD - BEARING WALL			
		FOLDED PLATE			
STRUCTURE IN THE DESIGN PROCESS	INTEGRATED DESIGN PROCESS				 Diagram (4)
	STRUCTURE-BASED DESIGN PROCESS				
	LINEAR DESIGN PROCESS				
GENERAL ASSESMENT					
Structure and Form Relation		Secondary structure(s) generates the form.			
		2 Primary structure(s) generates the form.			
Form Reasoning Process		One Topic			
		2 Two Topics			
		Three Topics			
Structural Systems in Design Process		Linear Design Process			
		Structure-Based Design Process			
		3 Integrated Design Process			
Space and Form Compatibility		Spatial configurations are not compatible with the form.			
		Spatial configurations are partially compatible with the form.			
		3 Spatial configurations are compatible with the form.			
REFERENCES: (1,2) https://www.dezeen.com/2022/05/18/frank-gehry-guggenheim-museum-bilbao-deconstructivism/ (3) https://www.guggenheim-bilbao.eus/en/the-building/the-construction , (4) https://www.dosde.com/museo-guggenheim-bilbao-original-gehry-lujo.html , (5) Bagneris, M., Moto, R., Maurin, B., & Pauli, N. (2008). Structural morphology issues in conceptual design of double curved systems. International Journal of Space Structures, 23(2), 79-87., (6) Zaera-Polo, A. (2006). The Politics of the Envelope. Log, 7, 31-39. (7) Veltkamp, M. (2007). Free Form Structural Design Schemes, Systems & Prototypes of Structures for Irregular Shaped Buildings. Amsterdam: IOS Press., (8) Kolarevic, B. (2009). Digital Production. In B. Kolarevic (Ed.), Architecture in the Digital Age: Design and Manufacturing (pp. 29-54). New York: Taylor & Francis.					

In terms of the structure-form relationship, Gehry aimed to achieve a sense of unity for the expression of the museum. He employed innovative design strategies, utilizing shapes that twisted and curved in multiple directions. These fluid forms give

the building its distinctive and sculptural character. However, during the initial design phase, the structural requirements were not fully considered, resulting in a need for engineers to develop solutions that would connect the complex forms with the structural integrity. Therefore, the building is considered to have an integrated design process. However, it is indicated that formal organization was prioritized before structural design parameters.

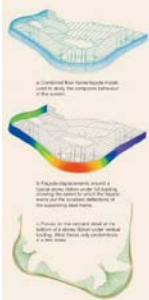
Regarding the structure-space relationship, the building is mostly composed of flexible spaces which function as solo spaces thanks to the free-form structural layout. The dynamic structure defines and shapes the interior spaces. The design includes large, open galleries and atriums that provide flexible exhibition areas, allowing for a dynamic flow of visitors through the museum. The structural elements, such as the curving walls and cantilevered spaces which are also distinguished in form, guide visitors through the museum.

5.6 Selfridges Building, 2003, Future Systems Studio

The objective for the design of the Selfridges Building (see Table 5.6) was to create a remarkable architectural landmark that harmonizes with the surrounding environment. The architects achieved this by developing a unique facade that highlights the building's curves, adds texture, and conveys a sense of scale. Due to the diverse beam lengths and support conditions, the optimization and rationalization process for this project was intricate, involving a complex matrix of requirements. For this, 3D models were analyzed and optimized using performance-based criteria, considering factors such as stability, surface curvature, internal organization, aesthetics, and lighting.

The primary structural system consists of a steel frame that provides support to the facade. Tubular steel columns and beams, connected with welded joints, form the steel frame. This system is designed to offer the necessary stiffness and strength to accommodate the building's intricate geometry. Most of the beams incorporate asymmetric plate girders, which are integrated with the concrete floor slab.

Table 5.6 Assessment of Selfridges Building

NAME, YEAR		SELFRIDGES BUILDING, 2003		GENERAL INFORMATION & GRAPHICS		
Architecture		Future Systems Studio		EXTERIOR IMAGE (1)		
Structural Eng		Ove Arup & Partners		INTERIOR IMAGE (2)		
Program		Commerce				
GFA		25,000 m ²				
FORM ANALYSIS						
FORM REASONING PROCESS	VISUAL PROPERTIES		The aim was to create an architectural landmark and the architects aimed to create a building that would blend in with the surrounding environment. So, they developed a distinctive facade that emphasizes the building's curvature, adds texture,			
	STANDARDIZATION IN CONSTRUCTION		Due to the various beam lengths and support conditions, the process of optimization or rationalization for this project was quite complex, resulting in a large matrix of diverse requirements. As a result, the final designs and selection of beam types were carefully balanced to achieve a combination			
	SUSTAINABILITY		The 3D model was optimized using a performance-based approach that considered various factors such as lighting stability, internal arrangement, surface curvature, and aesthetics. (5)			
STRUCTURAL ANALYSIS (F: Form Generation, S: Space Generation)						
			F	S		
STRUCTURAL SYSTEM	FORM ACTIVE	CABLED			Form Active - Cabled: The facade consists of aluminum discs arranged in a complex, curving pattern. These discs are hung from a series of steel tension cables, which are anchored to the building's steel frame. So, the system designed to support the building's freeform is a sprayed-concrete facade and it divides its surface into storey-height ribbons. (5)	
		TENT/ MEMBRANE				
		PNEUMATICS				
		ARCH				
	VECTOR ACTIVE	2D TRUSS			Section Active - Beam Grid / Frame: The primary structural system is a steel frame that supports the building's facade. The steel frame is composed of tubular steel columns and beams that are connected with welded joints and it is designed to provide the necessary stiffness and strength to support the building's complex geometry. There are asymmetric plate girders of standard depth for most of the beams, which were integrated with the concrete floor slab.(5,6)	
		3D TRUSS / SPACE FRAME				
		GEODESIC DOME				
	SECTION ACTIVE	BEAM GRID				Surface Active - Load Bearing Wall: Series of concrete cores that provide lateral stability to the building are part of the secondary structural systems. These cores are located at each corner of the building and are connected to the steel frame with steel struts, which
		FRAME				
		SLAB SYSTEM				
SURFACE ACTIVE	LOAD - BEARING WALL					
	FOLDED PLATE					
	SHELL / GRID SHELL					
STRUCTURE IN THE DESIGN PROCESS	INTEGRATED DESIGN PROCESS				 Horizontal spatial organisation Yellow Clustered Spaces Red Form-defining spaces Green Flexible spaces Ground Floor Plan	
	STRUCTURE-BASED DESIGN PROCESS					
	LINEAR DESIGN PROCESS					
GENERAL ASSESMENT						
Structure and Form Relation		1	Secondary structure(s) generates the form.			
			Primary structure(s) generates the form.			
Form Reasoning Process			One Topic			
		3	Three Topics			
Structural Systems in Design Process			Linear Design Process			
		3	Integrated Design Process			
Space and Form Compatibility			Spatial configurations are not compatible with the form.			
		2	Spatial configurations are partially compatible with the form.			
			Spatial configurations are compatible with the form.			
REFERENCES: (1,2) https://architectual.com/architecture/selfridges-birmingham , (3,4,5) Clark, E., & Gilpin, D. (2005). Selfridges, birmingham. The Arup Journal, 1, 3-10., (6) https://www.newsteelconstruction.com/wp/award-selfridges-structural-frame-the-bullring-birmingham/						

Furthermore, the facade comprises of aluminum discs arranged in a complex and curving pattern. These discs are suspended from a series of steel tension cables that are anchored to the building's steel frame. The system is designed to support the building's free-form features a sprayed-concrete facade, dividing its surface into story-height ribbons. Moreover, the secondary structural systems include a series of

concrete cores strategically placed at each corner of the building, providing lateral stability. These cores are connected to the steel frame through steel struts, which transfer lateral loads to the cores and offer additional support. Through the design process, various disciplines collaborated to ensure that the building's form, function, and construction were fully optimized for maximum efficiency. This integrated approach aimed to have a unity among structural, mechanical, and aesthetical elements, resulting in a cohesive and visually striking building.

In terms of the structure-form relationship, the form consists of a series of curved and undulating shapes that wrap around the structure, resembling a futuristic metallic exoskeleton. The structural elements of the building, including the steel frame and facade, closely follow and support the complex curvatures and forms. Consequently, the interplay between the building's structure and form becomes evident in the arrangement of aluminum discs, the use of steel tension cables, and the application of a sprayed-concrete facade system. Together, these elements create a harmonious and captivating building facade, simultaneously serving aesthetic and structural purposes.

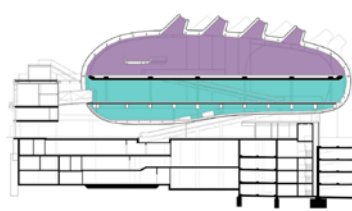
When the structure-space relationship is analyzed, it is observed that the building spaces are composed of flexible spaces by means of the flexible structural system layout. The irregular placement of the beam grid system and the steel frame structure provide the necessary support and stability, allowing for large open spaces, mezzanine levels, and dramatic voids.

5.7 Kuntshaus Graz, 2003, CRAB Studio

The proposed design for the Kunshaus Graz (see Table 5.7) the aim was to create a highly unique and iconic form. However, the designers sought to explore the free-form surface not only as an iconic shape, but also as an innovative "intelligent" skin that can display information and interact with users. The design process involved a close coordination between geometric analysis and structural engineering, and the concept was materialized through computer-generated 3D data sets and computer-driven manufacturing processes. Additionally, they met the client's programmatic requirements while minimizing any compromise to the original design concept. To enhance the building's performance, adjustments were made to its form, particularly by increasing the curvature of the roof in areas where it was deemed necessary.

Table 5.7 Assessment of Kunshaus Graz

NAME, YEAR		KUNSHAUS GRAZ, 2003		GENERAL INFORMATION & GRAPHICS	
Architecture		CRAB Studio		EXTERIOR IMAGE (1)	INTERIOR IMAGE (2)
Structural Eng.		Bollinger and Grohmann			
Program		Art Galleries			
GFA		GFA: 11.100 m ²			
FORM ANALYSIS					
FORM REASONING PROCESS	VISUAL PROPERTIES		The design aimed to have an iconic form. Hence, there was a creative engagement with the cultural and urban surroundings that sets it apart from modern instances of biomorphic architecture. It achieves this by exploring the organic surface not only as an iconic form but also as a novel form of "intelligent" skin, capable of showcasing information and establishing interactive connections with users. (3)		
	STANDARDIZATION IN CONSTRUCTION		The project necessitated close collaboration between architects and engineers, leading to the development of a design office that relied on digital 3D information instead of traditional paper-based methods. This shift towards a "paperless" approach enabled the project's concept to be realized through computer-controlled manufacturing processes.		
	SUSTAINABILITY		Throughout the project, there was a consistent evaluation of new design solutions to meet the client's programmatic needs, adhere to fire and safety regulations, and minimize any compromises to the original design concept.(4) To enhance the structural performance of the building, adjustments were made to its outer surface. Specifically, the curvature of the roof was increased in areas where it was deemed necessary. (5)		
STRUCTURAL ANALYSIS (F: Form Generation, S: Space Generation)					
		F	S		
STRUCTURAL SYSTEM	FORM ACTIVE	CABLED		Section Active - Frame: The hybrid structural system of the building consists a load bearing structure and surface structure. The primary load-bearing structure consists of a post and beam system with two exhibition levels. Also, the building is supported by a structural framework composed of welded steel beams. Between the exhibition spaces there is a conventional piloti and brace beam system which is the foundation for the free-form structure above. The same rigid floor system that resists the thrust from above, acts as a brace linking the columns at the ground floor. (6)	
		TENT/ MEMBRANE			
		PNEUMATICS			
		ARCH			
	VECTOR ACTIVE	2D TRUSS		Surface Active - Shell / Grid Shell: The building's surface functions as a shell that conforms to the complex, irregular form of the building. It's components are steel box girders and square tubes arranged in a specific pattern. The girders are rectangular in shape and serve as the primary frames, positioned in parallel at regular intervals. The square tubes fill the spaces between the girders in a triangulated pattern.(6,7)	
		3D TRUSS / SPACE FRAME			
		GEODESIC DOME			
	SECTION ACTIVE	BEAM GRID			
		FRAME			
	SURFACE ACTIVE	SLAB SYSTEM			
LOAD - BEARING WALL					
FOLDED PLATE					
SHELL / GRID SHELL					
STRUCTURE IN THE DESIGN PROCESS	INTEGRATED DESIGN PROCESS		The project embraced an integrated design process where the architectural and structural design procedures mutually influenced each other. Through an interactive approach, the form and structure were developed, enabling structural optimizations to impact the form. Consequently, the final form was achieved by integrating -optimizations and structural analyses into the architectural design process.(7)		
	STRUCTURE-BASED DESIGN PROCESS				
	LINEAR DESIGN PROCESS				
GENERAL ASSESMENT					
Structure and Form Relation		Secondary structure(s) generates the form.			
		2 Primary structure(s) generates the form.			
Form Reasoning Process		One Topic			
		Two Topics			
		3 Three Topics			
Structural Systems in Design Process		Linear Design Process			
		Structure-Based Design Process			
		3 Integrated Design Process			
Space and Form Compatibility		Spatial configurations are not compatible with the form.			
		2 Spatial configurations are partially compatible with the form.			
		Spatial configurations are compatible with the form.			
REFERENCES: (1,2) https://www.arkitektael.com/kunshaus-graz/ , (3) https://www.yvesjlu.com/teconic-iteration (4) Fournier, C., & Cook, P. (2003). Research outputs 1 and 2: KunsthausGraz. UCL Discovery, 1-59., (5) Chaszar, A. (n.d.). Cooperation of Bernhard Franken with Klaus Bollinger and Manfred Grohmann. B+G Ingenieure Bollinger und Grohmann GmbH. Retrieved from https://www.bollinger-grohmann.com/de/projekte/projekte-bernard-franken/ , (5) Szalapai, P. (2005). Contemporary Architecture and the Digital Design Process. Oxford; Burlington: Architectural Press. (6) Fournier, R., Colin, J., & Cook, P. (2003). Research Outputs 1 and 2: Kunsthaus Graz. UCL Discovery, 1-59. Retrieved April 30, 2013, from https://discovery.ucl.ac.uk/id/eprint/1468274/1/1468274.pdf , (7) Demir, Y. (2013). The assessment of a new relationship between form and structure in digital architectural design after 1990's.					

PLAN(S)	 Third Floor Plan Horizontal spatial organisation Clustered Spaces Form-defining spaces Flexible spaces	SPACE ANALYSIS
SECTION(S)	 Section Vertical spatial organisation Set-back spaces Co-axial spaces Sole spaces Attic spaces	

The building features a hybrid structural system consisting of a surface structure and a load-bearing structure. Furthermore, the load-bearing structure employs a beam and

post system with two exhibition levels, supported by a welded steel beam framework. Below the exhibition spaces, a piloti and brace beam system form the foundation for the structure above. The form acts as a shell, conforming to the complex and irregular form of the building. It is composed of steel box girders and square tubes arranged in a specific pattern, with the girders serving as primary frames positioned parallel to each other and the square tubes filling the spaces between them in a triangulated pattern. The building embraced a collaborative design process, where both the architectural and structural aspects influenced each other.

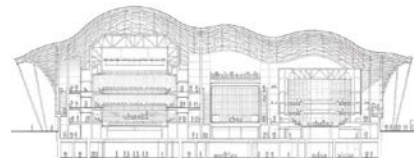
When the structure-form relationship is analyzed, it is observed that they have been developed simultaneously which allowed structural optimizations to make changes in the form during the design process. The final shape of the building was determined by conducting structural analyses and optimizations throughout the design process, ultimately resulting in a cohesive and optimized outcome.

The structure-space relationship references to the curving surface of the envelope which generates a sense of movement and flow throughout the exhibition spaces. Since the spaces are mainly composed of flexible spaces the flexible structural layout was developed accordingly. On the other hand, the form is perceived as a singular whole and the spaces are partially compatible with the form because they do not reflect the floor levels. Thus, the excessive use of flexible spaces allowed the structure to exist without any limits.

5.8 Sage Gateshead, 2004, Foster+ Partners.

The Sage Gateshead (see Table 5.8) building is conceived in a "blob" form, and it embraces the revival of the "blobitecture" style, characterized by its fluid and organic shape, with the purpose of establishing a prominent cultural venue for the region as described by the architects. Throughout the design process, parametric modeling techniques were employed, and it contributed to the standardization of construction elements. Sustainability considerations were also considered during the design phase, as the aerodynamic form harnesses the prevailing winds to provide natural ventilation.

Table 5.8 Assessment of Sage Gateshead

NAME, YEAR		SAGE GATESHEAD, 2004		GENERAL INFORMATION & GRAPHICS	
Architecture		Foster + Partners		EXTERIOR IMAGE (1)	INTERIOR IMAGE (2)
Structural Eng.		Mott MacDonald			
Program		Auditorium			
GFA		20,000 m ²			
FORM ANALYSIS					
FORM REASONING PROCESS	VISUAL PROPERTIES		The entire building is designed in a "blob" form, as the architects describe. It showcases a revival of "blobitecture" style with its free-flowing and organic form and intends to create a landmark cltural venue for the region.(5)		
	STANDARDIZATION IN CONSTRUCTION		During the design process, advanced parametric modeling software was utilized to simplify the intricate toroidal shape of the enclosure, making it possible to repeat and standardize the construction elements.(5)		
	SUSTAINABILITY		The design of the building took environmental considerations into account, aiming to optimize its sustainability. Its aerodynamic shape directs the prevailing local winds, facilitating natural ventilation. The orientation of the building also promotes natural cooling for the spacious concourse. Moreover, the concrete elements of the structure serve as thermal storage, radiating heat to the concourse area.(5)		
STRUCTURAL ANALYSIS (F: Form Generation, S: Space Generation)					
		F	S		
STRUCTURAL SYSTEM	FORM ACTIVE	CABLED		Form Active - Arch: The roof is carried by four steel arches that span 80 meters and they run the length of the building. They are connected to each other at the joints and are located at regular intervals along the sides of the auditorium. The arches are made up of a series of hollow steel tubes, which are connected to each other at the joints. The roof structure and the auditoriums stucture are separated from each other.(6)	
		TENT/ MEMBRANE			
		PNEUMATICS			
		ARCH			
	VECTOR ACTIVE	2D TRUSS		Section Active - Frame: The auditorium's structure is made up of a steel frame with concrete floors which provide a solid base for the structure. The steel frame is designed to support the weight of the building and provide the necessary stiffness and stability to withstand the high winds and vibrations caused by music performances.It is drilled and slotted floor piles of concrete and steel, completing the foundation with concrete spill. (6)	
		3D TRUSS / SPACE FRAME			
		GEODESIC DOME			
	SECTION ACTIVE	BEAM GRID		 Construction Process and	
		FRAME			
	SURFACE ACTIVE	SLAB		Surface Active - Shell / Grid Shell: The secondary steelworks curved sections extend across the arches, resulting in the roof's flowing form. The arched roof of the building has a curved shell design of trapezoidal glass and stainless steel panels. It encloses three independent structures while physically not touching them. The panels on it helps the whole structure to achieve the form while making the building look aesthetically pleasing.	
		PLATE			
		FOLDED PLATE			
SHELL / GRID SHELL					
STRUCTURE IN THE DESIGN PROCESS	INTEGRATED DESIGN PROCESS		The building's form, was developed through a series of sketches and models, with the aim of creating a dynamic and visually striking design. After the form generation, the structural system was designed using a combination of steel and concrete. They used advanced modeling programs to simplify the complicated toroidal shape of the enclosure and refine the construction elements after the determining the form.		
	STRUCTURE-BASED DESIGN PROCESS				
	LINEAR DESIGN PROCES S				
GENERAL ASSESMENT					
Structure and Form Relation			Secondary structure(s) generates the form.		
		2	Primary structure(s) generates the form.		
Form Reasoning Process			One Topic		
			Two Topics		
Structural Systems in Design Process			Three Topics		
		3	Linear Design Process		
			Structure-Based Design Process		
Space and Form Compatibility			Integrated Design Process		
		1	Spatial configurations are not compatible with the form.		
			Spatial configurations are partially compatible with the form.		
			Spatial configurations are compatible with the form.		
REFERENCES: (1,2,3) https://en.wikiaarquitectura.com/building/the-sage-gateshead-auditorium (4,5) https://arquitecturaviva.com/works/centro-de-musica-sage-gateshead-3 (5) https://www.re-thinkingthefuture.com/case-studies/a6553-sage-gateshead-by-foster-and-partners-concert-venue-in-gateshead/ (6) https://www.building.co.uk/focus/architectural-manoeuvres-on-the-tyne/1026048.article					

The roof of the building is supported by four steel arches spanning eighty meters and extending along the entire length of the structure. These arches are interconnected at

the joints and are individually supported by a series of four tubular steel props positioned at regular intervals along the sides of the auditorium. So, the arches form an independent roof structure distinct from the auditorium's framework. The auditorium itself is constructed using a steel frame and concrete floors, providing a stable foundation for the overall structure. Furthermore, curved sections of tertiary steelwork shape the undulating roof form. This steelwork features a design consisting of trapezoidal glass and stainless-steel panels, enclosing three separate structures without physical contact and they contribute to the overall form of the building but also enhance its aesthetic appeal. The overall form was developed through a series of sketches and models, with the aim of creating a dynamic and visually striking design. After the form generation, the structural system was designed using a combination of steel and concrete. They used advanced software's to simplify the complex toroidal shape of the envelope and refine the construction elements after determining the form. Therefore, the structural decisions were considered afterwards other parameters and the building had a linear design process.

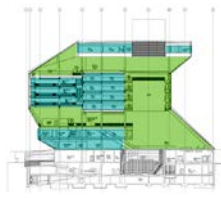
In terms of structure-form relationship, the free-form roof not only creates an aesthetically pleasing appearance but also serves functional purposes. They separated the spaces underneath the roof to isolate them and prevent acoustical problems. The structural elements, such as the steel framework and roof trusses, are carefully organized since they wrap the fragmented spaces and provide support and stability.

The structure-space relationship in the building displays an efficient use of space and the seamless integration of structural elements with the interior layout. The interior spaces are designed to accommodate divergent functions, including concert performances, rehearsals, and educational activities. The structural elements, such as columns and beams, are strategically positioned to maximize usable space and minimize obstructions. However, since the roof structure covers the volumes inside, the spatial configurations are not compatible with the envelope.

5.9 Seattle Central Library, 2004, OMA+ LMN

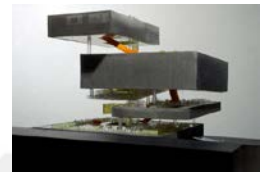
The Seattle Central Library (Table 5.9) has a glass and metal exterior aimed to create a continuous layer of transparency through an iconic form. Furthermore, the design has various performative aspects such as the thermal performance of the envelope.

Table 5.9 Assessment of Seattle Central Library

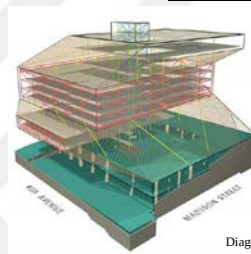
NAME, YEAR		SEATTLE CENTRAL LIBRARY, 2004		GENERAL INFORMATION & GRAPHICS	
Architecture		OMA+ LMN		EXTERIOR IMAGE (1)	INTERIOR IMAGE (2)
Structural Eng		Ove Arup & Magnusson Klemencic Associates			
Program		Library			
GFA		38,300 m ²			
FORM ANALYSIS					
FORM REASONING PROCESS	VISUAL PROPERTIES		The initial design concept for the library's exterior aimed to create the entire structure that has levels of transparency, creating a diagrammatic form. According to OMA, the approach involved modifying the arrangement of floors in a typical American high-rise, resulting in a building that exhibits contextual adaptability and iconic appearance. (5)		
	STANDARDIZATION IN CONSTRUCTION		They used seismic grid panels to carry the building both during and after the construction process. This required the panels to be put in place before the structure could progress upwards, and they had to be flexible enough to accommodate any movement during construction while still meeting strict construction standards. (7)		
	SUSTAINABILITY		The library was designed with various performative design aspects in mind, which contribute to the building's functionality, sustainability, and overall user experience. The thermal performance of the curtain wall played a crucial role in the design development process.		
STRUCTURAL ANALYSIS (F: Form Generation, S: Space Generation)					
		F	S		
STRUCTURAL SYSTEM	FORM ACTIVE	CABLED		Vector Active - 2D Truss: The grid operates as a massive braced frame, gathering seismic forces from each platform, transmitting them to the next platform, and eventually to the concrete foundation. The grid functions as an expansive braced framework, effectively capturing seismic forces from each platform and transferring them sequentially to the concrete base. This seismic structure, composed of interconnected I-beam steel in a lattice formation, establishes connections between platforms, offering essential reinforcement during seismic occurrences. Together with the primary structure, these components ensure the stability of the building while also generating distinct requirements for supporting the curtain wall glazing system.(8)	
		TENT/MEMBRANE			
		PNEUMATICS			
		ARCH			
	VECTOR ACTIVE	2D TRUSS		This seismic structure, composed of interconnected I-beam steel in a lattice formation, establishes connections between platforms, offering essential reinforcement during seismic occurrences. Together with the primary structure, these components ensure the stability of the building while also generating distinct requirements for supporting the curtain wall glazing system.(8)	
		3D TRUSS / SPACE FRAME			
		GEODESIC DOME			
	SECTION ACTIVE	BEAM GRID		Section Active - Beam Grid: The composition of the structure involves seismic systems and load-bearing systems. The load-bearing system, comprising columns and beams, provides support for the platforms that have various program spaces. It's important to note that the primary frame stands independently and does not rely on the seismic grid for reinforcement.	
		FRAME			
		SLAB			
SURFACE ACTIVE	PLATE		To precisely depict the intricate building envelope system, consisting of numerous glass panels affixed to a steel web, BIM technology was utilized. On a daily basis, the steel framework was scanned to generate a 3D as-built model. This model served as a reference for Hoffman's BIM team and the steel erectors, enabling them to make necessary adjustments during the construction process and uphold the desired geometry. (7)		
	FOLDED PLATE				
	SHELL / GRID SHELL				
STRUCTURE IN THE DESIGN PROCESS	INTEGRATED DESIGN PROCESS				
	STRUCTURE-BASED DESIGN PROCESS				
	LINEAR DESIGN PROCESS				
GENERAL ASSESSMENT					
Structure and Form Relation		1	Secondary structure(s) generates the form.		
			Primary structure(s) generates the form.		
Form Reasoning Process			One Topic		
			Two Topics		
		3	Three Topics		
Structural Systems in Design Process			Linear Design Process		
			Structure-Based Design Process		
		3	Integrated Design Process		
Space and Form Compatibility			Spatial configurations are not compatible with the form.		
		2	Spatial configurations are partially compatible with the form.		
			Spatial configurations are compatible with the form.		
PLAN(S)					
		 2nd Floor Plan			
		 5th Floor Plan			
SECTION(S)					
					
REFERENCES: (1,2,3) https://www.archdaily.com/11651/seattle-central-library-oma-lmn , (4,5) https://www.worldconstructionnetwork.com/projects/seattle-library/ , (6) https://twitter.com/seattlesdc/status/1093600422529589253?lang=tr , (7) https://www.hoffmancorp.com/project/seattle-central-library/ , (8) https://lmnarchitects.com/lmn-research/seattle-central-library-curtain-wall-design					



Construction Photo (6)

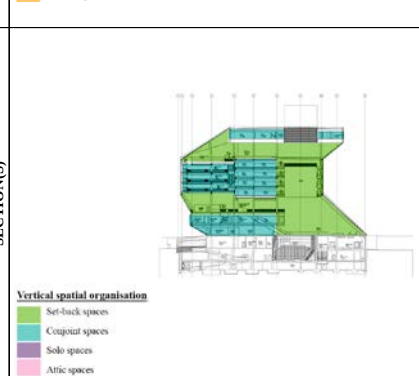


Physical Model (3)



Diagram

SPACE ANALYSIS

Horizontal spatial organisation
Clustered Spaces
Form-defining spaces
Flexible spacesVertical spatial organisation
Set-back spaces
Coaxial spaces
Solo spaces
Atrium spaces

On the other hand, the structure of the library incorporates load-bearing and seismic systems. The load-bearing system, comprising beams and columns, supports the elevated platforms housing the other spaces.

The primary frame functions independently without relying on the seismic grid for support. The seismic steel grid acts as a large, braced frame, collecting seismic forces from the platforms and transferring them to the concrete base. It consists of lattice-like arranged I-beam steel, connecting platforms, and providing bracing during seismic events. Together with the primary structure, the seismic grid ensures the stability of the building while also creating different conditions for supporting the curtain wall glazing system. To accurately model the complex envelope, which includes glass panels mounted on a steel web, BIM technology was utilized. The construction team continuously adjusted the steel framework to maintain the intended geometry.

In terms of structure-form relationship, the design concept aimed to create a visually striking building while achieving structural efficiency through form. The building features a dynamic combination of angles, diagonals, and cantilevered elements. The structural systems both support and create set-back spaces with the seismic steel grid as the volumes shift on each other. Thus, the structural elements of the building play a significant role in achieving the unique form.

Regarding the structure-space relationship, the structural elements define the spatial organization within the library. Columns and beams not only provide support but also function as spatial dividers, defining zones and creating distinct areas for different activities and functions. Furthermore, they both create large, open spaces and intimate and enclosed areas, accommodating various uses such as reading areas, study rooms, and collaborative spaces while providing necessary strength, stability, and flexibility for the complex geometries and cantilevered sections. Steel columns and beams form the primary framework, allowing for open and expansive spaces within the building. Moreover, the structural elements are intentionally exposed with large expanses of glass, providing natural light and panoramic views of the surrounding cityscape. The spatial layout incorporates atriums, bridges, and staircases that promote movement, interaction, and visual connections between different floor levels. So, the design integrates structural elements as architectural features, blurring the boundaries between structure and space.

5.10 Denver Art Museum - The Frederic C. Hamilton Building, 2006, Studio Libeskind

For the design of the Denver Art Museum, (see Table 5.10) the form is a notable aspect of its structure. The architect's inspiration from the craggy cliffs of the Rocky Mountains is evident in the building's jagged and angular exterior. The design incorporates a series of geometric volumes that intersect and cantilever, creating a dynamic and sculptural composition. To bring the design concept to life, advanced 3D modeling, analysis, and visualization tools were employed. The use of BIM became essential in creating templates for numerous physical models and drawings throughout the design process.

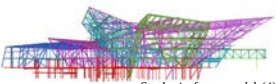
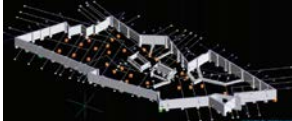
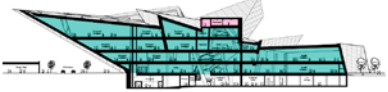
The building features a steel superstructure composed of interconnected leaning braced frames and trusses. The steel beams are carefully positioned, allowing the building to support itself and transfer its weight to concrete pillars anchored in the bedrock. Except for the central elevator core, the building's walls do not stand vertically. Instead, they lean outward, and a floor framing system effectively manages lateral loads, eliminating the need for columns within the exhibition space. To ensure stability and security, vertical columns made of concrete and steel extend to the foundation. They have involved structural system decisions together with other design parameters thus, the building had an integrated design process.

In terms of structure-form relationship, the distinctive form is made possible by the underlying structural system. The steel superstructure provides necessary support for the complex form. The strategic arrangement of steel beams and columns allows for the distribution of the building's weight, effectively transferring it to concrete pillars that anchor into the bedrock. Consequently, this structural arrangement ensures the stability and integrity of the building.

The structure and space relationship are evident in the building's interior. The structural system allows for open and flexible interior spaces, accommodating the diverse needs of the museum's exhibitions and programs. The structural elements, such as the leaning columns and trusses, become part of the spatial experience.

Table 5.10 Assessment of Denver Art Museum

NAME, YEAR		DENVER ART MUSEUM - THE FREDERIC C. HAMILTON BUILDING, 2006		GENERAL INFORMATION & GRAPHICS	
Architecture		Studio Libeskind		EXTERIOR IMAGE (1)	INTERIOR IMAGE (2)
Structural Eng		Ove Arup			
Program		Museum			
GFA		13,564 m ²			
FORM ANALYSIS					
FORM REASONING PROCESS	VISUAL PROPERTIES		The design drew inspiration from the rugged cliffs.(9)		
	STANDARDIZATION IN CONSTRUCTION		They used 3D modelling analysis and visualization tools to create the structural, mechanical, and architectural forms. Throughout the process, BIM models proved to be invaluable in generating templates for the numerous physical models and extensive drawings produced during the design phase..(7)		
	SUSTAINABILITY				
STRUCTURAL ANALYSIS (F: Form Generation, S: Space Generation)					
			F	S	
STRUCTURAL SYSTEM	FORM ACTIVE	CABLED			Section Active - Frame: The building consists of a steel superstructure comprised of an interconnected arrangement of inclined trusses and braced frames. With the placement of steel beams, the structure supports itself and transfers the load to concrete pillars serving as "anchors," reaching deep into the bedrock. Except for its central elevator core, the building has no true vertical walls. With walls leaning outwards, the floor framing system manages heavier lateral loads to create an exhibition space without columns. In order to ensure stability, the building incorporates 116 vertical columns made of steel and concrete that extend from the foundation deep into the bedrock.(7,9)
		TENT/ MEMBRANE			
		PNEUMATICS			
		ARCH			
	VECTOR ACTIVE	2D TRUSS			
		3D TRUSS / SPACE FRAME			
		GEODESIC DOME			
	SECTION ACTIVE	BEAM GRID			
		FRAME			
		SLAB			
	SURFACE ACTIVE	LOAD - BEARING WALL			
		FOLDED PLATE			
SHELL / GRID SHELL					
STRUCTURE IN THE DESIGN PROCESS	INTEGRATED DESIGN PROCESS		The contractor played a crucial role as the model manager, connecting the design models with the manufacturing models employed for construction purposes. This approach involved the utilization of various BIM software products to create system-specific models.(7)		
	STRUCTURE-BASED DESIGN PROCESS				
	LINEAR DESIGN PROCESS				
GENERAL ASSESMENT					
Structure and Form Relation			Secondary structure(s) generates the form.		
			2 Primary structure(s) generates the form.		
Form Reasoning Process			One Topic		
			2 Two Topics		
			Three Topics		
Structural Systems in Design Process			Linear Design Process		
			Structure-Based Design Process		
			3 Integrated Design Process		
Space and Form Compatibility			Spatial configurations are not compatible with the form.		
			2 Spatial configurations are partially compatible with the form.		
			Spatial configurations are compatible with the form.		
REFERENCES: (1,2,6) https://www.archdaily.com/80309/denver-art-museum-daniel-libeskind , (3,5,7) https://www.mortenson.com/-/media/project/mortenson/site/files/services/vdc/parallax/pdfs/denver-art-museum (4) https://zimmernan-metals.com/art-structures/building-art-features/ , (9) https://www.worldconstructionnetwork.com/projects/dam/ ,					

					
Construction Photo (3)					
					
Steel wireframe model (4)					
					
Concrete foundation model including 116 columns					
					
Physical Model Trials (6)					
SPACE ANALYSIS					
					
+1 Floor Plan					
Horizontal spatial organisation					
Clustered Spaces					
Form-defining spaces					
Flexible spaces					
SECTION(S)					
					
Vertical spatial organisation					
Set-back spaces					
Coupoint spaces					
Solo spaces					
Attic spaces					

Moreover, the exhibition spaces are characterized by their lack of vertical walls, with the walls leaning outward. This design approach eliminates the need for interior columns, providing unobstructed vistas and creating a sense of openness within the museum. The spatial layout and circulation paths enhance the visitor experience and

guide them through a sequence of dynamic and interconnected spaces. In short, the building contained many flexible spaces which allowed the structure to be independent as well.

5.11 Mercedes Benz Museum, 2006, UN Studio

The Mercedes Benz Museum's (see Table 5.11) design follows a trefoil shape, both internally and externally, to align with the surrounding car-driven context. The architectural concept draws inspiration from the double helix structure of DNA, emphasizing the company's history. To accommodate the intricate geometry, a concrete structure, which has a wide span, was planned through a digital design tools.

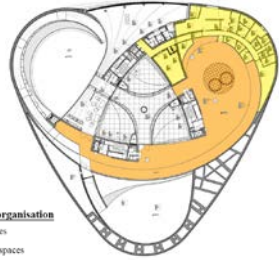
The structure consists of a cast-in-place concrete box girders, cast-in-place concrete core, and load-bearing angled columns. The curved box girders and floor plates work together to bridge the gap between the core and the angled columns. The twists in the design originate from the lift shafts as vertical walls and gracefully spiral outwards, supported by adjacent lift shafts. These twists, incorporating two turns, represent the most impressive innovation of the building. They are composed of three concrete elements encircling the atrium, housing the elevators, and incorporating mechanical and service spaces. As a result, they serve as the structural center or core of the building and each level spans up to 30 meters without the need for additional support. By developing a 3D model of the trefoil and double helix design, the team was able to organize the spaces while staying true to the overall concept. This approach enabled the designers to visualize and analyze the structure while ensuring its viability and structural integrity.

In terms of structure-form relationship, the inclusion of the "twist," the primary structural element, enabled them to achieve the desired form. The girders and floor plates form a cohesive framework that supports the overall architectural form. Emerging from the lift shafts as vertical walls, the twists gracefully spiral outwards, and create a captivating sweeping effect on the exterior. From the exterior, it is not possible to observe the structural logic of the building because the cladding system and angled columns may give a different expression. The building is conceived as

having three floor levels however, the structural logic which allowed to integrate sloped floor levels increase the total floor area composed of sloped floors.

Table 5.11 Assessment of Mercedes – Benz Museum

NAME, YEAR		MERCEDES-BENZ MUSEUM, 2006		GENERAL INFORMATION & GRAPHICS	
Architecture		UN Studio		EXTERIOR IMAGE (1)	INTERIOR IMAGE (2)
Structural Eng		Werner Sobek Engineering & Design			
Program		Museum			
GFA		25,000 m ²			
FORM ANALYSIS					
FORM REASONING PROCESS	VISUAL PROPERTIES		The museum is designed in the shape of a trefoil, incorporating this geometric pattern both in its internal layout and its appearance. This deliberate choice of geometry reflects the influence of the car-centric environment in which the museum is situated. The form is inspired by the double helix structure of DNA and this resemblance visually highlights the company's history.(6)		
	STANDARDIZATION IN CONSTRUCTION		The wide-span reinforced concrete structure of the building was meticulously designed using a comprehensive 3D approach, owing to its intricate and elaborate geometry. Each level of the structure spans an impressive distance of up to 30 meters without the need for additional supports.(7)		
	SUSTAINABILITY				
STRUCTURAL ANALYSIS (F: Form Generation, S: Space Generation)					
			F	S	
STRUCTURAL SYSTEM	FORM ACTIVE	CABLED			Section Active - Frame: The structure consists of a box girders, angled columns, and concrete core that bear the external load. The curved box girders collaboratively function with the floor plates to bridge the gap between the core and the angled columns positioned on the building's exterior..(5,6)
		TENT/ MEMBRANE			
		PNEUMATICS			
		ARCH			
	VECTOR ACTIVE	2D TRUSS			Surface Active - Load Bearing Wall: The twisting elements of the building originate from the lift shafts, and is supported by the adjacent lift shaft. These twisted sections, incorporating two rotations, serve as a remarkable architectural feature. Comprised of three cast-in-place concrete components, they encircle the atrium, accommodate the elevators, and contain mechanical and service areas. Essentially, they serve as the core and structural focal point of the building.(5,6)
		3D TRUSS / SPACE FRAME			
		GEODESIC DOME			
	SECTION ACTIVE	BEAM GRID			
		FRAME			
		SLAB			
	SURFACE ACTIVE	LOAD - BEARING WALL			
		FOLDED - PLATE			
		SHELL / GRID SHELL			
STRUCTURE IN THE DESIGN PROCESS	INTEGRATED DESIGN PROCESS			Following the development of the 3D models for the trefoil and double helix, the design team strategically organized the spaces while ensuring the concept's overall integrity. The special elements, "twist", the main structural element, they were able to achieve the desired form. They had organised the entire input into one digital model. (5)	
	STRUCTURE-BASED DESIGN PROCESS				
	LINEAR DESIGN PROCESSES				
GENERAL ASSESMENT					
Structure and Form Relation		Secondary structure(s) generates the form.			
		2	Primary structure(s) generates the form.		
Form Reasoning Process		One Topic			
		2	Two Topics		
		Three Topics			
Structural Systems in Design Process		Linear Design Process			
		Structure-Based Design Process			
		3	Integrated Design Process		
Space and Form Compatibility		Spatial configurations are not compatible with the form.			
		Spatial configurations are partially compatible with the form.			
		3	Spatial configurations are compatible with the form.		
REFERENCES: (1,2,3,4) https://www.archdaily.com/805982/mercedes-benz-museum-unstudio , (5) https://www.unstudio.com/en/page/12482/mercedes-benz-museum , (6) https://www.mercedes-benz.com/en/art-and-culture/museum/architecture/ , (7) https://www.wernersobek.com/projects/mercedes-benz-museum/					

		Axonometric Diagram (4)		Construction Photo of the "twist" (3)	
					
				Physical Model Photos (5)	
		SPACE ANALYSIS			
PLANS(S)					
	Horizontal spatial organisation - Clustered Spaces - Form-defining spaces - Flexible spaces				
SECTIONS(S)					
	Vertical spatial organisation - Set-back spaces - Conjoint spaces - Solo spaces - Attic spaces				

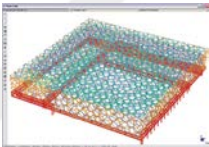
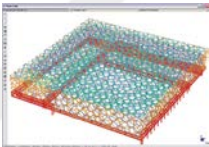
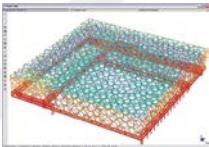
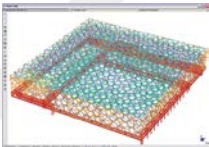
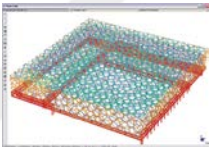
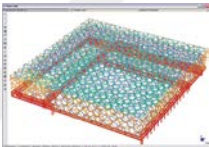
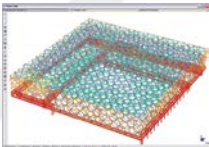
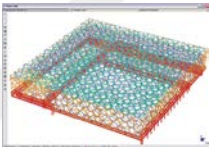
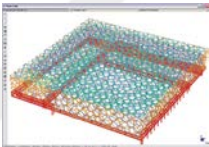
In terms of structure-space relationship, there is an intricate and close association because the structure, form and space are all united. The structural system serves as a

framework that organizes and defines the spatial layout of the museum. The trefoil form, guided by the underlying structural elements, influences the spatial arrangement and flow within the museum providing flexibility for various exhibits and displays. Since these spaces are flexible and exist as solo spaces the organization itself allowed room for such a unique formation. The structure creates interconnected spaces that seamlessly guide visitors through different exhibition areas while maintaining a cohesive spatial experience. Moreover, it accommodates clustered spaces such as elevators, mechanical, and service spaces through the cores of the building.

5.12 Beijing National Aquatics Center (Water cube), 2007, PTW Architects, Ove Arup

The design of the Beijing National Aquatics Center (see Table 5.12) draws inspiration from soap bubbles. The architects and engineers recognized that a structure based on their specific form could be both repetitive and feasible to construct, while also occurring naturally and unpredictably. Through a generative process, the structural envelope was developed, and its strength was evaluated using specialized software, considering various load scenarios. The steel members forming the bubble-like cells were finalized by conducting parametric analysis to determine the optimal relationships between size, shape, and weight. This approach allowed for the selection of steel members that were efficient and structurally sound. The building had a performative design approach in which the bubble-wrapped façade acts as an insulated greenhouse, reducing energy consumption by approximately 30%. The choice of using Ethylene Tetrafluoroethylene (ETFE) for the façade was driven by its excellent thermal insulation properties and the bubble cladding permits ample natural light, surpasses glass in thermal insulation, and self-cleans with rainfall.

Table 5.12 Assessment of Beijing National Aquatics Center (Water Cube)

NAME, YEAR				BEIJING NATIONAL AQUATICS CENTER (WATER CUBE), 2007				GENERAL INFORMATION & GRAPHICS					
Architecture				PTW Architects, Ove Arup				EXTERIOR IMAGE (1)		INTERIOR IMAGE (2)			
Structural Eng.				Ove Arup									
Program				Aquatics Center									
GFA				25,000 m ²									
FORM ANALYSIS													
FORM REASONING PROCESS		VISUAL PROPERTIES		The design of the building draws inspiration from the organic shapes formed by soap bubbles in nature. The design team recognized that a structure based on this distinctive geometry would possess qualities of repetition and constructability, while appearing organic and aesthetical.(4)									
		STANDARDIZATION IN CONSTRUCTION		The structural envelope created through the generative process was evaluated for its strength using specialized software and it was subjected to different loading scenarios. The steel members forming the bubble cells were finalized by determining the optimal relationships between size, shape, and weight through parametric analysis.(7)									
		SUSTAINABILITY		The building, resembling a structure wrapped in bubbles, functions akin to an insulated greenhouse, resulting in a significant reduction in energy consumption. ETFE was selected for the façade due to its excellent thermal insulation properties. The bubble cladding allows for enhanced natural light penetration and offers superior thermal insulation compared to glass, effectively self-cleaning with each rainfall. Additionally, solar energy is harnessed and utilized for heating purposes. Furthermore, the ample daylight entering the cube design providesreduction in the energy.									
STRUCTURAL ANALYSIS								(F: Form Generation, S: Space Generation)					
STRUCTURAL SYSTEM		FORM ACTIVE		CABLED		F		S					
				TENT/ MEMBRANE									
				PNEUMATICS									
				ARCH									
		VECTOR ACTIVE		2D TRUSS									
				3D TRUSS / SPACE FRAME									
				GEODESIC DOME									
		SECTION ACTIVE		BEAM GRID									
				FRAME									
				SLAB									
		SURFACE ACTIVE		LOAD - BEARING WALL									
				FOLDED - PLATE									
				SHELL / GRID SHELL									
STRUCTURE IN THE DESIGN PROCESS		INTEGRATED DESIGN PROCESS		They aimed to create a structure that interacted with each other while minimizing surface area. So, they developed a script based on this generative logic which used Weaire-Phelan cells to build the structure. Then, they rotated the structure in three dimensions, sliced it into horizontal and vertical and planes, and removed the interior spaces to form the structural envelope. Here, the architectural space, structure and facade are one and the same element.(8)									
		STRUCTURE-BASED DESIGN PROCESS											
		LINEAR DESIGN PROCESS											
GENERAL ASSESMENT													
Structure and Form Relation						Secondary structure(s) generates the form.							
				2		Primary structure(s) generates the form.							
Form Reasoning Process						One Topic							
						Two Topics							
				3		Three Topics							
Structural Systems in Design Process						Linear Design Process							
				2		Structure-Based Design Process							
Space and Form Compatibility						Integrated Design Process							
						Spatial configurations are not compatible with the form.							
				2		Spatial configurations are partially compatible with the form.							
						Spatial configurations are compatible with the form.							
REFERENCES: (1) https://www.dezeen.com/2008/02/06/watercube-by-chris-bosse/ , (2,4) https://www.arup.com/projects/chinese-national-aquatics-center , (3) https://moreaedesign.wordpress.com/2010/09/13/more-about-watercube-%E2%80%93-beijing-china/ , (5,6,7) Gonchar, J. (2008, July). Inside Beijing's Big Box of Blue Bubbles. Architectural Record. Continuing Education Center. Retrieved May 3, 2013. (8) https://structurae.net/en/structures/beijing-national-aquatics-center , (9) http://aecomag.com/case-studies-mainmenu-37/36-beijing-waterworld , (10) https://moreaedesign.wordpress.com/2010/09/13/more-about-watercube-%E2%80%93-beijing-china/													

The primary support and stability of the building are provided by a steel frame designed to withstand wind and seismic loads. This frame comprises curved, tubular

steel members that collectively form the overall shape of the building. The members are connected through welded joints, creating a grid-like structure that ensures the necessary rigidity to support the building's envelope. Furthermore, to allow natural light into the interior spaces while providing insulation and mitigating solar heat gain, the building incorporates a membrane. This membrane is attached to the steel frame using aluminum clamps, which accommodate contraction and expansion caused by temperature changes. Additionally, the concrete foundation has a crucial role in stabilizing the building by transferring the loads from the steel frame to the ground. It is reinforced with steel bars to enhance their resistance against bending and cracking caused by the weight of the building and seismic forces. Briefly, this structure-based design approach ensured that the structure, composed of 3D cells, minimizes the surface area of the envelope.

To achieve this, a generative logic was developed, employing specialized cells to construct the structure. The resulting structure was then rotated in three dimensions, sliced into horizontal and vertical planes, and interior volumes were removed to form the structural envelope.

The structure-form relationship is exemplified by the strategic use of materials and innovative construction techniques. The lightweight ETFE cushions, in conjunction with the steel frame, created a balance between structural stability and aesthetic transparency. The integration of these materials and the structure-based design process allowed efficient construction and realization of the complex free-form building.

In terms of structure-space relationship, the structural layout needed to correspond the form-defining spaces that function as solo spaces in section. This diverse range of aquatic facilities included swimming pools, water slides, and recreational spaces. The spatial layout of these amenities is strategically arranged to, and the unique structural system provided unobscured large span voids for certain areas. This strategy allowed the clustered spaces exist underneath the grandstands.

5.13 Beijing National Stadium (Birds Nest), 2008, Herzog & de Meuron

The Beijing National Stadium (see Table 5.13) features an innovative design that integrates elements from both China's historical and contemporary contexts, serving as a defining cultural landmark. Inspired by local Chinese art forms, the designers organized the structural system's primary, secondary, and tertiary elements in a pattern resembling crazed pottery. The geometric principles of the bowl structure influenced the development of the structural system. This structural system design went through a combination of seismic analysis thus, they incorporated various damping systems and seismic mitigation strategies. Furthermore, the building incorporates various performative design features that enhance its functionality and sustainability. The unique structural system minimizes construction waste, while the facade provides shading and rainwater collection.

The structure comprises two independent elements: a concrete seating bowl and an outer steel frame surrounding it. The outer steel frame consists of 24 portal girders arranged in a regular pattern. Secondary girders divide the primary structure at irregular intervals and provide bracing. This design approach enables different sheet thicknesses to bear specific loads. The inner concrete seating bowl shares a foundation with the outer steel structure. While the front side remains exposed, a roof covering composed of ETFE membranes is stretched across sections of the steel framework. The structure-based design process employed the parametric design platform CATIA, facilitating adjustments to related parameters in response to any changes. Finite element analysis was utilized to examine stress distribution among the members and their connections. Based on the analysis results, the structural system was optimized to enhance its performance.

The building with its iconic form, exemplifies a significant and unique structure-form relationship. The structural system of the stadium, composed of an intricate network of steel members, defines the form. The lattice-like structure, reminiscent of a bird's nest, is characterized by a series of intersecting and overlapping steel elements that create a sense of complexity and dynamism. It displays a combination of traditional architectural principles and modern engineering techniques. This synthesis of structural considerations and design aesthetics resulted in a form that is both visually captivating and structurally efficient.

Table 5.13 Assessment of Beijing National Stadium (Birds Nest)

NAME, YEAR		BEIJING NATIONAL STADIUM (BIRDS NEST), 2008		GENERAL INFORMATION & GRAPHICS	
Architecture		Herzog& de Meuron		EXTERIOR IMAGE (1)	
Structural Eng		Ove Arup& Partners		INTERIOR IMAGE (2)	
Program		Stadium			
GFA		258.000 m ²			
FORM ANALYSIS					
FORM REASONING PROCESS	VISUAL PROPERTIES		The building has an innovative design that combines elements from China's history and present and has been recognized as a landmark that defines its culture. The designers were influenced by local Chinese art forms and organized the primary, secondary, and tertiary structural systems in a pattern like there is in a crazed pottery.		
	STANDARDIZATION IN CONSTRUCTION		The development of the building's envelope design was driven by its structural logic, which took inspiration from the inner bowl design. By employing the geometric principles, the structural system of the envelope was carefully crafted, resulting in an inclined form and elliptical plan that elegantly embraced the bowl.(8)		
	SUSTAINABILITY		The building has several performative design features that enhance its functionality and sustainability. Its unique structural system reduces construction waste, while its exterior façade helps to shade the interior and reduce heat gain, resulting in a more comfortable environment for spectators. The rainwater collection system reduces the amount of potable water required and conserving water resources.		
STRUCTURAL ANALYSIS (F: Form Generation, S: Space Generation)					
				F	S
STRUCTURAL SYSTEM	FORM ACTIVE	CABLED			
		TENT/ MEMBRANE			
		PNEUMATICS			
		ARCH			
	VECTOR ACTIVE	2D TRUSS			
		3D TRUSS / SPACE FRAME			
		GEODESIC DOME			
	SECTION ACTIVE	BEAM GRID			
		FRAME			
		SLAB			
SURFACE ACTIVE	LOAD - BEARING WALL				
	FOLDED - PLATE				
	SHELL / GRID SHELL				
STRUCTURE IN THE DESIGN PROCESS	INTEGRATED DESIGN PROCESS		The structural design was created using the parametric design platform of CATIA. This allowed for easy adjustments to related parameters if changes were made to one of them.(8)		
	STRUCTURE-BASED DESIGN PROCESS		Based on the results of the finite element analysis, the structural system was optimized to improve its performance.(9)		
	LINEAR DESIGN PROCESS				
GENERAL ASSESMENT					
Structure and Form Relation		Secondary structure(s) generates the form.			
		2 Primary structure(s) generates the form.			
Form Reasoning Process		One Topic			
		Two Topics			
		3 Three Topics			
Structural Systems in Design Process		Linear Design Process			
		2 Structure-Based Design Process			
Space and Form Compatibility		Integrated Design Process			
		Spatial configurations are not compatible with the form.			
		Spatial configurations are partially compatible with the form.			
		3 Spatial configurations are compatible with the form.			
REFERENCES: (1,2,3) https://arquitecturaviva.com/works/estadio-nacional-en-pekín-6 , (4,8)Burrows, S. & Simpson, M. (2009). The Stadium geometry. The Arup Journal, 44(1), 16-19., (5,9)Lam, K. & Lam, T. (2009). Analysis model and results. The Arup Journal, 44(1), 20-23., (6) "Olympic Venue Construction Progressing Smoothly." Beijing This Month, 14 April 2006. 9 December 2006., (7) The Arup Journal					

In terms of structure-space relationship, there is an intricate and close association among them because the structure is also the form, and the spaces get directly

affected from them. The utilization of the steel lattice structure not only provides an efficient means of distributing loads but also allows for large uninterrupted spans, creating vast interior spaces that accommodate seating, circulation, and various functions. Furthermore, the structural system influences the spatial qualities of the stadium by creating a sense of transparency and lightness. The lattice structure, characterized by its open framework, enables natural light to permeate the interior spaces, reducing the need for artificial lighting and generating a visually dynamic ambiance. Overall, design integrates structural elements as architectural features, blurring the boundaries between structure and space.

5.14 Centre Pompidou-Metz, 2010, Shigeru Ban Architects

For the Centre Pompidou-Metz building (see Table 5.14), the architects' approach was to create an eye-catching architectural structure in a lesser-known city to attract tourism, similar to the successful "Bilbao effect." Digital tools were utilized to accurately reproduce the structure and mill the final surface of the roof. The structural system of the roof, known as the "Chinese hat" structure, consists of wooden beams and steel connectors, providing stability and support. The interlocking modules not only create a visually appealing design but also distribute loads efficiently throughout the roof structure. Moreover, white fiberglass membrane coated with Teflon was used to protect the entire wooden structure from direct sunlight, providing self-cleaning properties and enabling transparency at night. Also, the roof's aerodynamic properties were evaluated through wind tunnel testing to ensure optimal performance.

The roof structure is designed as a lattice system, comprising a grid of regular hexagons made up of glulam beams along each axis. It is partially supported by timber piers, forming four supports, with each support connecting to four foundation piles at the center. A central steel truss spire serves as lateral bracing for the roof canopy structure, consisting of trusses with cross bracing elements and welded connections. The spire acts as both a gravity and lateral superstructure, directly and indirectly linked to the foundation piles through a concrete slab. Furthermore, a tensile membrane is present on the lattice structure, securely fastened at the periphery of the canopy, the central spire, and within each pier. Moreover, the design process

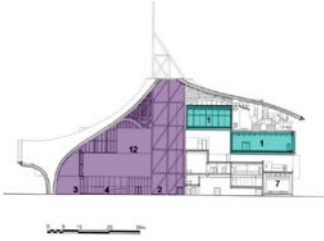
primarily focused on meeting the structural requirements of the building, with the hexagonal lattice roof playing a crucial role.

Table 5.14 Assessment of Centre Pompidou - Metz

NAME, YEAR			CENTRE POMPIDOU-METZ, 2010			GENERAL INFORMATION & GRAPHICS			
Architecture			Shigeru Ban Architects			EXTERIOR IMAGE (1)		INTERIOR IMAGE (2)	
Structural Eng			Ove Arup& Partners, Bollinger+ Grohmann						
Program			Museum						
GFA			11.330 m ²						
FORM ANALYSIS									
FORM REASONING PROCESS		VISUAL PROPERTIES		The architects implemented a strategy to design landmarks with the intention of attracting tourism. This approach proved highly successful, reminiscent of the renowned "Bilbao effect."					
		STANDARDIZATION IN CONSTRUCTION		The rationalization process involved digital tools to create an accurate reproduction of the structure, which was then used to mill the final surface of the roof.(7)					
		SUSTAINABILITY		The entire wooden structure is protected from direct sunlight by a white fiberglass membrane coated with Teflon, which has a self-cleaning property. This allows for transparency at night. To ensure its performance, the roof underwent testing in a wind tunnel to assess its aerodynamic properties.					
STRUCTURAL ANALYSIS (F: Form Generation, S: Space Generation)									
				F	S				
STRUCTURAL SYSTEM		FORM ACTIVE	CABLED			Form Active - Tent / Membrane: A fiberglass and tensile membrane is stretched over the lattice structure and firmly anchored along the canopy's edge, spire, and each pier.			
			TENT/ MEMBRANE						
			PNEUMATICS						
		VECTOR ACTIVE	ARCH			Vector Active - 3D Truss / Space Frame: The central steel truss spire provides lateral bracing to the roof canopy structure and consists of trusses with smaller cross bracing elements. It functions as both the gravity and seismic structure, establishing interdependent connections with the foundation piles, both directly and indirectly, via a concrete slab.			
			2D TRUSS						
			3D TRUSS / SPACE FRAME						
		SECTION ACTIVE	GEODESIC DOME			Surface Active - Shell/ Grid Shell: The roof is partially sustained by timber piers, resulting in four supports that intersect four foundation piles at their centers in a uniform pattern.(6)			
			BEAM GRID						
			FRAME						
		SURFACE ACTIVE	SLAB						
LOAD - BEARING WALL									
FOLDED - PLATE									
		SHELL / GRID SHELL							
STRUCTURE IN THE DESIGN PROCESS		INTEGRATED DESIGN PROCESS		The design process was primarily driven by the structural requirements of the building. The hexagonal lattice roof structure was the main design feature, and much of the design process revolved around developing a structurally sound and visually striking roof. While other factors such as sustainability, functionality, and aesthetics were considered, they were largely subordinate to the structural requirements of the building.					
		STRUCTURE-BASED DESIGN PROCESS							
		LINEAR DESIGN PROCESS							
GENERAL ASSESMENT									
Structure and Form Relation			Secondary structure(s) generates the form.						
			2 Primary structure(s) generates the form.						
Form Reasoning Process			One Topic						
			Two Topics						
			3 Three Topics						
Structural Systems in Design Process			Linear Design Process						
			2 Structure-Based Design Process						
			Integrated Design Process						
Space and Form Compatibility			1 Spatial configurations are not compatible with the form.						
			Spatial configurations are partially compatible with the form.						
			Spatial configurations are compatible with the form.						

Connection Detail and Structural Diagram. (2007). [Image]. Contractors World, 2010(7th ed.), 21-25. Print. (4)		
		
Roof Structure Model (5)		
		
One of the timber piers (6)		

SPACE ANALYSIS		
		
Horizontal spatial organisation		
Clustered Spaces		
Form-defining spaces		
Flexible spaces		

SECTIONS		
		
Vertical spatial organisation		
Set-back spaces		
Co-axial spaces		
Sole spaces		
Attic spaces		

REFERENCES: (1,2) <https://www.archdaily.com/490141/centre-pompidou-metz-shigeru-ban-architects>, (3) <https://www.dlupal.com/en/downloads-and-information/references/customer-projects/000277> (4,6) Connection Detail and Structural Diagram. (2007). [Image]. Contractors World, 2010(7th ed.), 21-25. Print., (5,7) https://www.architectmagazine.com/design/buildings/heydar-aliyev-cultural-center-designed-by-zaha-hadid-architects_o.

REFERENCES: (1,2) <https://www.archdaily.com/490141/centre-pompidou-metz-shigeru-ban-architects>, (3) <https://www.dlulbal.com/en/downloads-and-information/references/customer-projects/000277> (4,6) Connection Detail and Structural Diagram. (2007). [Image]. Contractors World, 2010(7th ed.), 21-25. Print., (5,7) https://www.architectmagazine.com/design/buildings/heydar-aliyev-cultural-center-designed-by-zaha-hadid-architects_o,

The emphasis was on developing a roof that is structurally robust and visually captivating. While sustainability, functionality, and aesthetics were considered, they

were of secondary importance compared to the structural design factors of the building.

The structure-form relationship in the building is evident in the way that the roof structure defines the form. The roof structure has a hexagonal shape that is made of wood and covered with a translucent membrane. This striking and memorable feature helps to make the building stand out from its surroundings. The roof structure also plays a vital role in the way that the building interacts with its environment and its translucent membrane allows natural light which also helps to regulate the temperature inside.

The structure-space relationship can be explained as the building's clustered interior spaces shifting on each other by attaching to the central spire which both support and organize their layout. Three large galleries are located on either side of the spire and are connected by the central forum which is a solo space that is used for events and exhibitions. Additionally, the structural elements, such as the wooden beams and steel connectors, are left exposed, becoming visually prominent features within the interior spaces.

5.15 Heydar Aliyev Cultural Center, 2013, Zaha Hadid Architects

The Heydar Aliyev Cultural Center, as described in see Table 5.15, draws inspiration from traditional Azeri architecture and showcases fluid curves and undulating surfaces. The design seamlessly integrates the walls with the roofs, blurring the boundaries between the interior and exterior spaces. The design team utilized computer analysis based on mathematical principles to develop the building, which offered practical solutions for construction challenges such as transportation, manufacturing, and assembly. It also addressed technical considerations such as forces caused by external loads, seismic activity, temperature variations, and wind loads.

Table 5.15 Assessment of Heydar Aliyev Cultural Center

NAME, YEAR		HEYDAR ALIYEV CULTURAL CENTER, 2013		GENERAL INFORMATION & GRAPHICS	
Architecture		Zaha Hadid Architects		EXTERIOR IMAGE (1)	INTERIOR IMAGE (2)
Structural Eng		AKT, Tuncel Engineers, MERO			
Program		Cultural Center			
GFA		57.519 m ²			
FORM ANALYSIS					
FORM REASONING PROCESS	VISUAL PROPERTIES		Azeri architecture and incorporates floral patterns throughout its interior. The decorative motifs seamlessly flow from the floors to the walls and extend up to the dome. The curvilinear cover unifies the walls and roofs, creating a harmonious connection between the volumes. This outer wrapper creates interconnecting spaces, giving the impression that all the buildings are part of a single unified structure. (5)	 Construction Photos (3)	
	STANDARDIZATION IN CONSTRUCTION		The engineers conducted a computer analysis based on mathematical principles during the initial design process. The fluid geometry of the building emphasizes its continual transformation and motion, and this approach also provides practical solutions for construction process. It also addresses technical concerns caused by factors like seismic activity, external loads, wind loading, and temperature change.(5,6)		
	SUSTAINABILITY				
STRUCTURAL ANALYSIS (F: Form Generation, S: Space Generation)					
		F	S		
STRUCTURAL SYSTEM	FORM ACTIVE	CABLED		Vector Active - 3D Truss / Space Frame: The space frame system used in construction allowed for the creation of a structure with a free-form shape, which helped save a lot of time during the construction process. The substructure was designed in a way that allowed for flexibility between the exterior cladding and the grid of the space frame.(5)	
		TENT/ MEMBRANE			
		PNEUMATICS			
		ARCH			
	VECTOR ACTIVE	2D TRUSS		Section Active - Beam Grid: The space frame is firmly linked to the reinforced concrete structure, providing support to the columns and ensuring the overall stability of the building. Special attention has been given to maintaining the structural integrity by connecting the space frame directly to the foundation. Additionally, innovative structural approaches have been employed, such as the utilization of curved "boot columns" on the western side, creating a unique inverse peel effect. On the eastern side, the cantilever beams supporting the building envelope have been skillfully tapered in a "dovetail" configuration, adding to the structural ingenuity of the design.(5)	
		3D TRUSS / SPACE FRAME			
		GEODESIC DOME			
	SECTION ACTIVE	BEAM GRID			Surface Active - Load Bearing Wall: Rigid reinforced concrete system composed of shear walls separates spaces and to supports the spaceframe structure. Moreover, it forms the footing of the building. (5)
		FRAME			
		SLAB			
SURFACE ACTIVE	LOAD - BEARING WALL				
	FOLDED - PLATE				
	SHELL / GRID SHELL				
STRUCTURE IN THE DESIGN PROCESS	INTEGRATED DESIGN PROCESS		The building's form, characterized by flowing curves and undulating surfaces, was developed using digital modeling techniques, with the aim of creating a seamless and organic design. Once the form had been established, the structural system was designed using a combination of steel and concrete, with the building's skin composed of a white aluminum panel system.(6)		
	STRUCTURE-BASED DESIGN PROCESS				
	LINEAR DESIGN PROCESSES				
GENERAL ASSESMENT					
Structure and Form Relation		1	Secondary structure(s) generates the form.		
			Primary structure(s) generates the form.		
Form Reasoning Process			One Topic		
		2	Two Topics		
			Three Topics		
Structural Systems in Design Process		1	Linear Design Process		
			Structure-Based Design Process		
			Integrated Design Process		
Space and Form Compatibility		1	Spatial configurations are not compatible with the form.		
			Spatial configurations are partially compatible with the form.		
			Spatial configurations are compatible with the form.		
REFERENCES: (1,2,5) https://www.archdaily.com/448774/heydar-aliyev-center-zaha-hadid-architects (3,4,6) http://buildipedia.com/aec-pros/from-the-job-site/zaha-hadids-heydar-aliyev-cultural-centre-turning-a-vision-into-reality					

The construction employed a space frame system, enabling the realization of a structure with a free-form shape and significantly reducing construction time. The secondary structure provides the flexibility required among the rigid space frame

grid and the cladding seams, which conformed to the free-form envelope. The space frame was connected to both the reinforced concrete structure, providing support for the columns, and directly to the foundation, ensuring optimal stability. Innovative structural approaches were employed, for example the implementation of curved “boot columns” on the west side, producing an inverse peel effect, and the refinement of cantilevered beams in a “dovetail” configuration on the east side, supporting the building envelope.

The project followed a linear design process, where once the overall form was established, the structural system was designed using a combination of steel and concrete. The building envelope was covered with white aluminum panel systems, providing a cohesive and visually striking appearance.

In terms of structure-form relationship, it is clear that the secondary structural system, space frame, defines the form. Since the form was developed using digital modeling techniques and with the aim of creating free-formed surfaces, the structural system needed to follow up its curves. Thus, the most appropriate and feasible structure was space frame system. In other words, the primary structural system did not have a visual effect on the form because of the secondary structural system and claddings.

For the structure-space relationship, the spaces within the building were arranged in a series of interconnected volumes. It is clear that the space frame structure does not fold and twist according to a spatial arrangement. The designers took advantage of the flexible spaces since the building constituted many. Moreover, rigid reinforced concrete was preferred for the shear walls as a partition that separates main spaces and to support the spaceframe.

5.16 Phoenix International Media Center, 2014, BIAD UFo

The intricate lattice façade of Phoenix International Media Center (see Table 5.16) is composed of a differentially stretched steel framework, indicates the difficulties of parametric modeling. However, the form relied on conceptual ideas rather than computational methods.

Table 5.16 Assessment of Phoenix International Media Center

NAME, YEAR		PHOENIX INTERNATIONAL MEDIA CENTER, 2014		GENERAL INFORMATION & GRAPHICS	
Architecture		BIAD Ufo		EXTERIOR IMAGE (1)	
Structural Eng		Beijing Tianrun Construction Co.		INTERIOR IMAGE (2)	
Program		Media Headquarters			
GFA		64,973 m ²			
FORM ANALYSIS					
FORM REASONING PROCESS	VISUAL PROPERTIES		The lattice-like facade, characterized by its varying tensioned steel web, presents a design that goes beyond mere computational complexities and emphasizes conceptual form generation. The underlying design concept aimed to establish an ecological shell that envelops distinct functional spaces, following a building-within-a-building approach. This arrangement provides shared public areas, fostering interaction between the two independent office towers enclosed within the shell. Moreover, the sculptural form draws inspiration from the intriguing geometry of the "Mobius Strip."		
	STANDARDIZATION IN CONSTRUCTION		The combination of the central core and the external shell creates a structure that is both aesthetically pleasing and structurally		
	SUSTAINABILITY		Energy-saving and low-carbon concepts are applied. For instance, they used a drain pipe on a flat surface, rainwater is collected naturally along the structural ribs, filtered, and stored for reuse in watering the artistic waterscape and landscape irrigation. The building's unique shape mitigates the impact of strong winds during winter and acts as a "Green Coat," providing a buffer space for functional areas to regulate the climate.(5)		
STRUCTURAL ANALYSIS (F: Form Generation, S: Space Generation)					
				F	S
STRUCTURAL SYSTEM	FORM ACTIVE	CABLED			Section Active - Frame: The central core, which contains the elevators, staircases, and other building services, is designed to resist vertical loads. Surface Active - Shell / Grid Shell: The shell is made up of a 'stretched' web of steel, provides lateral stability to the building. It consists of two layers of steel structure with a diagonal grid pattern. This pattern provides a high degree of stability to the building and helps distribute lateral loads throughout the structure. Construction Photos (3)  Mobius Strip Concept (4)
		TENT/ MEMBRANE			
		PNEUMATICS			
	VECTOR ACTIVE	ARCH			
		2D TRUSS			
		3D TRUSS / SPACE FRAME			
	SECTION ACTIVE	GEODESIC DOME			
		BEAM GRID			
		FRAME			
	SURFACE ACTIVE	SLAB			
		LOAD - BEARING WALL			
		FOLDED - PLATE			
STRUCTURE IN THE DESIGN PROCESS	INTEGRATED DESIGN PROCESS				To efficiently handle the intricate design and overcome the limitations of traditional 2D tools, the designers relied exclusively on BIM tools and paperless processes. BIM tools allowed the team to position the building's highest elements in a way that minimized shading on nearby buildings and enhanced energy efficiency. They utilized these tools to model and analyze wind-pressure distribution to prevent any adverse effects on air movement. It allowed data to flow between different stages of the process, saving time and reducing the risk of errors.(6)
	STRUCTURE-BASED DESIGN PROCESS				
	LINEAR DESIGN PROCESS				
GENERAL ASSESMENT					
Structure and Form Relation		1	Secondary structure(s) generates the form.		
			Primary structure(s) generates the form.		
Form Reasoning Process			One Topic		
			Two Topics		
		3	Three Topics		
Structural Systems in Design Process			Linear Design Process		
			Structure-Based Design Process		
		3	Integrated Design Process		
Space and Form Compatibility			Spatial configurations are not compatible with the form.		
		2	Spatial configurations are partially compatible with the form.		
			Spatial configurations are compatible with the form.		
REFERENCES: (1,2) https://parametric-architecture.com/tremendous-diagrids-shaping-the-canopy-layer-of-phoenix-media-center/ , (3,5) https://www.archdaily.com/165746/in-progress-phoenix-international-media-center-biad-ufo , (6) https://www.autodesk.com/solutions/bim/hub/2016-entry-335					

The distinctive sculptural form took inspiration from the "Mobius Strip " and the design concept was to construct an ecological shell that covers the clustered spaces,

creating a building within a building. This arrangement resulted in numerous shared public areas beneath the shell, accommodating two separate office towers. They combined a central core with an external shell to achieve an aesthetically pleasing and structurally efficient building. Moreover, to promote energy efficiency and sustainability, various strategies are implemented. For instance, a flat surface drainpipe is utilized to naturally collect rainwater along the structural ribs. Also, the unique shape of the building serves as a protective shield during winter, minimizing the impact of intense winds and acting as a "Green Coat".

The building's shell, composed of a stretched steel web, serves as a crucial element in providing lateral stability. It comprises two layers of steel structure arranged in a diagonal grid pattern, which enhances the building's stability and ensures the even distribution of lateral loads throughout the entire structure. On the other hand, the central core of the building, housing elevators, staircases, and other essential services, is specifically designed to bear vertical loads. Furthermore, during the integrated design process, designers relied on BIM tools and calculated every design decision through the process.

When the structure-form relationship is analyzed, it is observed that the latticed façade serves both aesthetic and functional purposes. This intricate lattice structure provides lateral stability to the building, ensuring structural integrity by effectively distributing lateral loads throughout its framework. With two independent office towers situated beneath the shell, the sculptural shape is inspired by the "Möbius Strip". Therefore, the combination of the external shell and the interior volumes is crucial in the structure and form relationship. Underneath the envelope, the central core supports vertical loads while facilitating efficient vertical circulation.

In terms of structure-space relationship, it is observed that the volumes underneath the shell have a regular layout which is common in conventional buildings. The organization in the section drawing indicates that the floor levels are not directly in relation to each other. On the other hand, interior spaces are designed with open floor plans and large areas, reducing the need for walls and partitions. This approach allows flexibility for the flexible spaces which are organized around form-defining spaces in-between the shell structure. Thus, this buffer space is an outcome of the secondary structure.

5.17 National Museum of Qatar, 2019, Ateliers Jean Nouvel

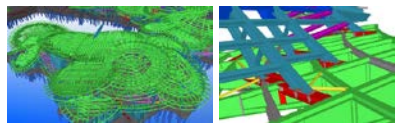
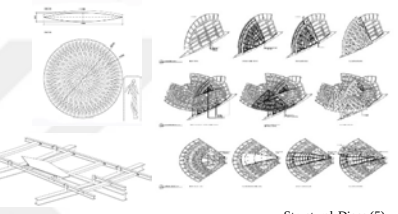
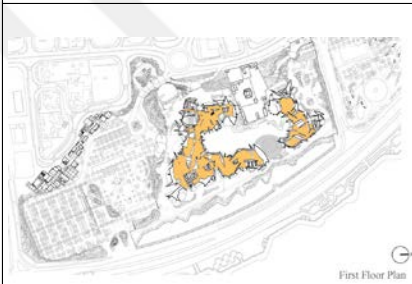
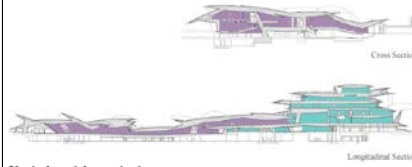
The concept of the National Museum of Qatar (see Table 5.17) draws inspiration from the natural formation known as the "desert rose". This unique design incorporates intersecting disks, creating a complex arrangement of geometric spaces. The envelope is constructed using high-performance fiber-reinforced concrete, segmented into panels along the disk-shaped structure. Moreover, the designers orientated these disks contribute to the energy efficiency of the building.

The building consists of a series of large interlocking disks, each with a spherical cross-section and varying sizes and curvatures. In total, there are 539 disks forming the structure. Some disks are positioned horizontally, resting on top of other disks, while the vertical disks serve as support, transferring the loads from the horizontal planes to the base. The primary structural system relies on radial and orthogonal steel frames, which provide support for the secondary structure composed of fiber reinforced concrete siding panels. There are stainless-steel members in the panels which connect the cladding to the underlying substructure. During the integrated design process, the team utilized BIM which united all the teams involved in the process. They worked comprehensively on the structural form of the desert rose, considering options such as the material properties and the incorporation of galleries within the disks. The interconnected relationship between the architectural and structural aspects presented a challenge, as any modifications to the walls would impact the overall structure. To address this, the team developed analysis models, which were continuously adjusted to optimize the building's design, including the interiors, overall shape, and integration of building services throughout the disks.

The structure-form relationship is based on a series of interlocking concrete shells nested in the form. The structural shells, composed of steel frames, are arranged in a spiral pattern, which creates a sense of movement and dynamism for formal expression. Their cladding in a white concrete that reflects the light, creating a bright and airy atmosphere. Briefly, the structure and form are closely related thus, the formal expression relies on their integrity.

Table 5.17 Assessment of National Museum of Qatar

NAME, YEAR		NATIONAL MUSEUM OF QATAR, 2019		GENERAL INFORMATION & GRAPHICS		
Architecture		Ateliers Jean Nouvel		EXTERIOR IMAGE (1)	INTERIOR IMAGE (2)	
Structural Eng.		Ove Arup& Partners, Werner Sobek				
Program		Museum				
GFA		52,167 m ²				
FORM ANALYSIS						
FORM REASONING PROCESS	VISUAL PROPERTIES	The concept draws inspiration from the natural formation of a mineral known as the "desert rose." This rock is created through the crystallization of minerals in the loose soil found beneath the surface of shallow salt basins.(7)				
	STANDARDIZATION IN CONSTRUCTION	Theunique structural design that is constituted of intersecting disks, forming a complex free-form building.				
	SUSTAINABILITY	The building's exterior is constructed using a durable and efficient material called high-performance glass fiber-reinforced concrete. This material is divided into segmented panels that cover the building's surface. The arrangement of these panels enhances the energy efficiency of the structure. Additionally, the building has been awarded the LEED Gold certification for its sustainable design and practices.(6)				
STRUCTURAL ANALYSIS (F: Form Generation, S: Space Generation)						
			F	S		
STRUCTURAL SYSTEM	FORM ACTIVE	CABLED			Section Active - Frame: The building consists of a series of interconnected disks that have a spherical shape and different sizes with varying curvatures. Some of them are positioned horizontally, resting on top of other disks, while the vertical disks serve as the support and transfer the loads of the horizontal planes to the foundation. The main structural system relies on radial and orthogonal steel frames, which provide support for the secondary structure consisting of fiber reinforced concrete siding panels. The cladding panels incorporate stainless-steel embeds that are cast within them, ensuring a secure connection between the cladding and the underlying substructure.(7)	
		TENT/ MEMBRANE				
		PNEUMATICS				
		ARCH				
	VECTOR ACTIVE	2D TRUSS				
		3D TRUSS / SPACE FRAME				
		GEODESIC DOME				
	SECTION ACTIVE	BEAM GRID				
		FRAME				
	SURFACE ACTIVE	SLAB				
		LOAD - BEARING WALL				
		FOLDED - PLATE				
STRUCTURE IN THE DESIGN PROCESS	SHELL / GRID SHELL					
	INTEGRATED DESIGN PROCESS		The planning process involved BIM models into which all planners involved. The team debated the structural form of the desert rose, including the use of concrete or steel and creating galleries with the disks. The interrelated architectural and structural form posed a challenge, as changes to the walls would affect the structure. Hence, they created analysis models. These were adjusted to optimize the building, including the interiors and overall shape, and to incorporate building services through the disks.(7)			
	STRUCTURE-BASED DESIGN PROCESS					
LINEAR DESIGN PROCESS						
GENERAL ASSESMENT						
Structure and Form Relation		Secondary structure(s) generates the form.				
		2 Primary structure(s) generates the form.				
Form Reasoning Process		One Topic				
		Two Topics				
		3 Three Topics				
Structural Systems in Design Process		Linear Design Process				
		Structure-Based Design Process				
		3 Integrated Design Process				
Space and Form Compatibility		Spatial configurations are not compatible with the form.				
		Spatial configurations are partially compatible with the form.				
		3 Spatial configurations are compatible with the form.				
REFERENCES: (1,2,6) https://architizer.com/blog/practice/details/national-museum-of-qatar/ , (3,4,7) https://www.architecturalrecord.com/articles/14043-national-museum-of-qatar-by-ateliers-jean-nouvel , (5) https://www.archdaily.com/913989/national-museum-of-qatar-atelier-jean-nouvel ,						

				Construction Photo (3)	
				Digital Model depicting the Structural Systems (4)	
				Structural Discs (5)	
		SPACE ANALYSIS			
					
		First Floor Plan			
		Horizontal spatial organisation - Clustered Spaces - Form-defining spaces - Flexible spaces			
		Vertical spatial organisation - Set-back spaces - Conjoint spaces - Solo spaces - Attic spaces			
					
		Cross Section			
		Longitudinal Section			

In terms of structure-space relationship, there is an intricate and close association among them because the structural disks are the actual walls of the building. The

spiral pattern of the disks creates a series of interconnected spaces, which are then used to create contrasting functions. The spaces are mostly composed of flexible spaces which act as solo spaces on the public ground floor while the private spaces are located on the upper floors as conjoint spaces. Overall, the design integrates structural elements as architectural features, blurring the boundaries between structure and space.

Overall, this chapter presents a critical analysis of seventeen carefully chosen cases, predominantly from the 21st century. These cases are analyzed based on various parameters related to form, structure, and space. Additionally, it has been observed that these parameters have a significant impact on the intricate relationships among form, structure, and space. According to the data obtained from the analyses, the following chapter includes discussions on these analysis results.

CHAPTER 6

DISCUSSION

In Chapter 5, seventeen cases of free-form architecture constructed between 1959 and 2019 are examined according to the analysis table which cases undergo evaluation through five sequential analysis steps, encompassing both data collection and analysis. Following the data obtained from the analyses, this chapter focuses on the analysis results regarding the four research questions mentioned in Section 1.2, including:

- common structural systems for free-form buildings and their role on formal and spatial configurations,
- the inclusion of structural systems in the design process and its impact on free-form buildings,
- key factors that influence the form reasoning process and the interplay between structure and form in a free-form building,
- spatial organizations in free-form buildings and the interplay between structure and space.

6.1 Structural Systems for free-form buildings and their role on formal and spatial configurations

The structural systems of free-form buildings play a crucial role in creating and supporting their unique forms and spaces. With reference to the structural analysis that is explained under section 4.2, the cases are analyzed (see Table 6.1).

Table 6.1 Structural Systems of the cases

	STRUCTURAL SYSTEM (F: Form Generation, S: Space Generation)												
	FORM ACTIVE				VECTOR ACTIVE			SECTION ACTIVE			SURFACE ACTIVE		
	CABLED	TENT/ MEMBRANE	PNEUMATICS	ARCH	2D TRUSS	3D TRUSS / SPACE FRAME	GEODESIC DOME	BEAM GRID	FRAME	SLAB SYSTEM	LOAD - BEARING WALL	FOLDED PLATE	SHELL / GRID SHELL
Solomon R. Guggenheim Museum									S		F		
Cristo Obrero Church													F
TWA Flight Center										F			S
Sydney Opera House									F				
Guggenheim Museum Bilbao					F				F				
Selfridges Building	F				S				F				
Kunsthhaus Graz									F				F
Sage Gateshead				F					S				S
Seattle Central Library					F				F				F
Denver Art Museum					S			S	S				
Mercedes Benz Museum									F		F		
Beijing National Aquatics Center		F				F				S			
Beijing National Stadium		S				S							
Centre Pompidou-Metz		F				S			F				F
Heydar Aliyev Cultural Center						S		S			S		S
Phoenix International Media Center									S				F
National Museum of Qatar									F				S

As it is observed from the table, free-form buildings structural system diversity increased over the years (From Solomon R. Guggenheim Museum, built in 1959 to National Museum of Qatar, built in 2019). The reason for this is the advancements in computer technologies which have facilitated the exploration of complex forms and the development of flexible computer-generated surfaces. These technologies have empowered architects to push the boundaries of traditional design limitations and unlock the potential for creating dynamic and visually captivating structures. Starting from Solomon R. Guggenheim Museum, built in 1959, the complexity of structural organization increased and the most recent case, National Museum of Qatar constructed in 2019, although it seems to have a comparatively simple system

composed of frame structures, the detailed analysis showed that the structural design was unique for the particular form, and it had innovative structural solutions.

The order of the structural systems, ranging from the most frequently used to the least used, was established as follows: section active, surface active, vector active, and form active. Additionally, it is crucial to emphasize that the selection of cases is not confined to specific building programs, scales, locations, or structural systems. The selection process remained consistent throughout the analysis to ensure objectivity. Consequently, the absence of form-active structural systems suggests that among the chosen cases, these systems are statistically less utilized.

Section-active structural systems, which are the most used, rely mainly on bending and can withstand various forces such as tension, compression, shear, and torsion. They provide efficiency through their component's shapes, material properties, and the uninterrupted nature of their members. They can create large open spaces without interruptions and allow to achieve long spans. This may be the reason that these systems are frequently used in free-form buildings. However, these section-active systems efficiency may be problematic in some conditions because even though these systems are versatile, they have varied stress distribution. Thus, they may result in unused capacity due to their adaptability to different load-bearing conditions.

The second most used systems, surface-active systems, comprise rigid surfaces capable of withstanding compression, tension, and shear forces by utilizing surface resistance and specific surface forms. One of the key advantages of surface-active systems in free-form buildings is their ability to distribute loads evenly across the surface. This is achieved through the continuity of the surfaces, ensuring that forces are efficiently transferred throughout the structure. By eliminating the need for traditional columns and load-bearing elements, surface-active systems enable the creation of large open spaces with long spans, which are often desired in free-form designs. The design and implementation of surface-active systems require careful consideration of form and material efficiency. Thus, shaping the surfaces to ensure optimal performance and prevent wasteful use of materials is crucial. By utilizing the enclosure structurally, load transfer through surface action becomes a suitable mechanism for supporting the building. Moreover, surface-active elements can be incorporated into other structural systems, enhancing their capabilities, and

transforming them into superstructures for themselves. This flexibility allows adapting and customizing the structural design according to the specific requirements of the free-form building. However, deviating from the efficient form may result in waste of materials and economic challenges.

As it is observed, form-active and vector-active systems are the least used systems through the cases. Form-active structure systems use flexible and non-rigid materials, which employ specific design elements and stabilization methods to redirect forces. These systems operate under single-stress conditions, where external forces and loading conditions govern the flow of forces. It should be noted that structures utilizing the form-active mechanism derive their shape from specific loading considerations, implying that free-form shapes cannot be designed without taking this loading into account as defined by Engel (1967). On the other hand, vector-active structural systems are composed of linear elements that redirect forces by splitting them into vectors along compressive and tensile elements in multiple directions. These systems employ straight members, which means that achieving free-form curved shapes is only possible through approximations using polygons. The size of the members plays a crucial role in determining the deviation between the intended curved shape and its polygonal approximation. Unlike bending, torque, or shear, the distribution of material stresses in vector-active systems is even across the cross sections of the members. This promotes efficient utilization of structural materials. However, it is important for the members to possess some resistance to section action to prevent instability and local bending. Although straight members impose limitations on form, structural efficiency is maintained and can still be employed if other elements of the structure are designed to resist bending through a different structural system.

Furthermore, the data illustrated in Figure 32, indicates that section-active structural systems are the predominant category for space generation, whereas form-active systems are the least utilized. On the other hand, for form generation, the distribution among different structural system categories is comparatively homogeneous.

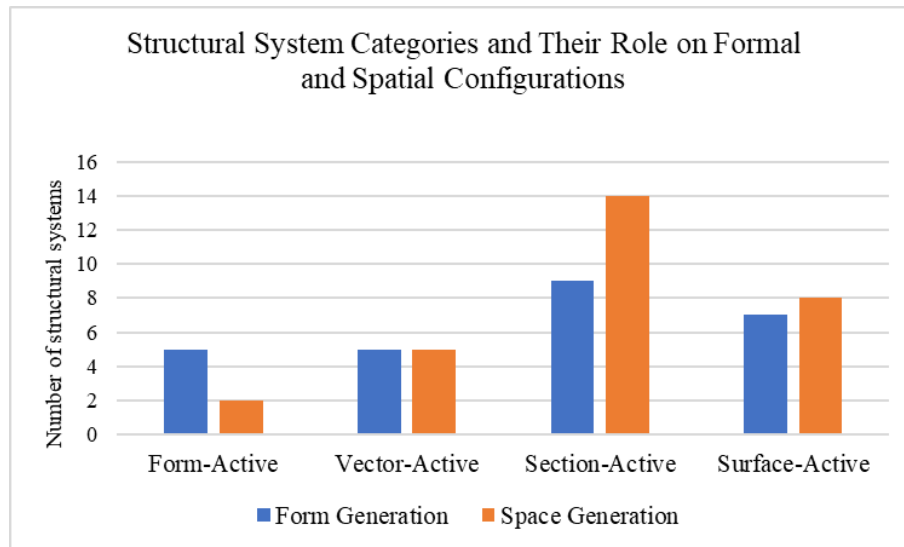


Figure 32. Structural System Categories and Their Role on Formal and Spatial Configurations

As stated in Chapter 3, the hierarchical organization of structural systems is necessary to understand free-form buildings which usually contain multiple structural systems as it is seen in Figure 32. These systems have distinct roles on space and form generation as it is indicated thus, their design and integration are critical for achieving structural efficiency while providing formal and spatial requirements.

6.2 Inclusion of structural systems in the design process and its impact on form and space integrity in free-form buildings

The emergence of free-form architecture has brought about a need to understand the role of structural design within its intricate design process. These varying design processes were categorized into three main topics: linear design process, structure-based design process, and integrated design process. Accordingly, the cases are analyzed, and the results are shown in Figure 33.

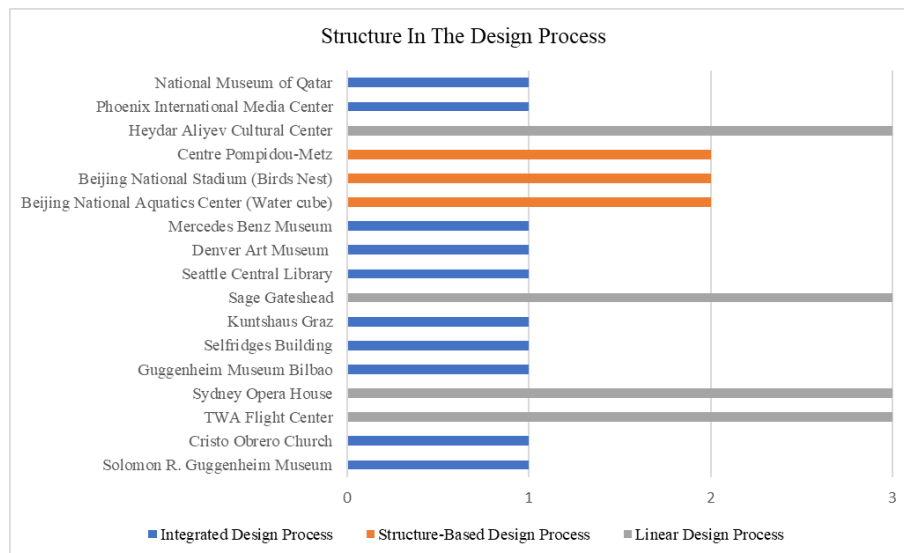


Figure 33. Structure in the design process

In linear design processes, the sequence typically involves first creating the form, followed by designing the structural system based on the form's geometric limitations, and finally making material choices. During this process, the form is often generated without considering the structural requirements or the need for an efficient structural system. This lack of integration between form and structure results in limited information related to the construction of the form. To make the form feasible, architects and engineers subsequently design a suitable structural system, select appropriate cladding materials, and add thickness to the building's outer layer. This separation of the structure from the form-making process can lead to the neglect of the structure's role in the aesthetic program. Through the cases, it is observed that four out of seventeen cases have a linear design process, and these buildings presented challenges in terms their design, realization, and construction.

A structure-based design process is an approach where the design of a building or structure is primarily guided by considerations of structural design. In this process, the structural system and its requirements become the starting point and the driving force for the design process. The emphasis is placed on understanding and incorporating the structural and material concepts early on in the design phase, with structure becoming the generative basis for the overall design. This approach shifts the focus away from purely formal factors and emphasizes the importance of integrating structural design parameters in the beginning of the process. Since the relationship between structure and architecture are closely intertwined in this

approach, the structural systems directly affect the form and spaces. Three out of seventeen cases had a structure-based design process.

The integrated design process involves the simultaneous development of form and structure in architectural design. It encompasses the integration of various disciplines and considers factors such as form-finding, mathematical geometry, and structural behavior from the early stages. Furthermore, structural analyses and optimizations modify the form, ensuring the integration of structural design throughout the entire design process. Buildings which have in integrated design process mostly use Building Information Modeling (BIM) which is a comprehensive and collaborative method to collect and share data among project participants. This integrated computational process enables the simultaneous consideration of form, structure, and material within a single model, streamlining the design process. The aim is to achieve cohesive and efficient design processes that involve all stakeholders and produce successful architectural outcomes. From the case studies, it is observed that they commonly have an integrated design process.

6.3 Key factors that influence the form reasoning process and the interplay between structure and form in free-form buildings.

The form analysis section of the table categorizes the form reasoning process for each case study building into visual properties, standardization in construction, and sustainability. Visual properties prioritize the overall aesthetic appeal of the building, encompassing elements such as shape, size, proportion, texture, color, and materials to create a visually pleasing and harmonious structure that enhances the surrounding environment. Standardization in construction involves rationalizing complex designs into manageable parts to facilitate efficient construction, especially in the case of free-form buildings with unique shapes that can pose challenges in terms of time, cost, and waste. The emphasis on rationalization becomes crucial for successfully constructing such structures. Lastly, sustainability focus on integrating performance-based strategies to minimize negative environmental impacts and improve energy efficiency in the built environment, aligning with sustainability goals and considering various technical, financial, spatial, social, and cultural factors in the design approach.

As observed in Figure 34, all the cases in the form reasoning process exhibited visual and standardization in construction. However, out of the seventeen buildings, only nine showed consideration for sustainability.

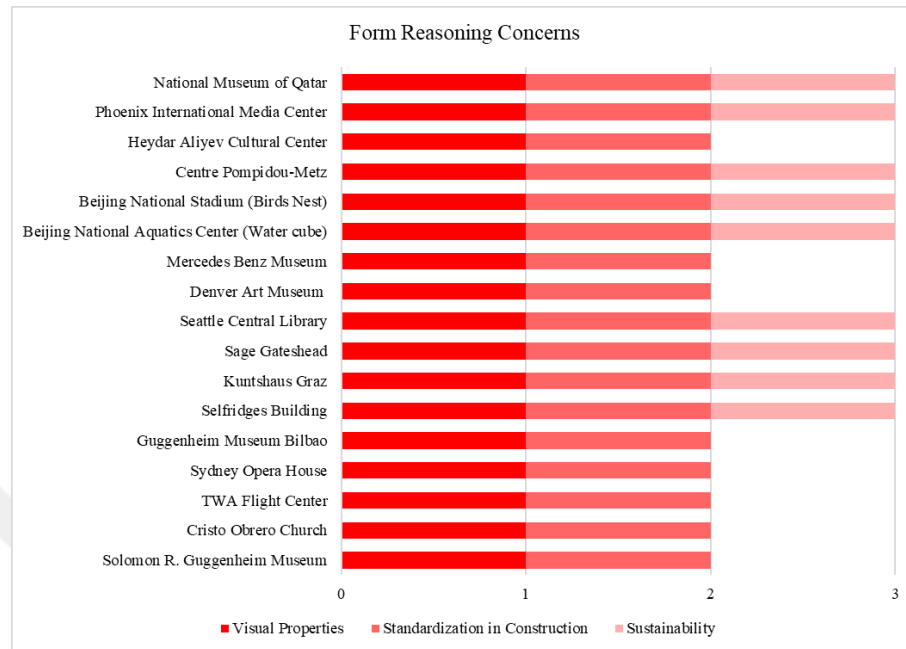


Figure 34. Form reasoning process of cases

6.4 Spatial organization and the interplay between structure and form in free-form buildings

As explained under the 4.2.3 Space Analysis section, the analysis contains two categories; categories obtained from horizontal spatial organization and categories obtained from vertical spatial organization.

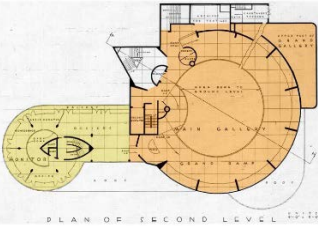
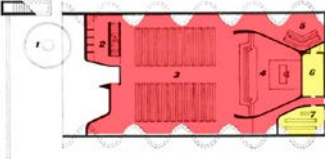
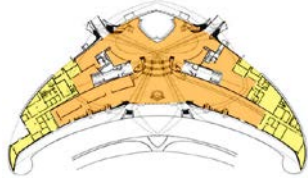
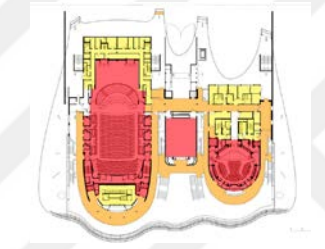
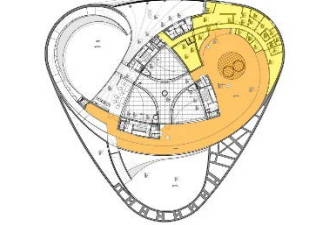
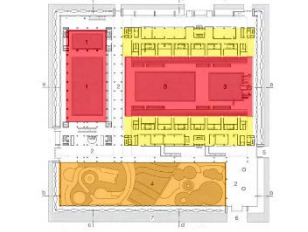
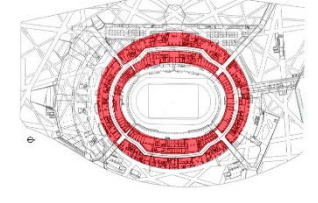
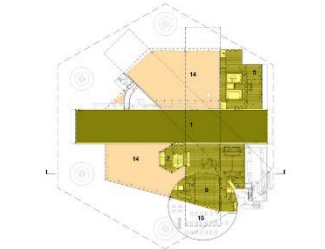
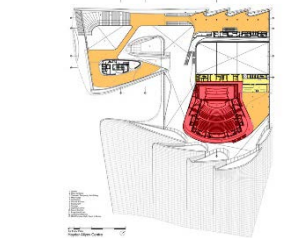
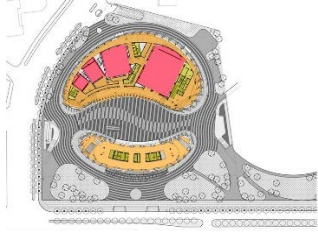
The plan drawings, where the horizontal spatial relationships are analyzed (see Table 6.2), indicate that flexible spaces are the most common spaces through the buildings. Form-defining spaces are spaces with unique functional and technological requirements that influence the overall form of the building. These spaces have specific functional and technical needs and play a significant role in determining spatial forms, such as auditoriums, conference rooms, and theaters. As it is observed through the cases, these spaces did not directly impact the building forms like they are supposed to do in terms of their definition. The main reason is that buildings have secondary and sometimes tertiary structural systems in addition to their primary structural systems. When this is the case, form-defining spaces cannot affect the form

of the building because they remain enclosed underneath the secondary and tertiary structural systems (tertiary structures existence is not necessary). The cases have two different spatial conditions related to this discussion. The first one is the Cristo Obrero Church which supports the argument that if buildings do not have secondary or tertiary structural systems, the form-defining spaces influence the overall form of the building. In this case, the structure, form, and space are all integrated. Second one, Beijing National Stadium has a different kind of relation where the form-defining spaces are shaped by the primary, secondary, and tertiary structural systems.

In addition, spaces that possess inherent flexibility and are influenced by the formal expression of the building's envelope exhibit adaptability, allowing them to be shaped by neighboring spaces or groups of spaces. Among the various cases examined, flexible spaces emerged as the most prevalent spatial type. This is primarily due to their compatibility with the complex, intricate, and irregular nature of free-form building forms and structures. The concept of flexibility in terms of formal expression, as outlined in Ching's spatial form categories, closely aligns with the methods employed by architects. Modernist architectural principles emphasize that the form originates from its interior. According to Le Corbusier's statement in 1985, the design of a building starts from the inside and extends to the outside, with the exterior reflecting the interior. This idea highlights the importance of spatial functions and their relationships in shaping the formal expression of a building's form. On the other hand, when architectural design prioritizes the building's form itself, with the spatial configuration dictated by that form, it can be described as a process of the building growing from the outside in. Both the "outside in" and "inside out" approaches, as emphasized by Venturi, R. (1992), represent significant aspects that generate a meaningful tension, constituting the essence of architectural production.

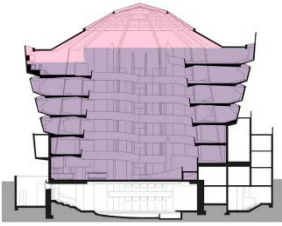
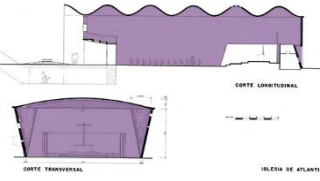
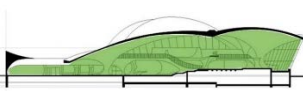
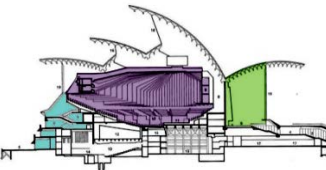
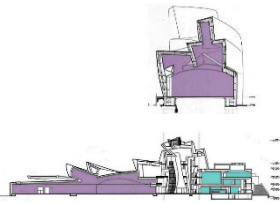
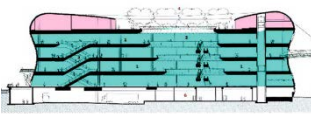
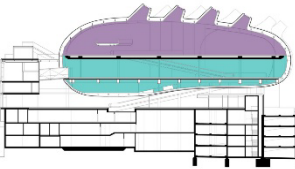
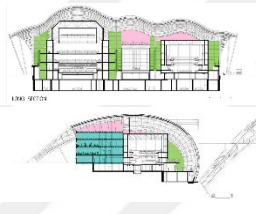
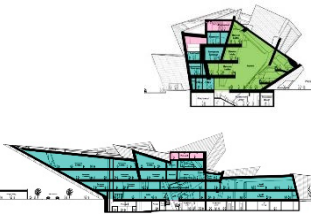
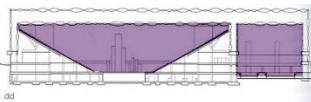
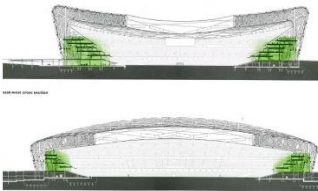
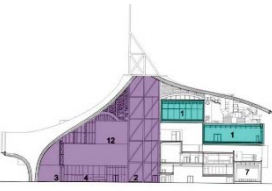
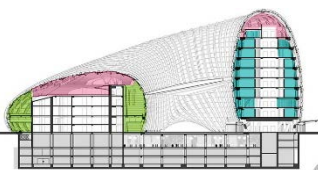
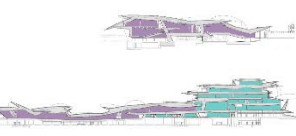
Moreover, clustered spaces are comprised of spaces arranged in clusters, which can serve multiple functions and possess compact yet distinct purposes. Examples of such spaces include office modules, which can be arranged into clusters. In various cases, it is evident that clustered spaces either coexist alongside form-defining spaces, if present, or operate independently from the limitations imposed by the structural systems and form when flexible spaces are dominant.

Table 6.2 Categorization of spaces in plan drawings

Solomon R. Guggenheim Museum  PLAN OF SECOND LEVEL 1:21.25	Cristo Obrero Church 	TWA Flight Center 
Sydney Opera House 	Guggenheim Museum Bilbao 	Selfridges Building 
Kunsthhaus Graz 	Sage Gateshead 	Seattle Central Library 
Denver Art Museum  + 1 Floor Plan	Mercedes-Benz Museum 	Beijing National Aquatics Center 
Beijing Natinal Stadium 	Centre Pompidou-Metz 	Heydar Aliyev Cultural Center 
Phoenix International Media 	National Museum of Qatar 	Horizontal spatial organisation - Clustered Spaces - Form-defining spaces - Flexible spaces

Through the section drawings, vertical spatial relationships are analyzed (see Table 6.3). Set-back spaces which refer to spaces that have visual or spatial continuity by detaching from the building form/envelope. And these indicate that, the form specifies the appearance of these spaces. Furthermore, conjoint spaces which refer to spaces that are situated on distinct levels, entirely isolated from one another, and adjacent to the building form/envelope indicate that they are not necessarily the outcome of the flexible character of free-forms. They are similar to the spaces in traditional building forms; however, the form dictates the appearance of the small segment of these spaces that are visible. On the other hand, solo spaces, which express singular spaces that fully interact with most of the building form/envelope, are the spaces that show the features of the form the most. This can lead to either the form being directly influenced by the solo spaces, or the form of the solo space being determined by the building envelope's form. Moreover, attic spaces, which refer to areas situated at the upmost levels of the buildings have a significant connection with a substantial portion of the building's form/envelope. Their form is primarily determined by the form.

Table 6.3 Categorization of spaces in section drawings

Solomon R. Guggenheim Museum 	Cristo Obrero Church 	TWA Flight Center 
Sydney Opera House 	Guggenheim Museum Bilbao 	Selfridges Building 
Kunsthaus Graz 	Sage Gateshead 	Seattle Central Library 
Denver Art Museum 	Mercedes-Benz Museum 	Beijing National Aquatics Center 
Beijing Natinal Stadium 	Centre Pompidou-Metz 	Heydar Aliyev Cultural Center 
Phoenix International Media 	National Museum of Qatar 	Vertical spatial organisation - Set-back spaces - Conjoint spaces - Solo spaces - Attic spaces

6.6 General Assessment

As it is explained in detail under section 4.1.5, the analysis tables included a part named general assessment contains general expositions of the table. In this part, the information that is gathered from all of the categories is presented in an organized manner.

The evaluation of the "Structure and Form Relation" is based on the hierarchical classification of the structural system, comprising primary and secondary structures. Within this framework, structural elements are categorized according to their role and significance in supporting the overall load of a building. The primary structure encompasses load-bearing components responsible for stability, transmitting the building's weight to the foundation, and resisting external forces. On the other hand, the secondary structure complements the primary elements by distributing the load evenly throughout the building, thereby enhancing its structural integrity. This study argues that a stronger relationship between structure and form is achieved when the primary structural system predominantly shapes the building's form. Such instances get a higher score of 2. Conversely, if the secondary structural systems predominantly influence the building's form, leading to shared roles among the structural systems, the structure-form relationship is weaker, assigned a lower score of 1. As it is observed, some of the structural systems would generate the spaces and some of them would generate the form (see Table 6.1) thus, this organization effects the direct dictation of the structure on the formal expression. Figure 35 shows that thirteen out of seventeen free-form buildings have secondary structures where the structure and form relations are indirect.

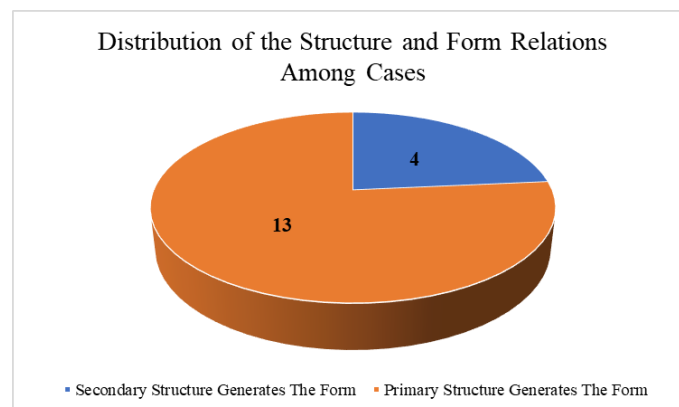


Figure 35. Distribution Of Structure and Form Relations Among Cases

As it is mentioned under section 4.2.1, there are three sub-categories which are visual properties, standardization in construction, and sustainability. So, if a building had a comprehensive form reasoning process which relates to multiple categories, has a higher score. In Figure 36, it is observed that each free-form building had covered two topics during their form reasoning process. Moreover, the analysis tables indicate that in all cases two topics, visual properties, and standardization in construction, were covered, however only eight of them covered sustainability in addition to these.

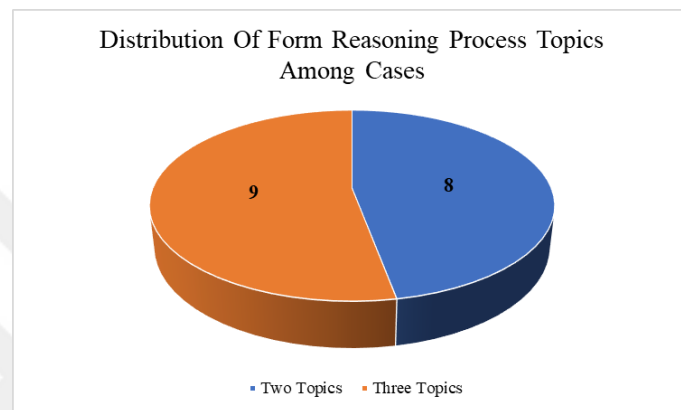


Figure 36. Distribution Of Form Reasoning Process Topics Among Cases

In each instance, the architects demonstrated a keen awareness of the visual impact their designs would have on the surrounding environment. They skillfully employed elements such as shape, proportion, texture, color, and choice of materials to create visually captivating structures that harmonized with their context while leaving a lasting impression on observers.

Moreover, standardization in construction was given due diligence, translating intricate and non-repetitive design concepts into practical and manageable building components. The architects adeptly navigated the complexities of free-form geometries, breaking them down into smaller, feasible units using standard construction techniques and materials. This rationalization process was vital in ensuring the successful execution of their visionary designs, mitigating potential challenges related to time, cost, and waste during the construction phase.

Furthermore, the integration of sustainability into the form reasoning process illustrated a commitment to sustainable and responsible architecture. By prioritizing performance-based strategies, the architects sought to minimize negative

environmental impacts and enhance energy efficiency in the constructed environment. This environmentally conscious approach not only reflected a commitment to addressing pressing global concerns but also served as a testament to the architects' dedication to creating buildings that coexist harmoniously with the natural world.

On the other hand, the “Structural Systems in Design Process” part is related to the Structural Analysis explained under section 3.3. The integrated design process involves architectural and structural design, while form and structure develop simultaneously during the design process. Figure 37 shows that ten out of seventeen buildings had an integrated design process.

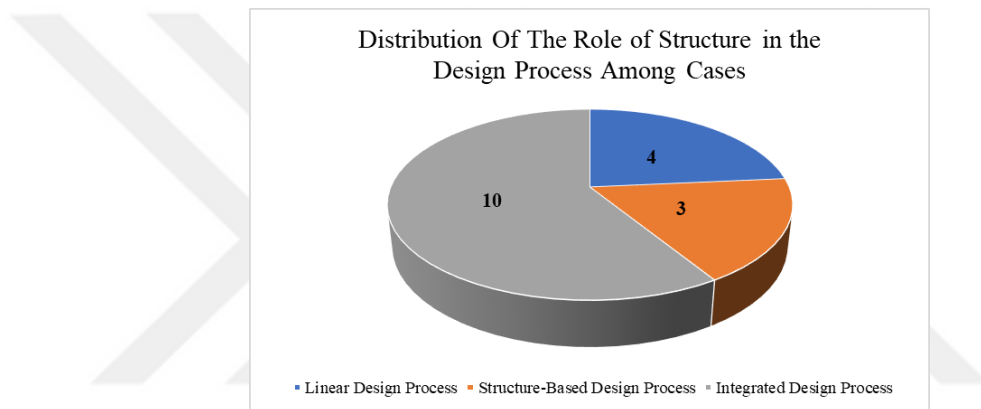


Figure 37. Distribution Of the Role Of Structure In The Design Process Among Cases

Lastly, the “Space and Form Compatibility” part is based on the Space Analysis thus, and Table 6.3 provided the necessary data. Figure 38 shows that the distribution among buildings space and form compatibility conditions are homogenous.

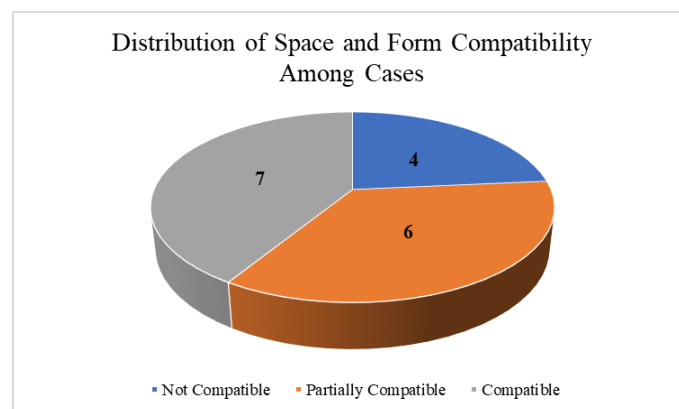


Figure 38. Distribution Of Space and Form Compatibility Among Cases

As mentioned previously, the general analysis sections of the tables are responsible for examining and rating various scenarios. Figure 39 presents these distinct conditions observed in seventeen free-form buildings. Despite the diverse parameters associated with structure, form, and space relationships, the cumulative evaluation scores enable comparisons and contrasts regarding the integration among structural systems, form, and spaces within the buildings. Furthermore, the organization of cases based on the timeline allows for the observation of changes over the years.

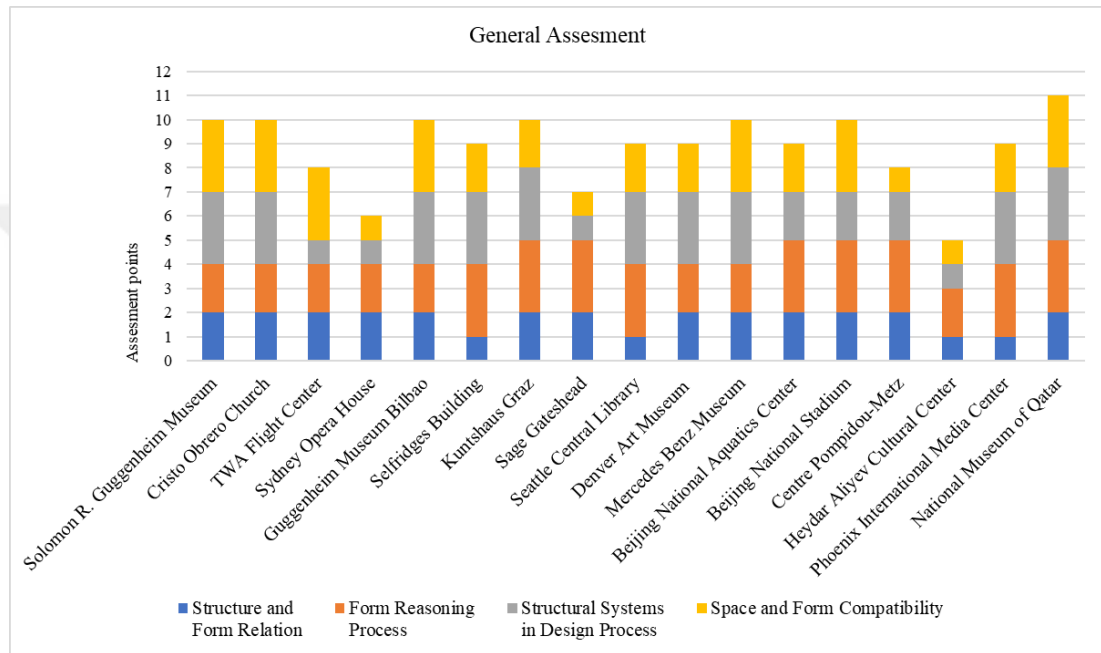


Figure 39. General Assessment Through Cases

In conclusion, this study has provided a comprehensive analysis of the relationship between structure, form, and space in free-form architecture. The evaluation of the structure and form relation was based on a hierarchical classification of the structural system, distinguishing between primary and secondary structures. The primary structure, consisting of load-bearing components, has a critical role in shaping the form of a building by transmitting weight, ensuring stability, and resisting external forces. In contrast, the secondary structure complements the primary elements by distributing the load evenly, thereby enhancing structural integrity. The findings suggest that a stronger relationship between structure and form is achieved when the primary structural system predominantly shapes the building's form, while a weaker relationship arises when the secondary structural systems have a more influential role, resulting in shared roles among the structural systems.

Furthermore, the study emphasized the importance of considering multiple categories, including visual properties, standardization in construction and sustainability through the form reasoning process. The comprehensive evaluation of free-form buildings revealed that each building had at least two concerns, with sustainability being optional. On the other hand, the integration of form and structure in the design process is highlighted, as an integrated approach involving simultaneous development of form and structure contributes to the successful realization of free-form buildings. In relation to this, the analysis of space and form compatibility demonstrated that the cases have various conditions that are equally distributed as compatible, partially compatible, and not compatible.

Despite the diverse parameters associated with structure, form, and space relationships, the cumulative evaluation scores allowed for meaningful comparisons and contrasts regarding the integration among structural systems, form, and spaces within the buildings. The organization of cases based on the timeline further enabled the observation of changes and developments in free-form architecture over the years. Overall, these findings provide important insights on the complex interplay between structure, form, and space, contributing to the design and evaluation of free-form buildings. Architects and designers can leverage this knowledge to inform their decision-making processes and create innovative architectural solutions that achieve harmonious relationships among structure, form, and space.

CHAPTER 7

CONCLUSION

Since the exhibition at the Museum of Modern Art (MOMA) was held in 1998, the popularity of free-form architecture has increased. These free-form buildings are driven by the desire to push boundaries, to challenge conventional notions, and explore novel materials and concepts related to architectural form and structure. This exploration has brought to light the significance of previously overlooked aspects, such as manipulating surfaces and articulating spaces. However, at its core, architecture is about understanding the relationship between mass and space, with form serving as the crucial link between them. The quality of buildings depends on a designer's ability to effectively utilize and connect the elements of form within the spaces and the context. In terms of the three fundamental principles in architecture, *utilitas*, *firmitas*, and *venustas*, which were introduced by the ancient Roman architect Vitruvius, it is possible to provide a comprehensive framework that guides architects in achieving a balance between functionality, structural integrity, and visual appeal in their designs (Eekhout et al. ,2015 ,WBDG Aesthetics Subcommittee, 2016).

To briefly mention, *Utilitas* emphasizes the importance of functionality and practicality in architectural design, ensuring that a building efficiently serves its intended purpose and serves for the needs of its users. *Firmitas* focuses on the structural stability and durability of a structure, considering the selection of appropriate materials and construction techniques to create a stable and long-lasting building. And *Venustas* highlights the significance of aesthetic beauty, proportion, and harmony in architectural design, aiming to create visually pleasing structures that evoke a sense of delight and emotional response. During a time when architectural forms were constrained by available materials and construction techniques, those who followed in Vitruvius's footsteps had a limited range of aesthetic principles.

However, modern culture values a variety of architectural styles, and it fosters the development of new architectural vocabularies. Considering this emphasis on diversity, designers agree that the most successful design arises from a comprehensive approach. Thus, the discipline of architecture, particularly free-form design, has evolved beyond the classical notion of Vitruvius' three principles.

Briefly, free-form architectures possess a notable attribute in its capacity to produce visually striking, iconic appearance. These distinct forms often acquire the status of landmarks and cultural symbols, thus contributing to the unique identity and character of a city or region. Furthermore, free-form buildings seamlessly blend distinct shapes and fluid design elements, often incorporating captivating irregular curves and tilts. The purpose is to emphasize the profound impact of various influences on the design process, including aspects like separation, fragmentation, and distortion. By departing from conventional building norms, free-form architecture empowers architects to delve into unconventional geometries and push the boundaries of form and expression, resulting in structures characterized by organic and amorphous shapes, intricate geometries, and polished surfaces.

At the core of free-form architecture lies a profound understanding of the relationship between mass and space, where form serves as the vital medium connecting them. Architects' ability to skillfully integrate the interior and the surrounding outdoor spaces of buildings plays a pivotal role in shaping the quality of architectural forms. As designers embrace this approach, they must consider both the inside and the outside aspects of their creations, ensuring a holistic design that responds to specific site conditions and cultural influences, resulting in highly personalized and context-sensitive free-form buildings. Additionally, free-form architecture offers optimized functionality as its lack of rigid geometries allows for flexible spatial planning. This adaptability ensures that interior spaces can be tailored to meet specific functions and requirements. Together with advanced technologies, architects can bring intricate free-form structures to life with precision and efficiency.

A fundamental goal of designing free-form buildings is to establish a harmonious relationship between the built environment and its surroundings. These structures have the remarkable ability to respond to the site's context, topography, and natural

elements, fostering a sense of unity and integration. This sensitivity towards the environment nurtures a sustainable approach to design, enabling the optimization of solar orientation, natural ventilation, and energy efficiency within the buildings. Consequently, free-form architecture not only represents a cutting-edge design approach but also embodies a responsible and conscientious vision for the future of architecture.

While free-form architecture opens up new horizons for architectural design, it also presents its share of challenges. The complexity of construction, elevated costs, and the seamless integration of building systems and structural integrity require careful consideration and expertise. Nevertheless, free-form buildings might excessively emphasize aesthetics at the expense of structural rationality and spatial quality due to their infinitive innovative solutions. Thus, the possibilities and constraints of their flexibility concerning architectural components, structure, form, and space required exploration.

In this study, the aim was to evaluate the influence of structural systems on the integrity of form and space in free-form buildings. The methodology employed involved a case study approach, analyzing seventeen pioneering free-form buildings through a comprehensive analysis table that consists of: general information and graphics, form analysis, structural analysis, space analysis, and general assessment. The exploration of free-forms has led to a greater understanding of their definitions and distinctive characteristics, revealing their potential to challenge traditional geometric forms in architectural design. Furthermore, the study has highlighted the significant role of appropriate structural systems in influencing the formal and spatial arrangements of free-form buildings.

Through the analysis on seventeen free-form buildings, it is concluded that the increasing diversity of structural systems in free-form buildings can be attributed to the advancements in digital design, manufacturing, and realization techniques which have allowed architects to explore complex forms and develop flexible surfaces. Also, the progression of structural organization complexity over time becomes evident, showcasing innovative and unique approaches. Among the structural systems used through the cases, section-active and surface-active systems are the most common. Section-active systems provide efficiency through component shapes

and material properties, enabling the creation of large open spaces and long spans. However, their adaptability to different load-bearing conditions may lead to unused capacity. On the other hand, surface-active systems distribute loads evenly across surfaces, eliminating the need for traditional load-bearing elements and allowing for the creation of large open spaces. For this, it is crucial to consider form and material efficiency carefully to achieve optimal performance. Form-active and vector-active systems are less commonly used, with form-active systems utilizing flexible materials and specific design elements, while vector-active systems employ linear elements to redirect forces.

Furthermore, understanding the hierarchical organization of structural systems is crucial in comprehending free-form buildings, as each system plays a distinct role in shaping the space and form. Effective integration of these structural systems becomes critical for achieving both structural efficiency and meeting the formal and spatial requirements of the design. Unlike traditional rectilinear buildings that may rely on regular and repetitive structural components, free-form buildings demand a more tailored approach, where each structural system must be carefully customized to suit specific areas and respond to unique forces. This necessitates a deep understanding of how different systems interact and support each other, ultimately leading to the creation of an integrated and efficient building.

The successful integration of form and structure in free-form buildings heavily relies on the design process employed. The linear design process, characterized by the independent creation of form without considering structural requirements, often leads to construction challenges and neglects the aesthetic role of the structural system. In contrast, the structure-based design process prioritizes structural design factors from the outset, resulting in a design that is primarily driven by the requirements of the structural system. However, the most effective approach is the integrated design process, which incorporates form-finding, mathematical geometry, and structural behavior from the early stages. This process utilizes tools like Building Information Modeling (BIM) to facilitate collaborative data sharing among stakeholders. By embracing an integrated design process, architects can ensure cohesive and efficient design processes that lead to successful architectural outcomes. The analysis of case studies reinforces the effectiveness of the integrated design process in achieving the desired integration among form, structure, and space.

In the design of free-form buildings, tension and compression members may be strategically placed to support the sweeping curves and cantilevers, distributing loads efficiently and ensuring stability. Additionally, advanced computational tools and simulations can be utilized to analyze the complex forces acting on the structure, aiding in the optimization of structural components and their connections. This integrated approach not only contributes to the stability and safety of the building but also allows for a more creative and expressive architectural outcome.

Consequently, the integration of structural systems in free-form buildings goes beyond mere functionality; it becomes an integral part of the overall design concept. The structural elements themselves can contribute to the aesthetics of the building, showcasing the beauty of engineering and celebrating the dynamic forms that characterize free-form architecture. In this way, the structural systems become an essential element of the architectural expression, enhancing the visual appeal and cultural significance of the building.

Moreover, the analysis of horizontal and vertical spatial organization in free-form buildings provides valuable insights into the relationship between form and space. Plan drawings reveal that flexible spaces, which accommodate the complex and irregular nature of free-form forms and structures, are the most prevalent. Also, flexible spaces, influenced by the formal expression of the envelope, exhibit adaptability, and can be shaped by neighboring spaces. In contrast, form-defining spaces, with specific functional and technological requirements, often do not directly impact the form of the building due to the presence of secondary and tertiary structural systems. Nevertheless, some cases demonstrate that in the absence of these additional systems, form-defining spaces can indeed influence the overall form. In terms of clustered spaces, which are arranged in clusters and serving multiple functions, can coexist alongside form-defining spaces or act independently. In terms of vertical spatial relationships, set-back spaces, conjoint spaces, solo spaces, and attic spaces demonstrate the varying degrees of influence the building form has on these spaces. Ultimately, the analysis highlighted the intricate interplay between form and space in free-form buildings and how they affect each other throughout the design process. If the design process is dominated by the building's form and shapes the spatial configuration based on that form, it can be described as a process where the building grows from the outside in. These contrasting approaches, known as

"outside in" and "inside out," as highlighted by Venturi, R. (1992), play essential roles in creating a significant tension that forms the essence of architectural production.

The findings and discussions from the analysis indicate that contemporary free-form buildings contain overly complex and hierarchical structural organization, such as primary and secondary systems. These have significant influences on the formal and spatial configurations and have various interrelations. Likewise, the form reasoning process for each case showed that emphasis on visual, construction and sustainability contributed to an integrated building design. Because this holistic perspective on architectural design ensured the creation of integrated and cohesive buildings that seamlessly merged functionality, artistic expression, and environmental responsibility.

Furthermore, a considerable portion of the analyzed buildings prioritized the integration of structural and architectural design processes. However, it is observed that to ensure the integrity of form and space, it is imperative to consider various scenarios and foster simultaneous development of the design parameters. In addition, the study showed a remarkable level of consistency in agreement between domain and format across the cases analyzed. Related to the research question whether an integrated design process for a free-form building is sufficient to ensure the integrity of form and space, it is founded that these buildings necessitate a distinct perspective and specialized design knowledge on structural systems. According to these findings, this study suggests that an integrated design process should be supported by a comprehensive knowledge of structural systems, their hierarchical organization and how they simultaneously effect formal and spatial configurations.

Besides, it is important to note that analyzing the structural systems of free-form buildings posed unique challenges that require a different approach compared to conventional buildings because intricate and unconventional shapes of free-form buildings introduced complexities that demand specialized analysis techniques. Since free-form buildings challenge these norms by incorporating irregular forms and unique spatial arrangements, the complex geometries and non-linear load paths of free-form structures necessitate advanced computational modeling, sophisticated structural analysis tools, and innovative design strategies. The irregular distribution

of loads and the interplay between form and structure require engineers to adopt a holistic approach, considering both the aesthetics and the structural integrity. Therefore, designing free-form buildings and their structural systems requires expertise, adaptability, and a departure from the conventional methods employed for regular buildings.

Another important point is that this thesis is one of the first and few efforts to analyze the structural systems, form, and space parameters simultaneously. By doing so, it aimed to fill the gap in literature and contribute to a clearer understanding of this complex subject matter. Moreover, this research effort serves as a fundamental reference point for defining the concept of free-form architecture, highlighting the prevailing conceptual ambiguities, and demonstrating the multifaceted nature of the topic. The implemented research methodology and case studies provided a systematic framework that not only clarifies the theoretical aspects but also showcases the practical manifestations of the observed phenomenon in real-life contexts. Through this comprehensive approach, the thesis advances our understanding of the intricate relationships between architectural form, structural systems, and spatial configurations, offering valuable insights for improving design practices, education, and further research endeavors.

To contribute to future studies, it is crucial to consider the limitations of this thesis. Several constraints are associated with this study, and they should be considered in future research endeavors. Firstly, it is essential to acknowledge that the case numbers are relatively small, encompassing seventeen free-form buildings that were included in the case study. While the thesis study provides valuable insights into the order of structural systems based on frequency of use, it presents a limitation in the absence of form-active structural systems among the selected cases. This implies that the study may not offer a comprehensive representation of all possible structural approaches, potentially limiting the generalizability of the findings. To address this weakness and enhance the study's comprehensiveness, future research could explore a larger and more diverse sample of architectural projects. Including a broader range of building programs, scales, locations, and structural systems would provide a more robust dataset for analysis. Additionally, conducting a comparative study of form-active structural systems in conjunction with the other identified systems could shed light on their relative merits and applications in various architectural contexts. Such

efforts would contribute to a more holistic understanding of the utilization and significance of different structural systems in contemporary architecture.

Secondly, while the current research focuses on specific criteria such as structural systems, formal configurations, and spatial aspects, it is important to recognize that there are other significant factors related to free-form buildings that warrant consideration. These include aspects such as cultural significance, environmental performance, material selection, and manufacturing techniques. Future investigations should aim to incorporate these additional dimensions to provide a more holistic understanding of free-form architecture.

Thirdly, it is crucial to note that this study is confined to buildings that were either completed or under construction during the research period, thereby limiting the examination of potential future advancements in free-form building design and construction. Future studies should strive to include a longitudinal perspective, allowing for the exploration of emerging trends, technological advancements, and innovative approaches to free-form architecture.

Finally, the educational dimension of this research holds immense potential for further exploration. Incorporating the findings and insights from this study into architectural education can be instrumental in fostering the development of specialized courses, workshops, and design studios focused on the integration of structural systems with the form and spatial aspects of free-form buildings. By doing so, architectural students can acquire a deeper understanding of the intricate relationship between structure, form, and space, and gain the necessary skills to design in a manner that seamlessly integrates these elements within the context of free-form architecture. By incorporating real-world case studies, hands-on experiences, and multidisciplinary collaborations, architectural education can equip students with the necessary knowledge, skills, and critical thinking abilities to engage with and shape the future of free-form architecture. Moreover, cultivating this skillset will prove advantageous in various design contexts beyond just free-form building designs. The ability to integrate structural systems with form and space will be invaluable across a wide range of architectural projects, allowing designers to create cohesive and harmonious designs that prioritize both aesthetic appeal and structural rationality.

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