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數位化綠建築：

結合數位科技及永續設計的新設計過程

Digital-Green Architecture:

A new design process that integrates digital technology and sustainable concepts

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中文摘要

隨著數位科技的蓬勃發展與技術應用的日益普及，這個時代所追求的建築不再侷限於外在形體，不論是數位建築或綠建築的發展進程，都朝向數位軟體與資訊科技的運用，期許以數位整合多面相的趨勢前進。然而，當數位建築過於傾向技術層面的設計方法時，建築師所追求的不應僅是建築技術或形體上的突破，更大的考驗則在深入探討新設計過程的同時，得以了解數位建築真正的重要性。因此，本論文提出數位綠建築(Digital-Green Architecture)的新觀點，思索在數位與節能功能並進的年代，如何融合數位化技術與節能功能於設計的思考及過程，藉由「數位綠建築」重新詮釋數位建築的設計思考模式，進而系統化的結合數位與節能的元素，發展新的數位綠建築理論(Theory of Digital-Green Architecture)。在數位科技與發展節能需求並重的設計中，經由設計過程(Design Process)、設計媒材(Design Media)與設計結果(Design Outcome)三項設計架構的分析，將所衍生數位綠構築的元素特徵，加以歸納為十二個結合數位與永續設計的新構築因子，藉以探討新的數位綠建築理論與設計過程的變化。

Abstract

The trend of digital freeform in association with high-tech technology and the awareness of sustainable issues have propelled the development of architecture to a new level by comprehensively merging digital architecture and green concepts during the design process. There are several critical phenomena of digital-yet-green tectonics (so called the Digital-Green) evolving due to broad applications in the design process, design media and design outcomes. Based on preliminary thinking of Digital-Green architecture, twelve factors are generated through the structure of the design process, design media and design outcomes. The factors are employed to analyse ten chosen projects, wherein the digital and sustainable concerns are portrayed for a comprehensive overview. From this, a more systematic framework is suggested for integrating digital and sustainable elements and processes to explore a new approach for understanding the new needs in the era of Digital-Green Architecture. The design process is no longer a result of a parallel development between new sustainable thinking and digital tectonics but a comprehensive fusion of both. This new approach may elevate the design process from a bilateral stream to a unified level where the impact of streamlining sustains digital and sustainable development in the future stage of architecture.

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Chapter 1 Introduction

1.1 Introduction

Digital technology has made free-form designs in architecture possible through computer-aided design media. These technological developments have raised the bar, enriching the field with extraordinary knowledge and potentialities, and are making the building of the impossible much more possible (Mitchell 1990). As architecture has made the leap into the digital age, new technologies have also transformed the way architects and researchers approach sustainability and other environmental issues. Therefore, these parallel developments suggest that a new theory is necessary to explore the relationship between sustainability and architecture in the digital age.

With the advanced technological capacity to compute, calculate, and simulate, contemporary architecture should no longer be directed only towards aesthetic and functional aspects, but should also consider habitability, self-sufficiency, and sustainability (McDonough 2002; Koleravic 2004). The development of the green concept has advanced from linear focus on energy saving to “non-linearity” (Deleuze 1987; De Landa 2000; Koleravic 2004). It is important that buildings are redesigned to be more self-sufficient and self-organized, with the capacity to generate renewable energy. Traditional architectural methods are changing in conjunction with the invention of new technologies and the concern about sustainable issues. The integration of

CAD/CAM technologies and concepts of sufficient/sustainable buildings is no longer only a vague discussion but an important part of the progression of values in architecture (Emery 2002). Therefore, the emerging digital design process must accommodate energy-saving and environmental concerns, as researchers and digital architects attempt to integrate sustainable innovation into contemporary architecture. Integrating an understanding of classical, digital and sustainable historical backgrounds, a more systematic framework is needed to integrate all of these elements into a comprehensive design process.

1.2 Problem Statement and Objective

When using digital CAD/CAM technologies, Rapid Prototyping (RP) and Computer Numeric Control (CNC), architects and researchers recognize the need for a new digital design process to increase efficiency (Mitchell 1998; Ryder et al. 2002; Burry 2002; Kolarevic 2003; Sass 2004; Schodek et al. 2005; Dritsa 2004; Lim 2004; Lee 2005). The traditional stages of the design process—including schematic design, design development, detail design, and construction—have evolved into a new structure with the use of the digital design process. This evolution suggests four new stages in the design process, including computational concept design (topological space, isomorphic surfaces, motion kinematics and dynamics, keyshape animation, parametric design, and genetic algorithms), analysis, manufacture, and assembly method (Kolarevic 2000).

The distinctive features of this dissertation are to re-organize the design process such that digital and sustainable factors are incorporated in a comprehensive fashion. It is time to rethink how the marriage between digitalization and green concepts can reshape the existing process of digital architecture. The question is whether the free forms reveal not only buildings applying higher technology but also sustain the needs of green innovation. Could the merger of digitalization and green concepts unlock the potential of both cutting-edge design and sustainable characteristics? How are the new digital and green elements acquired from the old classical elements? How can the classical factors, sustainable factors, and digital factors function together with new digital-green factors? The digital free forms are created by these technology initiatives and are combined with new, sustainable materials to generate new approaches in design. How do the new design approaches differ from the classical ones? Are the old factors still useful in the new framework? How does the evolution of technology and design fit with the theories of the past? Further, how does this new design process influence the adoption of new construction methods?

The relationship between the preliminary theory of digital-green architecture and its new design process are an important consideration. The goal is to explore the possible ways of merging digitalization and sustainability from the existing digital/sustainable buildings and possible developments in the future, to fulfil the dual purposes of architectural aesthetic and energy-efficient functions. What is more significant is to respond to the environmental needs of sustainability by the introduction of a new design process. Through the discussion of “digital and sustainable architecture,” architects must re-evaluate the new structure of the design process to address the broader sustainable needs of the structures. This exploration could elevate the design process from a micro to a macro level. Perhaps architects can focus on a comprehensive fusion of new design processes and the overall interactions of digital technology and sustainable thinking. Planning would go beyond simply applying green building standards; rather, new design processes would use the expressions of free-form designs and digital technology to merge developments in both areas with the new sustainable movement. The purpose of this dissertation is to develop a perspective that moves from the idea of the design of a digital sustainable object to an extensive design process that integrates both digital technologies and green issues. Such a shift in perspective will emphasize the broad range of issues in the design process that intimately bond digital architectural manipulation and sustainable expressions.

1.3 Methodology and Steps

The main purpose of this research is to determine whether digital free-form design, integrated with new technologies and ecological concerns, may contribute to the sustainable needs of a New Digital-Green design process. To explore this question, a four-step approach to research will be used. These steps include:

1) Select ten cases for a comprehensive evaluation of factors used in the new design process;

2) Construct a framework to analyze the logic and characteristics of factors used in the digital-green design process;

3) Analyze the cases based on the framework designed to examine the digital-green design process; and

4) Incorporate the elements of general, sustainable, digital, and preliminarily digital-sustainable architecture in order to devise a new model for the Digital-Green design process.

1.3.1 Step One: Selection of Cases

Ten projects were selected for both their digital and green possibilities in the new architectural conceptualization. The ten cases were selected based on several criteria.

1) Projects were selected from a variety of countries in Asia, the Middle East, North America, and Europe, with varying site conditions and weather patterns. This variety presents different concerns and challenges in terms of the design and construction processes when integrating digital technologies and sustainable issues.
2) The structures embrace different architectural scales, from a small-scale private residence to a large public pavilion. The ten cases include three office buildings, one factory building, two showrooms/mixed-use buildings,

one educational building, and one bridge construction. With the wide range of building types, the features of digital and green emergence have been revealed and processed.

3) Cases are architectural projects from a targeted time period; in this case, from 1999 to 2011. With the improvement of technologies and the increasing level of sustainable issues, the focus during these years has been on the digital and sustainable applications in architecture.
4) The chosen architects are sophisticated in experimenting with designing digital architecture with elements of sustainability. Award-winning designers and architects experienced in the digital design process with sustainable thinking are included.

By analysing the design processes that involve digital manipulation and sustainable design thinking, the examination of the ten cases aims to explore various characteristics of digital-green architecture. Using these ten projects, the relationship between digital technologies and sustainable characteristics plus the logic of design processes are explained with broader applications.

TABLE 1. Selected Case Studies

Case #	**Project Name**	**Architect(s)**	**Location**	**Year**
Case 1	Swiss Re Headquarters	Foster and Partners	London	1999
Case 2	Chesa Futura	Foster and Partners	Switzerland	2004
Case 3	Carbon Tower	Peter Testa and Ove Arup	Dubai	2005
Case 4	BMW WELT Munich	COOP Himmelb(L)au	Germany	2007
Case 5	Silver Drop	Steven Holl	Connecticut	2007
Case 6	Zaragoza Bridge Pavilion	Zaha Hadid	Spain	2008
Case 7	CSET Building	Mario Cucinella Architects	Ningbo, China	2009
Case 8	Japan Pavilion	Yutaka Hikosaka	Shanghai	2010
Case 9	Nine Bridges	Shigeru Ban	South Korea	2010
Case 10	EEA and Tax offices	UN Studio	The Netherlands	2011

1.3.2 Step Two: Analysing Framework

The preliminary structure of digital or sustainable architecture might be insufficient for the needs of digital-green design process. Therefore, it is necessary to apply new factors to analyze the effectiveness of integration of both digital technology and sustainable concepts in the new design process. In addition, it is important to determine whether classic factors can be further extended or can coexist in the new design process. The use of computers and CAD/CAM technology in the design process transformed the expression of digital architecture into a combination of digital and sustainable operations. A comparison of these two sets of factors can be analyzed to determine which will support the foundation for a new design process.

1.3.3 Step Three: Case Analysis

The third step is designed to portray the characteristics of the ten selected projects through the review of twelve Digital-Green factors. The ten projects, with both digital and sustainable factors, will be reviewed chronologically from 1999 to 2011. It is anticipated that by employing the new Digital–Green factors to review the selected projects, the digital and energy-efficiency related issues will be systematically analyzed. Throughout this time period, the importance of technology sophistication and the concerns of sustainability have increased. As a result of the analysis and discussion of these ten projects from the perspective of the new systemic framework, the relationship between digital technologies and sustainable features will be identified and used to extend current theory to a new logic of Digital-Green design processes.

1.3.4 Step Four: Modeling the Design Process of Digital-Green Architecture

Based on the analysis of the previous design processes and the information gained from the case-study factors, the process of merging digital technology and green aspects will be initiated within the design process. To maximize the capacity of a dynamic digital design process, the features of computational design media and digital graphics (such as topological surface, isomorphic field, kinetic skeleton, field of forces, parametric model, genetic algorithm) will allow architects to shape the form freely and create a more functional skin/envelope. As a result, the elements of conceptual design, computational concept, and envelope study will provide possibilities for unexpected new forms and sustainable influences in the new Digital-Green design process. Such a process can help designers to merge both digital and sustainable aspects during the design process.

Chapter 2 Previous Work

2.1 The Transition from Classical to Digital Architecture

2.1.1 Conventional Techniques

The development of design processes, as well as the transition of styles throughout history, has been influenced both by changes in design media and social needs (Liu 2003). In ancient Egypt, drawings with plans, elevations, sections, and details demonstrate that a basic design process had already been established. The Greeks later designed mechanical tools, such as cranes and pulleys, to be used in hoisting heavy rocks, allowing for significant temple designs for religious purposes and the classical beauty of asymmetry (Goldberg 1983). The Romans adopted this classical architectural style from the Greeks, adding new architectural features designed to meet social needs. For instance, the invention of a concrete-making technique was useful to address the issues of increasing population density of the cities and the wealth of the citizens. This new solution provided fast and firm production of building materials, while allowing a wider vault span. As a result, interior space was expanded and Roman architecture achieved a new look (Lancaster 2005). The Medieval architects adopted three styles as a primary form for subsequent development—the Greek cross or Latin cross plan, the style of Roman basilica, and the Byzantine dome style. New forms and styles, such as cross-shaped windows and crenulated walls, were developed and used in much of the secular architecture. These inventions were not only for decorative purposes, but also for defence, which was critical for the war time in the Medieval Period (Braun 1951; Fletch 1996). Due to the rapid growth of trading and the growing association in medieval towns, regional influence was demonstrated through the wealth and pride of the towns. The lofty and structural characteristics of Gothic Architecture during the late Medieval Period were the preferred style for cathedral designs. However, the most significant motivation for this climax of vertical skeleton constructions was to get closer to God. Therefore, innovations and new construction techniques for the pointed arch, the ribbed vault, and the flying buttress, were also developed for meeting this purpose (Crook 2002).

2.1.2 The Era of Crafting

The 14th century was a time of world exploration. During this time, book printing developed, trade expanded, and a thirst for knowledge and education increased. In addition, architecture became a matter of theoretical analysis rather than simply a question of practice (Panofsky 1960). Designers expanded their exploration of space from two-dimensional to three-dimensional aspects. For example, Brunelleschi (1550) was the first to combine technical drawings with physical models when studying buildings. Furthermore, Buonarroti (1560) used models to study three-dimensional design space. With the revival of the scientific spirit during the Renaissance, architects showed a strong interest in exploring empirical evidence and mathematics. The style of this period revived aspects of Greek and Roman elements for inspiration, while focusing on symmetry, geometric balance and regulation of the various parts of the structures. The classical style of the Greek and Roman periods was re-analyzed and integrated with new understandings and construction methods to serve the new purposes (Booth 1996).

Similar to the architecture of the Renaissance, Baroque architecture used logic and mathematics to incorporate geometric relationships into the design process, creating variety in structure and scale. The influence of the wealthy and powerful Catholic Church also played a leading role to encourage the bold expression of lighting emotions to show the religious force to improve enthusiastic piety. Motivated by new religious orders, bold and irregular shapes in design allowed more expression through the use of shape, color, and varying levels of light and shade, such as curving facades and distinctive oval ceiling style with the result of larger open spaces (Toman 2008).

2.1.3 New Materiality and Machine-Based Manufacturing

In the 18th century, the Industrial Revolution brought about tremendous changes in agriculture, mining, manufacturing and transportation. The invention of machine-based manufacturing also marked a turning point for the design process and architectural style. Developments in iron-making and the use of refined coal led to improved roads, railways and canals for trade expansion. In addition, the development of durable metal machine tools not only increased the production capacity in manufacturing, but also provided new materials for architectural structural design thanks to the new iron-making technology. In the 1740s, the production of raw steel led to the development of steam engines and railways, allowing for industrial growth, and urban development for the growing population

(Hudson 1996). Building materials such as brick and stone gave way to the newly invented materials such as steel, iron and glass. Architectural projects emphasized the use of these new building materials, as well as new construction methods involving the prefabrication of the structural parts, allowing for the rapid development of skyscrapers and large scale architecture (Crossman 1906). This transformation affected both style and design, allowing for greater creativity of external appearance and the increased load-bearing capacity—a major breakthrough in the area of structural constraints.

2.1.4 New Societal Needs and High-rise Buildings

With the reformation of industrial architecture, Morris (1870s) suggested that form and function should be integrated without distinction in order to meet the changing architectural style of new materials and technologies. The use of architectural elements, such as larger windows and thinner interior walls, not only allowed designers to have taller buildings but also provided a floor plan that was freer and more open. Therefore, weight-bearing steel constructions such as the famous Eiffel Tower (1890) and the first modern skyscraper (in Chicago) were born. This change in design style demonstrates how the needs of a society are met when design and technology are integrated. Some researchers have addressed the explorations based upon the changes of design theory mentioned above (Scully 1988). Around this time, Sullivan (1891) addressed the changes with the phrase “form follows function” to stress the importance of practical uses over aesthetics. Later, Eugene Viollet-le-Duc (1892) presented the idea of structural rationalism, particularly the process of mixing the classic elements with new materials and structural ideas.

During the Art Nouveau period, a new design style combined the classical form of architecture with the traditional style of decorative arts. The use of modern materials like wrought iron technology expressed a fresh and freer form during the Modern Movement. This integration led Morris (1867), as the functionalist wing of modern architecture, to pursue artistic potential and functionality to make everyday objects into art. Voysey’s free plans and L-shaped design were declared one of the most influential works in the Modern Movement. His dictum, “fitness for purpose,” and the ambition to pursue simplicity echo Sullivan’s “form follows function” (1898). Gaudi (1910) presented his own sculptural style of the curvilinear expression from the merger of decorative arts in the Arts and Crafts movement. He used special model studies during his design process to bring innovation to his design process, resulting in the use of hanging small filled sacks upside-down from the ceiling. The use of industrial materials like concrete and glass also helped to his attain the outline of his project, Sagrada Famila.

2.1.5 Functional Aesthetics and Modern Movement

Gropius (1910) began his own architectural practice with Meyer and was instrumental in designing a shoe factory that promoted friendly working conditions for the employees. Then in 1913, he became the master of an arts and crafts academy in Weimar, which he transformed into the Bauhaus school.

Gropius' work at the school and his writing influenced other modernist architects, including Le Corbusier, whose International Style emphasized the simplification of form, the disaffirmation of ornament, and the use of modern materials—like glass, steel and concrete. He also proposed the five points of architecture and the Domino system of the open floor plan as the prototypical housing solution in most of his design processes. Through the pursuit of functional aesthetic and asymmetric balance, Le Corbusier (1923) coined the phrase "a house was a machine for living," which was one of the major theories in Modern architecture. Similarly, Mies (1929) stated his aphorisms—such as "less is more" and "God is in the details"—through his use of extreme simplicity in the design process. The trend toward simplified forms, functionality, and the technologies of mass-production led to a more systematic design process. Giedion (1920) encouraged the idea of "irrational-organic," using modern elements, transparency, and flexibility.

With the development of reinforced concrete for use in shell construction in 1920, Maillart suggested the idea of eliminating all linear elements by using flexible materials to make use of surface tension. Instead of using the old technologies of heavy arches and buttresses for structural support, lightness and flexibility of form—such as the large-scale, thin-shell construction or stressed-skin types—became the new standard of design and construction. The study of mechanical development, based on structural engineering, became one of the most important concerns in developing harmony with the new needs of industry. The flowing form of curved shells built from prefabricated elements of heavy material—as seen in Eero Saarinen’s (1950) approach to J.F.K International Airport or Jorn Utzon’s (1957) Sydney Opera House—show how construction methods support the organic forms of these structural designs.

2.1.6 Digital Forerunners and New Construction Methods

In the 1960s, computer-aided design (CAD) and computer-aided manufacturing (CAM) technologies were introduced to the aircraft and automobile industries (Hull and Jacobs 1992). While the processes and production methods of shipbuilding technology are similar to the building industry, some digital forerunners such as Buckminster Fuller started to connect the production methods from industry. His Dymaxion House helped the development of building skills on framing and cladding techniques for digital manufacturing, which was also known as energy-efficient and low cost for such a "radically strong and light tensegrity structure" (Buckminster 1983). This prototype was famous not only for its round structure, but also for its use of natural winds for cooling and air circulation (Buckminster 1983). The wedge-shaped metal aluminum on the roof of the Dymaxion house later inspired Frank Gehry’s Guggenheim Museum in Bilbao. Furthermore, Fuller’s ‘blobby’ and formlessness design came to be popular during the 1960s and early 1970s (Zellner 2001; Koleravic 2004).

In the 1960s, Peter Cook, Warren Chalk, Ron Herron, Dennis Crompton, Michael Webb and David Greene formed an avant-garde architectural group called Archigram (Cook and Webb 1999; Sadler 2005). The development of new construction methods during the Late Modern movement allowed new spatial forms to emerge. With the use of new materials and modern technology, the interrelationship of material, joints, detail and structure were the prime focus (Giedion 1967). With the idea of “high tech, light weight, and infra-structural approach,” works by the Archigram Group included Renzo Piano’s High tech 'Pompidou centre' 1971. Early Norman Foster works, designs by Richard Rogers, and early works of Future Systems reflected the inspirations for the blending of high tech technology and the initial stage of digital architecture (Cook and Webb 1999; Sadler 2005). This approach brought about eclectic styles, rather than rectilinear designs, leading the design process to more organic forms since the1980s.

2.1.7 Three-Dimensional Design Thinking

A successful architectural project relies on a carefully considered design process. Lawson (1990) suggested that various design processes can be addressed based on the different methods. The process of design could be transformed into different factors during different periods by the changes of style, the inventions of new technology, and the change of society concerns (Lawson 1990). As the complexity of design content and new technologies emerged through the decades, the need for an efficient design process became necessary. Some digital pioneers tended towards less “machine aesthetic” design. In subsequent development, the architecture evolution and improved computer-aided technology have generated freeform design options. Such techniques were known as 3D surface construction and Numerical Control (NC) programming of the mathematical description work on curves.

This methodology of integrating CAD/CAM was applied to produce more efficient manufacturing processes not only in the industrial field, but also in different manufacturing areas. This was especially explicit in the architecture industry a decade ago by Streich (1991). Peter Zellner's Hybrid space shows that "today's experimental architects are deploying novel 'hard' (manufacturing and material) and 'soft' (digital) technologies to engender an architecture of incorporation and conjunction, to test the radical generative and creative potential made possible through computer application" (1997). Concept Modeling technologies and the continuing development of Rapid Prototyping technologies can offer designers the opportunity to conduct their design processes in a faster and more affordable way. For example, Ryder demonstrated the applicability of Layered Manufacturing (LM) technology in the field of architecture (Ryder 2002).

2.1.8 CAD/CAM Technologies and Digital Design Thinking

Based on the framework of algorithmic structure for designs hypothesized by Stiny and March, Wang and Duarte brought in the methods of Rapid prototyping and manufacturing generating the possibility of mass-produced architectural designs in 2002. By using cutting-edge 3D graphics technology, geometrically complex designs can be easily introduced with a few basic shapes and rules on using 'shape grammars' to create new designs (Stiny and March 1981; Wang and Duarte 2002). By manipulating the computer modeling platform, Greg Lynn (1995) redefined the term 'blob architecture' to the public with the concept of a "more fluid logic of connectivity," which is involved with the mathematical knowledge such as nonuniform rational B-Splines, NURB, freeform surfaces, and the digitalized sculpting forms (Lynn 1993). Koleravic (2003) later defined the term Digital Fabrication to offer the understanding of ‘architectural design and production processes and their material and economic constraints’. That manifested together with manufacturing advances in the architectural applications of the latest digital design and fabrication technologies. With the advancement of digital fabrication through developmental history, Mitchell (1999) indicated that one of the advantages of digital production was to support the derivation of complex processes by CAD/CAM fabrication. Thus, the complex computer-aided calculations in design process not only broadened the range of flexible appearance by digital fabrication but also reconnected the relationship between conception and production. The new digital processes of production re-generated the possibilities of construction and the functions of computability (Kolarevic 2003).

With the transition from classical to digital architecture, the development of design processes and style were affected by the innovation of design technologies, the invention of new materials, and societal needs (Liu 2003). While the engagement of computer technology and new digital processes of production had directly generated architectural conception in the digital period, the design process needed to integrate with the new factors were based on green concerns and transformed to fit both digital and green design processes (Kolarevic 2006).

2.2 Green Concept and Sustainability

2.2.1 Early Thinking about Sustainability

According to Carson (1962), Bender (1970), Yeang (1995) and McLennan (2006), the beginning of green thinking in design process can be traced back to ancient times. The green concepts have been summed up as four evolutionary stages through history: the biological beginning, the ingenious beginning, the industrial, and the modern sustainable design movement (McLennan 2006). As early as the ancient Egypt, Greek and Roman periods, Plato had already pointed out the demand of sustainable practices for maintaining the environment in the light of human activities (Columella 1948; Strabo 1949; Van Zon 2002). In the 19th Century, John Stuart Mill (1848) promoted an idea similar to the contemporary term "sustainable development," but only discussed the need for remedial solutions of human impact on the natural environment (Mill 1883; Wines 1932; Lowenthal 1958). Up until then, most sustainable concerns were focused on pursuing comfort for one's living environment. During this period, Clausius (1850) mentioned the link between nature and society related to energy waste and the use of renewable material. Later, Haeckel (1866) coined the term "ecology" to define the relationship of the organism with the comprehensive science related to the environment. Similarly, Thoreau (1856) anticipated the findings of ecology and environmental history as the source of environmentalism in the modern days. While the sustainable concerns were mostly developed on the theoretical concept for environmentally sensitive architecture during the 1850s, many large buildings included ingenious systems for ventilating the space without the use of electrical or mechanical equipment. For example, Joseph Paxton's Crystal Palace introduced not only a modern glass structure as part of the design approach, but also provided a roof ventilator for comfort and sustainability issues (Roth 1993). To provide ventilation for a long -pan space, Giuseppe Mengoni (1877) contrived a useful solution (later referred to as a labyrinth) for air-circulation (Gissen 2009). The Flatiron Building (1903) had deep-set windows to avoid the solar exposure (Gissen 2009). There were more examples with similar passive strategies during this ingenious period. However, the green system advocated in these decades was mostly related to philosophical issues of environmental degradation or concerns with passive technique for interior comforts rather than the focus of specific design elements.

2.2.2 Sustainable Movement after the Industrial Revolution

After the Industrial Revolution, Le Corbusier and other well known modernists, such as Walter Gropius and Mies Van der Rohe, advocated the employment of modern materials, new technology, and industrial forms in Modern architectures period. In 1926, Le Corbusier introduced his five points with the concepts of "free plan" and "free façade," which bring in the advantage of maximum ventilation and light to the interior (Corbusier 1923). The progress of production techniques, the increased transparency in glass structure, and the thinking of glass is greener constitute the New Architecture thinking of the Modern Movement. Moreover, the modern technologies invented through the centuries also encouraged the new aspect of green concepts (McLennan 2004). While architects moved away from passive strategies such as operable windows or external sunshades under the exploration of air-conditioning, there were also new forms and concepts developed that reflected the new language of technologies (McDonough 2003). By expressing both modern and sustainable characteristics in his design process, Frank Lloyd Wright (1937) was the first to address the role of Organic Architecture as one of the important green concepts during the Modern Movement. Other architects, such as Antoni Gaudi, Louis Sullivan, John Lautner, and Claude Bragdon, intended to translate the organic design approaches as the relationship between natural surroundings and the unified organism of the building itself included in the design process (Van Zon 2002, McLennan 2004). However, while those forerunners pursued these green ideas, most Modernists were more concerned with how buildings were put together rather than how to incorporate sustainable beliefs. Therefore, although the green influences emerged in the period of the Modern Movement (1920s - 1940s), the application of the green concept in architecture was mostly engaged with technical systems of passive solar design, bioclimatic design, bio-regionalism and so forth (Vale 1991).

2.2.3 Modern Movement and Sustainable Design Thinking

In response to the oil crisis of 1973, the issue of sustainability emerged as an important matter in society. Social awareness of the Green Architecture Revolution was inspired by Rachael Carson’s book *Silent Spring*, in response to the widespread public concerns about the environmental problems of the 1960s (McLennan 2006). One of the most prevailing green concepts during this period was developed with the Earthwork Movement of the 1970s. Peter Noever (1971) introduced a new perspective of evolutionary design processes by examining the possibility of living spaces built completely underground with earth-sheltered roofs. As new technologies offered possibilities for green designs during this movement, Wells (1981) advocated the idea of underground architecture to step up the integration of landscape and architecture. Ambasz (1981) proposed the concept of Green Town by responding the Architectural Modern Movement of The house in the Garden in a more extensive way (Wells 1981, Wines 2000). In the ACROS Building, Emilio Ambasz presented his environmental architecture by integrating vegetation and terrain into buildings in order to maintain natural resources.

2.2.4 Organic Forms and Green Concepts

Reflecting a similar interest in combining technological advances with nature and organic forms, architects such as Jersey Devil, Ushida-Findlay, James Cutler, Arthur Quarmby, and Peter Vetsch extended the concept of borrowing nature's organic forms and integrating them with the developments in sustainable technology (Crosbie 1985; Wagner 1994). Jersey Devil (1970) presented his project Snail House, merging the use of sustainable technology with curvature expression. The curved window strip and the central thermal mass chimney reflected to the heating and natural ventilation by matching the solar arc from east to west (Crosbie 1985; Stitt 1999). In his project, Soft and Hairy House, Ushida-Findlay (1994) integrated the modern concept of "inside out" and sustainable programs. The organic form not only suggested the fluid continuity, but the extensive roof garden also maintained a steady interior temperature, among its green features. The flowing volumes of the Nine Houses by Peter Vetsch (1993) expressed his environmental intentions with the perspective of earth-friendly technology; the flowing organic appearance could represent both contemporary design-centered architecture as well as green design principles with ecological consciousness. The earth-centric philosophy has been an approach similar to Wells's aspect of underground architecture, which became a progressively more prevalent way to respond to the green concept during this period (Wells 1981, Wines 2000).

2.2.5 Curvature Expression and Sustainable Technologies

Around the same time, the architectural impact of the oil crisis also led architects and theorists to focus on function-oriented green concepts for environmental purposes. The passive strategies were, again, rediscovered, such as the innovative potentials which coincided with the Environmental Movement to address the major concerns of the oil and ecological crises in the 1960s and 1970s (Carson 1962; McDonough 2003). Responsive to social-ecological awareness, Buckminster Fuller (1950) was known as an early pioneer in sustainable design and was the first to develop prefabricated mass-produced houses. The movement toward renewable energy such as solar or wind-derived electricity was a new theory in his period. His famous geodesic dome with a complex network of triangles forming a high-efficiency light weight structure was based upon the concepts of the Modern Movement that focused on low-cost mass production and using fewer materials. Its efficient ventilation system and the great use of recycled material inspired many digital and green designers such as William McDonough across generations (McDonough 2003). Some architects began to use advanced technologies to create solutions to the problem of energy shortage, such as the double-skin wall technique for ventilation, solar panels on the roof, and thermal labyrinths for pre-cooling systems. One of the pivotal buildings in the origins of Green Architecture, Foster and Partner's Willis Faber and Dumas Headquarters (1975), was constructed using mirrored windows which provided the functions of reducing heat gain, while providing large amounts of daylight in the space. This energy-efficient building features the combination of advanced technology and passive techniques (Pawley 1999; Melet 1999; Weston 2004). The term "sustainability" had finally been created by the United Nations' World Commission on Environment and Development in 1987 and was widely applied to various fields. Diverse green architectural theories gradually prevailed, such as Bruce Goff's concept with connections to Wright's "organic simplicity," "bio-functional eco-architecture," and Walter Segal's "small is beautiful" with the idea of self-build housing. The theorists started to generate technological innovations in architectural thought and practices related to green issues and sustainability (Fuller 1969; Segal 1983; Holzman and Goff 1998).

2.2.6 Ecological Modernization

At this time, diverse groups of architects and designers reflected varying perspectives on green issues. For example, some architects believed that sustainability or green architecture might diminish aesthetics and digital appearance. This type of design-centered thinking can be observed in Frank

Gehry's Bilboa Guggenheim Museum, where tremendous sense and contributions from digital architecture are found. However, using non-renewable resources like titanium for cladding shows a lack of consideration for ecological issues. Furthermore, Simon Guy and Graham Farmer (2001) presented "the logics of the six competing logics" of sustainable architecture. One of the six logics, named The Ecotechnic Logic, suggested that "science and technology can provide the solutions to environmental problems" (Farmer 2002; Guy 2002). The term "ecological modernization" indicates the possibility of overcoming the environmental crisis without leaving the path of modernisation (Spaargaren 1992). Architects such as Renzo Piano, Steven Holl, Norman Foster, Glenn Murcutt, Kenneth Yeang, and Herzog & de Meuron started to experiment on building self-sufficient green architecture, combining design thinking with the development and progress of digital materials and technologies. By the 1990s, architects had re-generated sustainability from the environmental movement in the 1970s. The visible design processes for environmentally progressive architecture included the effective use of recycled materials, advances of green-conscious construction techniques, and concern for urbanism (McDonough 2002; Braungart 2002; Gissen 2003). At the Challenge of Sustainability Conference in 1993, Cooper reinterpreted the green concept and focused on true sustainability instead of environmental performance (Guy 2005; Moore 2005). Within the sustainable architecture movement, Haggard presented the idea of a transition from "a period of deterioration of the natural environment to a more humane and natural environment." Haggard also pointedly insisted that the term "sustainable architecture" should also represent "the social and cultural shift in the world order, patterns and styles of living." (Haggard 1980; Haggard 1995)

2.2.7 Intelligent Materials and Sustainable Technologies

While people focused on the new trend of large scale architectures or skyscrapers using the technologies of the last century, the negative effects of wasting energy and materials in large buildings became an increasing concern. Battle mentioned about the evolution of the building envelope with the advances of renewable energy systems in large-scale building (1980). Similarly, Wines (1999) proposed a shift in the way skyscrapers were envisioned, from a sculptural aspect to the conceptual individuality of a vertical garden. Braungart (2002) promoted dematerialization, a term referring to the use of recycled materials for construction practices, and described how the new design process might change the appearance of architecture when integrating intelligent materials with new technologies (McDonough 2003). Since the re-analysis of a sustainable design process was provided through essays and critics, architects of some of the great large-scaled buildings have infused their designs with more environmentally sensitive components. Hellmuth, Obata and Kassabaum (HOK)'s Edificio Malecon (1999) and Skidmore, Owings & Merrill (SOM)'s Manulife Financial (2003) demonstrate how consideration of the shape of the building can work with solutions needed for sustainability. In other projects, such as T.R. Hamzah and Yeang's EDITT Tower (1998) or MVRDV's Dutch Pavillion (2000), architects incorporate the multi-level greenery or other living organisms into buildings in order to mitigate the structure's impact on its surroundings. Other projects, including Shigeru Ban’s Japan Pavilion (2000), Nicholas Grimshaw’s Eden Project (2001), and Peter Testa’s Carbon Skyscraper (2002) incorporate the green design process by exploring environmental friendly materials or inventing new materials through technologies for new ways of construction. Furthermore, Adriaan Beukers (2005) promotes thinking about the trinity logic of material, shape, and process in his book *Lightness*. He suggests that lightweight materials or new composite materials could waste less energy during construction (Beuker 2005; Hinte 2005). With new technologies and inventions, the approach to design must respond to the new technologies and new design thinking (McLennan 2006). Therefore, the development of the green concept has been advanced from a linear focus on energy saving to a non-linear perspective based on diverse green factors. Such a focus leads to redesigning buildings to be more self-sufficient and self-organized, while generating their own renewable energy (Van Zon 2002).

2.2.8 Integration of Digitalization and Sustainability

The development of new technologies, such as computational fluid dynamics (CFD), acoustic wave propagation simulation systems, digital models of buildings, and CAD/CAM technologies not only help compute curved forms, but also “alter the geometry in response to optimizing a particular performance criteria” (i.e., acoustic, thermal) (Kolarevic 2004). The form of the building can be automatically adjusted by computing and simulating airflows, transfers of heat mass, phase changes, deformation of building structure, and so forth. Thomas Leeser’s Helix Hotel demonstrates his approach to green designs through the use of amorphous shapes and the high-tech systems. This project expresses not only a unique flowing appearance, but also makes a contribution to sustainability through a curved wall that functions for the adjustment of indoor ventilation. The use of new material also has capabilities for wind harnessing.

As Branko Kolarevic suggested, “Foster’s performative approach to the design of the GLA building could imply a significant shift in how ‘blobby’ forms are perceived. The sinuous, highly curvilinear forms could become not only an expression of new aesthetics, or a particular cultural and socio-economic moment born out of the digital revolution, but also an optimal formal expression for the new ecological consciousness that calls for sustainable building” (2004). Successfully designed green projects concerned with the development of innovative materials, functionality, and green design concepts will help move contemporary green architecture from a microcosmic to macrocosmic perspective (Van Zon 2002).

Chapter 3 Selection of Cases & Analysis Framework

3.1 Selection of Cases

Case 1: Swiss Re Headquarters

Swiss Re Headquarters is a commercial building designed by Foster and Partners in London, a winner of the Pritzker Prize in 1999. It is also an award-winning architecture recognized by the Royal Institute of British Architecture (RIBA). The Swiss Re Tower, a 591-foot building, stands in the financial district of London. With its glass dome and aerodynamic form, the shape of the tower not only minimizes wind flow of the building, but also consumes half the energy of office buildings of its kind. Foster promotes energy-saving, double glazing and introduces the shaft system to provide passive solar heating to the building. Known as the first eco-friendly office building in London, the tower is constructed with innovative and technological concepts where the structure stiffness is increased, allowing column-free design, more natural light, and better ventilation. The continuous, triangulated, perimeter structure is also generated by its radial plan for building reinforcements (Abel 2004). The key design strategy of this project is based on a careful balance of sustainability and digital technologies, which coincide with the challenge of a new generation of skyscrapers for the early stage of the digital age (Wells 2005).

Figure 3-1. View of Swiss Re Headquarters

Case 2: Chesa Futura

The Chesa Futura was designed by Norman Foster in 2004 in the Engadin Valley, Switzerland. Located along a slope, 1800 meters above sea level, the blob-form apartment is not only a combination of high-tech construction methods and traditional workmanship, but also environmentally-sensitive with the use of timber materials. The three-story building consists of six residential apartments and two stories for underground parking plus storage and planting, which accommodate the sloping site and the severe weather conditions through its sustainable timber superstructure and copper roof. With the conceptually simple yet complicated high-tech timber construction, Foster has struck a shingle-cladding shell by means of digital computation to arch a modern shape and to fulfil the purpose of environmental sustainability.

Figure 3-2. View of Chesa Futura

Case 3: Carbon Tower 2005

The Carbon Tower is an experimental project of a forty-story prototype skyscraper, designed by Peter Testa and Devyn Weiser from Emergent Design Group at MIT in 2005. The construction is known for its combination of new materials and computer intelligence, which generated the mass customization for its unique characteristics - the lightest and strongest building of its type. Although the tower has never been built, the evolution of composite materials, carbon fiber, Kevlar and fiberglass, are an innovation of deign thinking, which makes the construction technology of the high-rise building tangible and accessible. Replacing traditional construction techniques, the application of computer modeling tools has fostered the transformation of the building industry in the 2000s and allows cutting-edge experiments with new sustainable materials for more efficient energy saving (Knecht 2004).

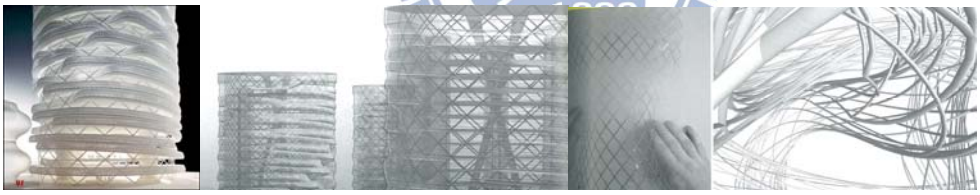


Figure 3-3. Physical Models of Carbon Tower

Case 4: BMW WELT Munich

BMW Headquarters is a multi-functional BMW exhibition center, designed by architects Coop Himmelb[l]au in Munich, Germany (2007). This project was the winner of the BMW design competition not only because of its freeform façade, but its sustainable ventilation systems for intensive gas exhausting and release during car delivery. The building of BMW Welt Munich presents a computational design that burnishes its luxury brand and exhibits the complexities of digital appearance, while precisely carrying out the sustainable details of the project.

Figure 3-4. View of BMW WELT Munich

Case 5: Whitney water purification facility and park

The Whitney water purification facility and park in Connecticut, also known as Silver Drop, was designed by Steven Holl in 2005. This project was honored by the Van Alen Institute International Projects in Public Architecture in 2001, AIA NY Honor Award in 2005, and AIA Environment Top Ten Green Projects in 2007. The construction plan features both water treatment facilities and a public park. In contrast to the complicated digital freeform of contemporary architectures, the water treatment facilities were built in a simple, curvilinear form and its roof garden is humbly integrated in harmony with the landscape of the public park. The environmental aspect of the complex design is to preserve and expand the existing wetland area where the site is located. The project also addresses the importance of water resources for sustainable development in general.

Figure 3-5. View of Whitney Water Purification Facilities and Park

Case 6: Zaragoza Bridge Pavilion

Zaragoza Bridge Pavilion was designed for the Zaragoza Expo 2009 by Zaha Hadid Architects. The Pavilion functioned as the exhibition halls and pedestrian bridge to cross the River Ebro. As the entrance of Expo 2008, the Zaragoza Bridge Pavilion connects the diamond shaped sections by four structural objects. The slightly curved shape of the Bridge Pavilion with the triangular truss pockets designed not only contains the space-frame structure for the pathway but also offers the spatial enclosures for exhibition halls. The bridge design maintains traditional nature and also involves technical innovations in digital technology of construction. The shark scales, shapes on the bridge surface, serve as sustainable, weather coping devices. The transformation of architectural form makes use of computing and energy-saving concepts, which makes possible a stiffer structure than the traditional ones. The complex structure of the Zaragoza Bridge Pavilion challenges cutting-edge construction techniques and technologies through which the engineering elements of the bridge and architectural elements of the pavilion are merged into one building typology (Hadid 2008). While bridge design is usually concerned more with structural engineering and function, the trend of freeform and sustainability in architecture is also presented in the design of the Zaragoza Bridge Pavilion.

Figure 3-6. View of Zaragoza Bridge Pavilion

Case 7: CSET building designed by MCA

The Centre for Sustainable Energy Technologies (CSET) was designed by Mario Cucinella Architects in 2009, and is the MIPIM Green Building Award winner. This new research centre, at the University of Nottingham Ningbo, is located in China, the world's second largest energy consumer. The purpose of this centre is for numbers of research laboratories to investigate sustainable technologies such as wind, solar power, and photovoltaic energy. The success of the building suggests a combination of digital freeform and innovative energy system has become an unstoppable trend in the sustainable development of architecture design. It also serves as a demonstration of sustainable construction techniques and promises an environmentally friendly, plus energy-efficient future.

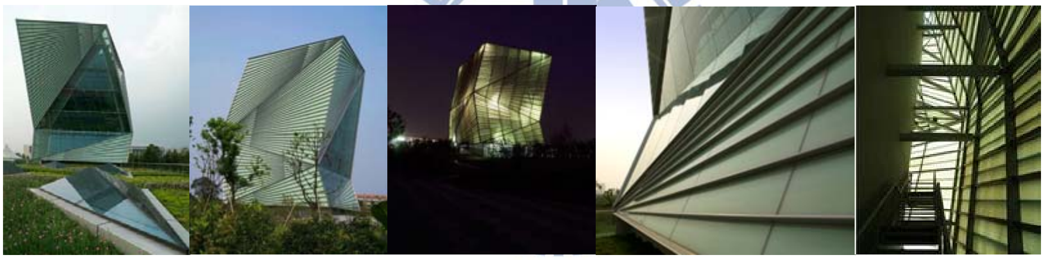


Figure 3-7. View of CSET Building

Case 8: Japan Pavilion 2010

The Japan Pavilion is an energy efficient architecture with inflated lightweight structure, designed for the Shanghai Expo 2010 by Yuntaka Hikosaka. The large-size building composes a large membrane roof with the materials of steel-framed ETFE_film on the surface for sustainable purposes. Considering the air pollution and high temperature in Shanghai, the Pavilion’s Eco-Tube system showcases a new energy-efficient cooling technology as an experiment of downsizing environmental loads in a building (Hikosaka 2011). The inflated structure, with the energy system of innovative ETFE pillow membrane, could be applied to any location and benefit in any kind of weather. Due to the light-weight and vertical structure, the Eco Tube becomes a protocol of low-energy consumption in construction (Nanami 2011).

Figure 3-8. View of Japan Pavilion 2010

Case 9: Haesley Nine Bridges

The Haesley Nine Bridges Golf Club House on Jeju Island, completed by Shigeru Ban in 2010, is a 16,000-square meter facility that consists of a main building, VIP lobby area, and private suites structure. The roof measures 36x72 meters over the main building, which is supported by timber columns and a glass curtain wall. Taking advantage of advanced technology in wooden weaving technique, Shigeru Ban highlights the prefabricated construction of Nine Bridges with advanced technology and the innovative aspects of reducing energy consumption by its structural timber structure. With a simplified assembly process for a wooden grid shell structure, the approach of modular components carries out the uniqueness of digital and yet sustainable features in its woven structure. The perforations on the tree-like columns and roof act as a solar screen for an efficient, passive, cooling system. Based on the advanced technology for the elaborative timber structural simulation and calculation, the building brings the concept of freeform structure, digital techniques and sustainability in one.

Figure 3-9. View of Haesley Nine Bridges

Case 10: IBG and Tax offices

Awarded with the Dutch Building Prize, the project was designed by UN Studio, from 2007 to 2011, in the Netherlands. The IBG and Tax offices are a ninety-two meter high, massive office complex, designed for the Dutch federal tax services and college students' grant system. The technical aerodynamic freeform façade and skeletal structure are constructed with ecological concerns and sustainability. Simulating airplane wings or a whale's curving-top rib, the aluminium fin-shaped terraces provide sun shading, wind regulation, daylight penetration and fabrication to the building. This computational design of the building aims to apply its digital freeform innovation to environmental principles, which present an intelligent approach toward energy saving (Dumiak 2011). The success is made possible by its digital design process, the computerized construction techniques, and the innovation of sustainability.

Figure 3-10. View of IBG and Tax offices

3.2 Analysis Framework

In the original design process, five classic factors—detail/joint, material, object, structure, and construction—are categorized based on the classic theory of tectonics (Semper 1951; Botticher 1852; Sekler 1965; Frascari 1983; Gregotti 1983; Frascari 1983; Moneo 1988; Vallhonrat 1988; Frampton 1995 and Gao 2004). Other essential factors such as light, color, sound, temperature, ventilation, and material were suggested by Unwin, (2003) stressing the dialogue between architecture and the environment. In addition, Deplazes (2006) summarized four factors based on construction techniques—1) material, 2) boundary (such as transparent or translucent surface), 3) structure of tectonic (or non-tectonic), and 4) figuration. After rethinking the classic factors, Lim (2005) initiated a set of seven factors—namely: joint, detail, material, object, structure, construction and interaction (Semper 1951; Botticher 1852; Sekler 1965; Frascari 1983; Gregotti 1983; Frascari 1983; Moneo 1988; Vallhonrat 1988; Frampton 1995; Gao 2004; Liu and Lim 2005). With the digital design process and new methods of assembly, some of the classic factors were insufficient to merge with digital ones. To meet contemporary needs, these factors were reorganized to be more effective. Gao (2004) proposed five digital factors including concept, manipulation, construction, form, and space, with four additional factors—motion, information, generation, and fabrication—suggested by Liu and Lim (2005).

By merging the digital design manipulation technique with green thinking, the new method of design process is different from the original expression of digital architectural manipulation. According to *the HOK Guidebook to Sustainable Design* (Mendler, Odell and Lazrus 2006), the new perspective of sustainable design factors were proposed as site, water efficiency, energy, materials, and environmental quality such as acoustics. Another set of sustainable factors suggested by Chan (2007) are site specificity, connection with habitat (namely environmental interface), conservation of resources, and the use of building materials. In addition, Ali and Armstrong (2008) concluded that site context, environment, structure, materials, energy, water are the principal factors in the contemporary sustainable design.

In considering the operation of sustainable factors, this study addresses the key areas of structure, building form (envelope), electrical power, technical principles (ventilation, heating, cooling, lighting, etc.), environment (water, waste, energy, noise), site (microclimate, green space) and material (Trotter 1892; Olgyay 1973; Hancock 1992; Fanchiotti 1995; Mak 1996). However, this analysis is not specifically concerned with purely sustainable mechanical issues, but rather addresses the new design process that integrates digital technology and sustainability.

An emerging concept of design framework was proposed by Liu in 2003. In the design process, the design outcome could vary due to different design media employed. Design process and design outcome could evolve differently in accordance with different design media (Schon and Wiggins, 1992; Liu 1996). With the evolution of digital architecture, new design outcomes were affected by digital design media, which may also transform the design process (Zevi, 1981; Liu 1996; Lim, 2003). This model still emphasizes strong interactions among Design outcome, Design media, and Design process (Figure 1). While being engaged in digital technologies and Green issues during the last decade, architects need to transform the basic design theories by integrating green elements and digital technologies (Schodek 2000; Kieran and Timberlake 2004; Schodek et al. 2005; Sass and Oxman 2006).

Based on the development of Liu's classic framework (Figure 3-11), the new design diagram was redefined as an analytical framework to cope with the changes of Digital-Green architecture (Figure 3-12). The diagram illustrates the engagement of new elements.

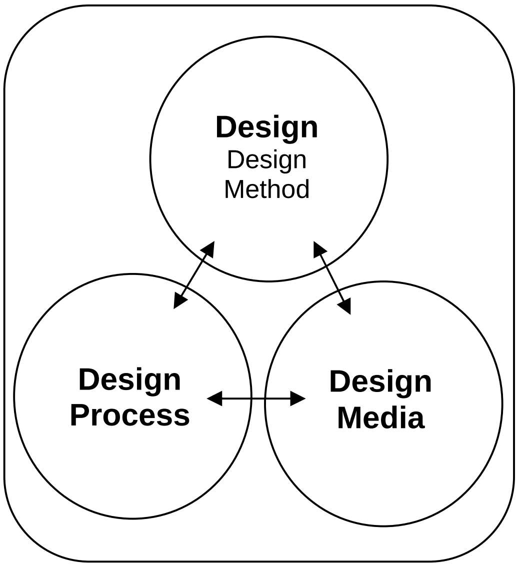


Figure 3-11. Design Relationship (Liu, 2003)

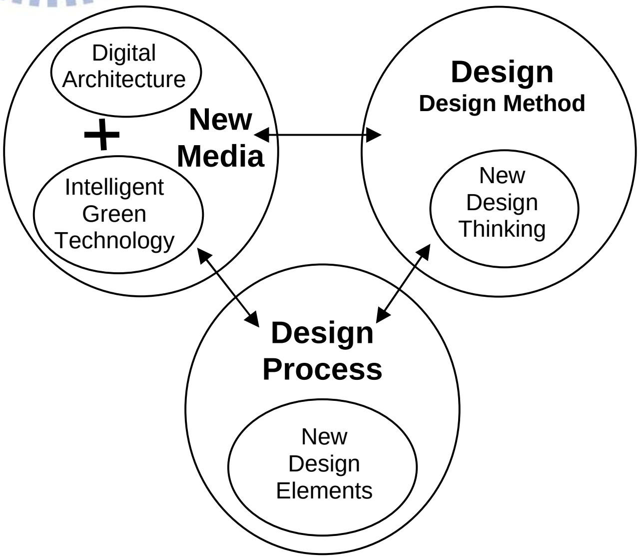


Figure 3-12. New Digital-Green Design Relationship

According to the factor analysis of classical, digital, and sustainable fields, some of the factors, with further adjustment or re-definition, are still suitable in the new operation of the Digital-Green concept. Therefore, in response to the new needs of Digital-Green design thinking, fourteen factors, clustered in three categories, are applied in this research, as listed below.

(1) Design Process

1. *Concept:* The advanced digital media provide a diversity of design thinking of more curvilinear form plus environmental sensitivity. The notion of geometrically free forms is made possible due to the emergence of digital computing, which combines structural technology, morphology and energy-efficiency.
2. *CAD / Simulation:* A process of computer modeling techniques make possible the creation and analysis in an architecture design. With the digital application, a building's structural system can be calculated with the automatic generating system, which offers several design operations in virtual forms. By simulating complex geometric models, the parametric approach and scripting interface ensure that the design options are considered in both complex form aesthetics and energy-efficiency purpose.
3. *Detail:* The joints connect materials, structure or components to the whole tectonics as a connectivity system. While "Detail" is defined as the formation of placing and making, where an architectural form is joined as a continuous surface that is regarded as the characteristics of a structural detail. Digital technologies provide possible locations for the generation of

connections via computer simulation. Some digital, structural techniques of morphology are employed to simplify the joint assembly. Details of a building's digital skin formed by the Digital-Green materials are reinterpreted as the generator of construction skills.

4. *Fabrication / Construction:* A new method of construction and assembly techniques use new technologies to explore more accurate processes of producing, fabricating, testing and assembling the digital components. The CAD/CAM fabrication technology of rapid-prototyping (RP), computer numeric control (CNC), and 3D scanning provide new methods of assembly to fabricate precise form.

(2) Design Media

1. *Generation*: Through manipulating different computer modeling processes, the form evolution and design concept are evaluated to help initiate architectural solutions for innovative forms and sustainable impacts. The automatic generating process generates freer forms through algorithms or computer generative systems with dynamic processes such as animation or morphing. Such comprehensive, digital application promises flexible modifications in meeting the needs for energy efficiency at every stage of the construction. The environmental factors of the site also function as the driving force of dynamic deformation.
2. *Motion*: Either virtually or physically, the manipulation of design concepts has been engaged in a variety of form evolutions with natural factors in

which a serial process of dynamic operation is deployed. The dynamic form change is influenced by environmental factors.

3. *Structure*: The structure can be interpreted as a system, a unit, or a concept influencing architecture tectonics that joins all elements of a building in unity. In light of the rapid development of digital technologies, new possibilities are explored in combining structural system with building surface or with new materiality. The multi-functional structure system is redefined through the making of stiff, curvilinear form via computer simulation with the spirit of energy-saving.
4. *Material*: The selection of the skin (surface of the building) controls solar gain, heat loss and/or other environmental factors. By merging the new technologies or computer analysis with sustainable materials, greater structural performance and more efficient surface materials could be developed. To enhance the composition of architectural construction, materials are not only chosen due to being lightweight and durable in strength, but also for a cost-effective construction.

(3) Design Method

1. *Envelope:* Provides efficient and functional *structure* that frees the form for energy saving by the application of computer modeling systems. This is also the extended definition for Object as the architectural parts and perhaps also part of the architectural whole in the Digital-Green procedure.
2. *Form:* This is the direct result of responding to the requirements of both digital and sustainable needs. Through the use of computer calculating

and modeling, the form transforms the fluidity of the exterior conditions to maximize ventilation, maintain view, or structural needs.

3. *Energy:* The use of computer modeling analysis and calculations to manipulate environmental impacts, such as thermal, ventilation, air flow, natural light, etc.
4. *Interaction:* The relationship between site and people, green space and architecture, or people and architecture is considered. Moreover, this also refers to the interaction between architecture and natural energy such as light, air, water, and green.

Chapter 4 Case Studies

*4.1. **Case 1:** Swiss Re Headquarters*

Completed by Norman Foster in 1999, this project is a 40-story office building with renowned aerodynamic form and sustainable design approach. The project analysis is based on the twelve Digital-Green design factors as follows.

(1) Design process

1. Concept

The concept of the sustainable system emerges from an energy-efficient structure which interacts with the surroundings. As shown in *Figure 4-1*, the design adopts a continuous triangulated skin and its diagonally braced structure for the energy-conscious enclosure, which allows for a column-free floor and entirely glazed façade for the open view and natural lighting. The project attempts to generate a closer relationship between nature and the workplace through such a design concept .

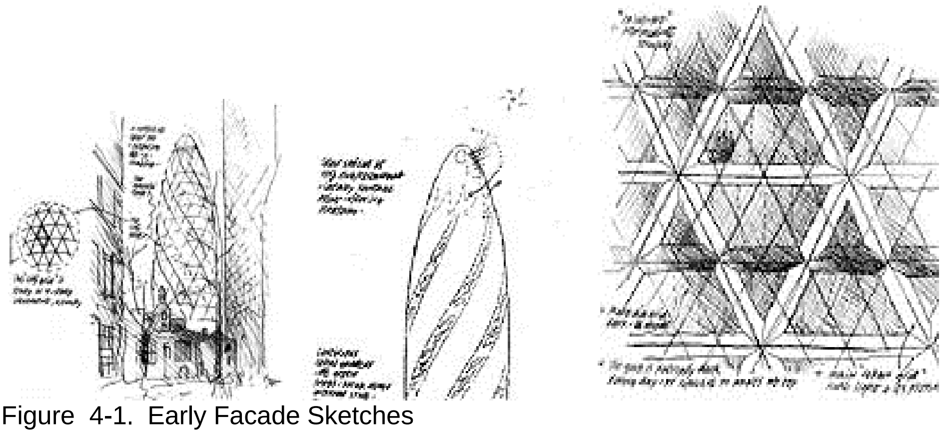


Figure 4-1. Early Facade Sketches

2. CAD / Simulation

The project is designed with sensitive response to the sun paths, local climate, wind direction, ventilation and air temperatures. By using the digital technology, Dynamic Thermal Modeling (DTM), the energy performance of the building is initially calculated at the beginning of the design process and the computer generation results are used for the aspect of design. As shown in *Figure 4-2*, Foster achieved both energy efficiency and technological requirements in using the Catia process and dynamic techniques such as CFD (Computational Fluid Dynamics) programs, which simulate the virtual prototype for both building performance and appearance before the fabrication of such a complex form.

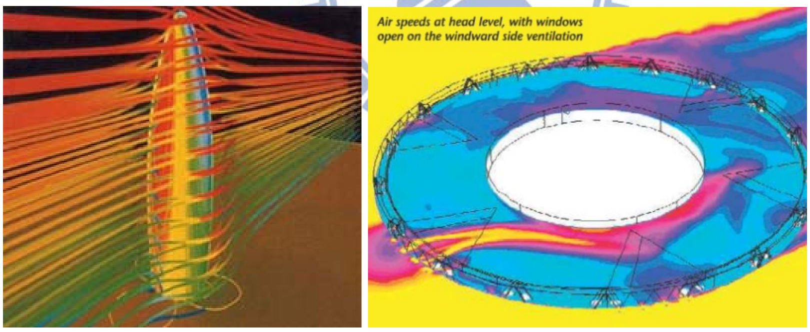


Figure 4-2. Wind Patterns Around the Aerodynamic Form

3. Detail

The project demonstrates a marriage of high-level techniques and energy-efficiency in a contemporary building well. Function-wise, the building is prided for high performance solar glass façade, ventilated floor plan, air flow entrance and lung-like lighting. Details such as triangular glass panels and light wells make up the entire spiral form, which is based on the logic of geodesic structures and tubular frame towers. The triangulated glass panel detail on the spiral curtain wall resolve the loads and pressure from the walls and roofs.

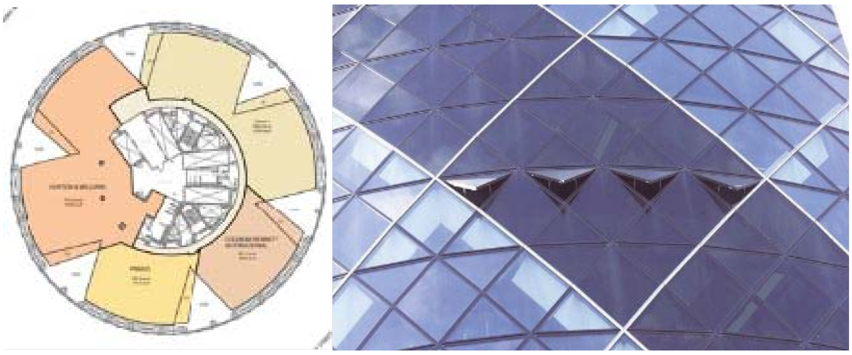


Figure 4-3. Triangular Glass Panels and Light Wells

4. Fabrication / Construction

This design is a manipulating process with the aim of computer modeling analysis and calculating environmental impacts such as thermal, ventilation, air flow, natural light, etc. During the design process, the initial form development was affected by computer simulation for structure and energy analysis. The structural envelope of these metal and glass panels are pre-fabricated in the factory and fixed to the ‘Diagrid’ for assembling on the site. With the construction methodology of “Pre-cambering”, the mock-ups of the structural connections were constructed for simulating and calculating. Those are applied for testing the performance of the structure.

Figure 4-4. Swiss Re Headquarters under Construction

(2) Design Media:

1. Generation:

This project applies analysis software for a three-dimension model of environmental simulation. By using the computer modeling techniques, the design solutions, ranging from the conceptual stage to fabrication, are all digitally intertwined with sustainable factors. The shape of the building is also specified and automatically generated, based on the calculation of variables - heating and cooling systems, angle of the sun orientation, and airflow geographic location. During the preliminary scheme of the design process, FLUENT software simulates air flow conditions and calculates air pressure on the surface of the building, which helps to generate the overall design results.

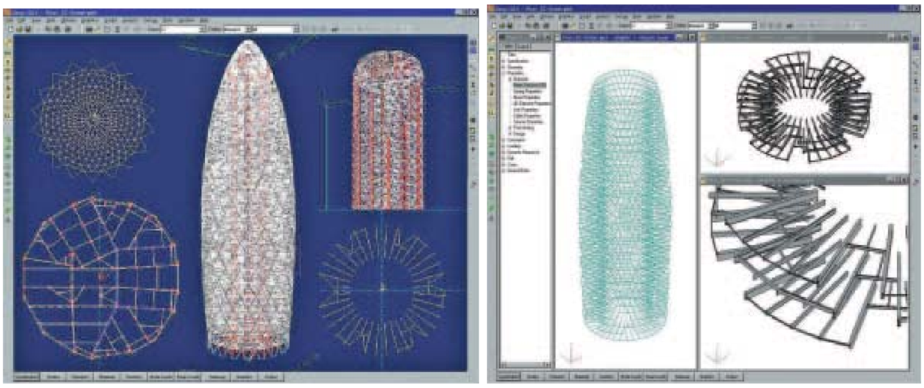


Figure 4-5. FLUENT Software Simulation

2. Motion

The building, with its circular perimeter, ias generated by a radial plan with five degrees rotation of each floor for natural ventilation. This design effectively sustains energy such as sunlight or air flow and provides a helical appearance for the exterior. By responding to the constraints of the site and wind load, the building form is dynamically simulated with 3D software to decide its form of alteration, which appears to widen in the profile as it rises, and then slims towards its apex (see Figure 4-6).

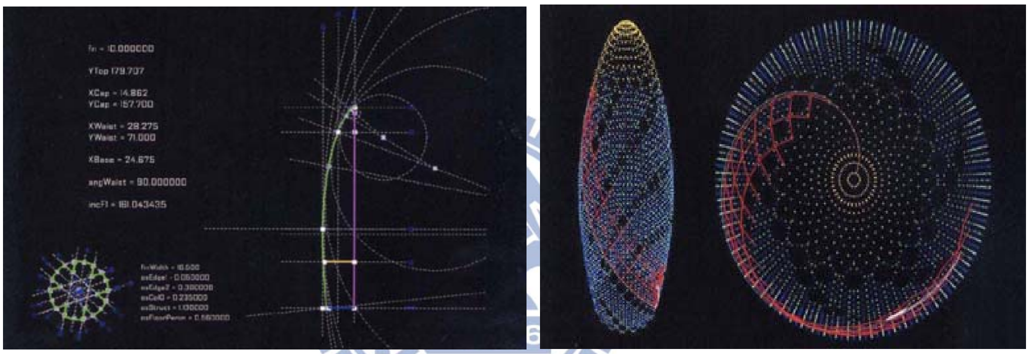


Figure 4-6. The Parametric Nodes of the Tower's Computer Model

3. Structure

The perimeter ‘Diagrid’ structure is developed especially for constructing a large building with the need of structural efficiency. In order to support an unusual geometry like this project, triangular structures for supporting beams diagonally are created from structural steel. The ‘Diagrid’ steel structure with its triangular nodes helps support the outer weight of the overall structure and makes possible the glass exterior façade. With the support of advanced modeling software, the steel nodes used in the building frame are simulated and tested for the amount of deflection by the effects of building load and wind load.

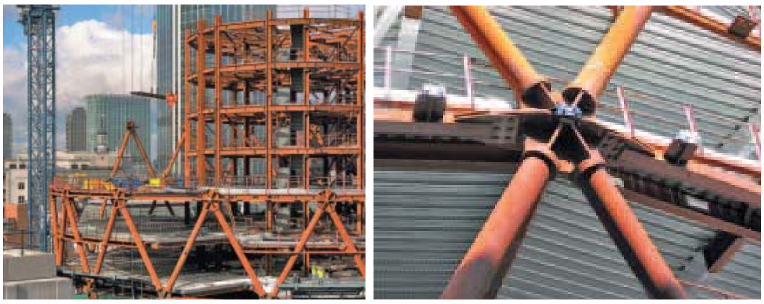


Figure 4-7. The ‘Diagrid’ Steel Structure

4. Materials

To create a light-weight and column-free structure for the high-rise tower, the structural steel and the flat triangular glass panels are combined to construct the framework of the aerodynamic glass-walled building. Therefore, two kinds of material systems, the framework of the skeleton and the surface for the building envelope, are presented as the main materials of the design. Full glazed and double-skinned façade with approximately five thousand glass panels comprise the exterior cladding system. Flat triangular and diamond-shape glass panels are also employed to fix to the ‘Diagrid’ structure. In the office areas, the glass materials are enhanced to reduce solar radiation; high-performance glass is used in the area of the light well for the same purpose.

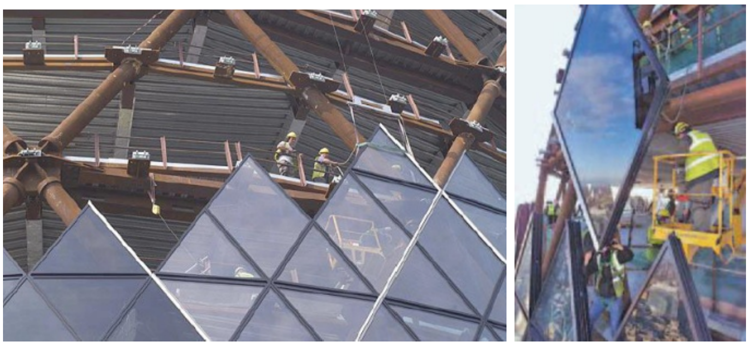


Figure 4-8. The Flat Triangular Glass Panels

(3) Design Method

1. Envelope

The structural skin, helical and curved, functions as the curtain wall and major structure of the building. The envelope of the tower consists of double-glazed outer layers and a single-glazed inner screen, which function as a double-wall system. The shading devices are located in between the walls, which serve as a ventilation chimney for the whole building. The ventilated façade not only appears as the double-skin structure to reduce energy consumption, but also performs as blinds to intercept the solar gain from the outside.

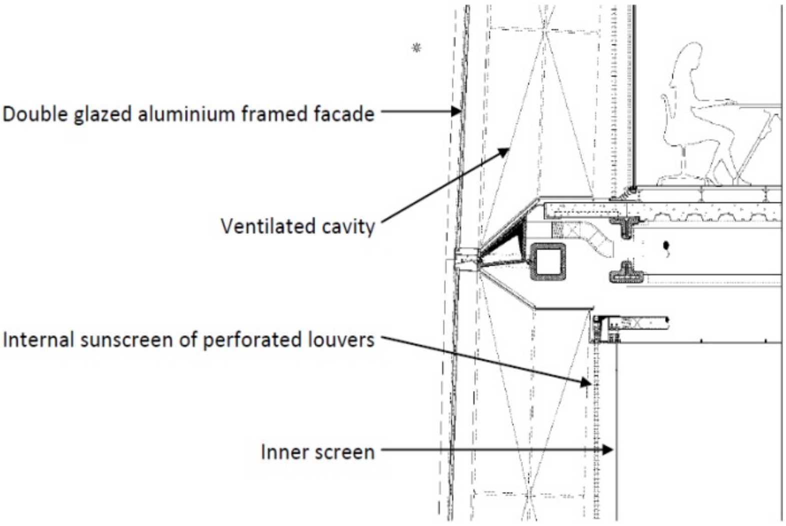


Figure 4-9. Curtain Wall Details

2. Form

The shape of the building is created for reducing wind pressure. The external building form is determined by the direction of the wind and solar exposure in order to achieve natural ventilation and better thermal conditions. The project demonstrates how the spiraling form guides the wind flow through the building and how energy is saved. Thanks to the dynamic simulation process with 3D software, multiple spiraling forms are created. Analysis of their efficiency is conducted by incorporating environmental factors (see Figure 4-10).

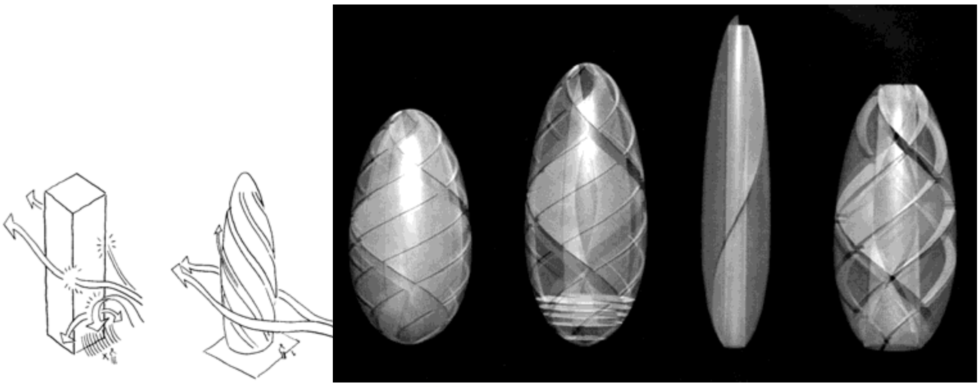


Figure 4-10. Key Parameters

3. Energy

The design employs the gaps of each floor to create natural ventilated shafts for double glazing effect, which directs warm air out of the building in summers and generates solar heating in winters to warm up the building. The light wells on the façade pump, as the small lungs of the building, and allow daylight to shine through and serve as an energy-saving feature. The wind pressure is driven through the interiors by the light wells, following the helical shape of the building. This feature minimizes the uses of air conditioning and ventilation systems. In response to various weather conditions, the double-skin façade makes the best use of heating and cooling systems and reduces the energy consumption. As Figure 4-11 shows, the radiating fingers of each floor create the atria space that distribute fresh air as it spirals up vertically through the building and function as the building's 'lungs'.

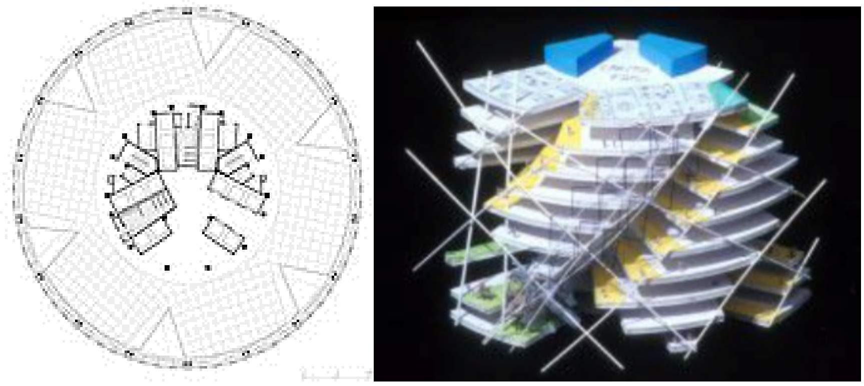


Figure 4-11. The Parametric Computer Model

4. Interaction

The column-free building is resolved by the triangulated load-bearing glass on the façade, which unfolds views from the outside. Therefore, the spiral form of the project provides inside viewers with a 360-degree interaction, corresponding to outside surroundings. The building also allows a closer interaction with the natural air and sunlight flow through the light wells on the skin of the building façade.

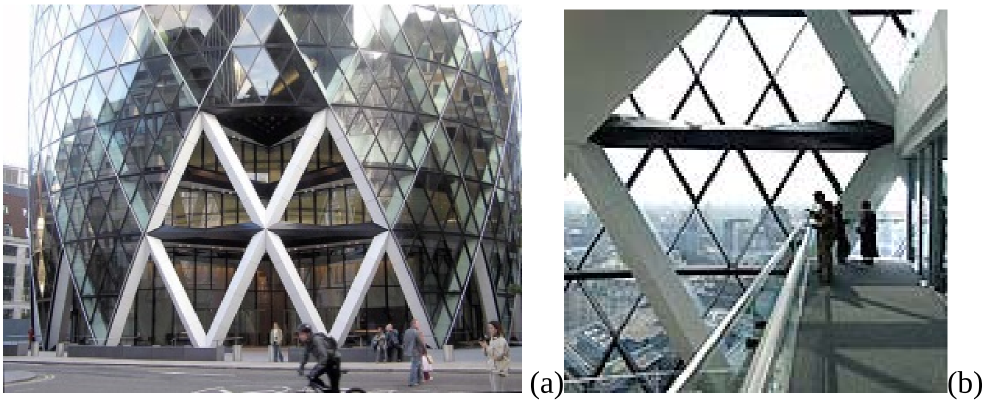

(a) (b)

Figure 4-12. (a) Tepee-style Entrance (b) View of London from an Atrium Balcony

4.2. **Case 2:** *Chesa Futura*

The Chesa Futura is an apartment building designed by Norman Foster in 2004. In order to design an environmentally sensitive building to reflect the natural site, the apartment on the edge of a slope emerges as a result of both advanced computer design tools and Swiss traditional construction techniques. The project analysis is based on the twelve Digital-Green design factors as follows.

(1) Design process

1. Concept

   The building design is conceived via merging advanced computational technology and the ecological design of Swiss traditional fashion. In the process of exploration, the design approaches engage in computer modeling techniques and 3D model generation, where the geometrical shape/ structure, severe local weather conditions and sustainable factors are taken into consideration for tackling the challenges.

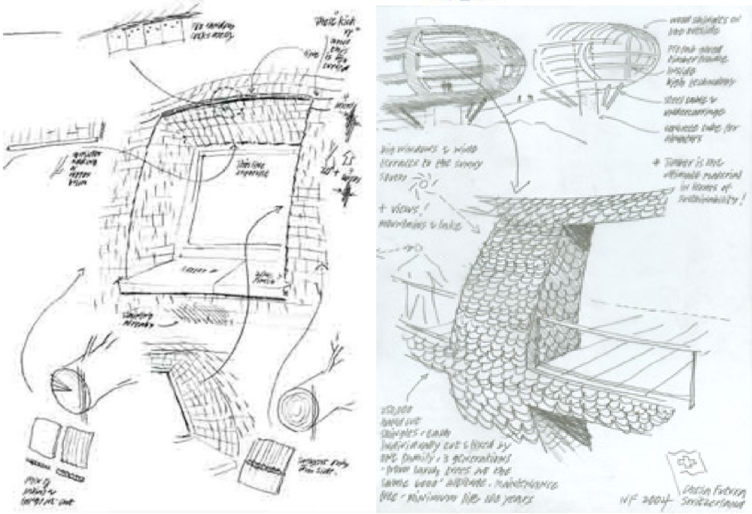


Figure 4-13. Early Facade Sketches

2. CAD / Simulation

The building form is automatically generated based on the calculation of variables -- heating and cooling systems, angle of the sun orientation, and airflow in its geographic location. At an early stage of the design process, the application of CAD software is aimed for one of the surfacing techniques - constructing the curvature. The use of Boolean subtractions helps perforate the shell-shape wall (Figure 4-14) and the logic of radial geometry provides smooth transitions to parametric relations.

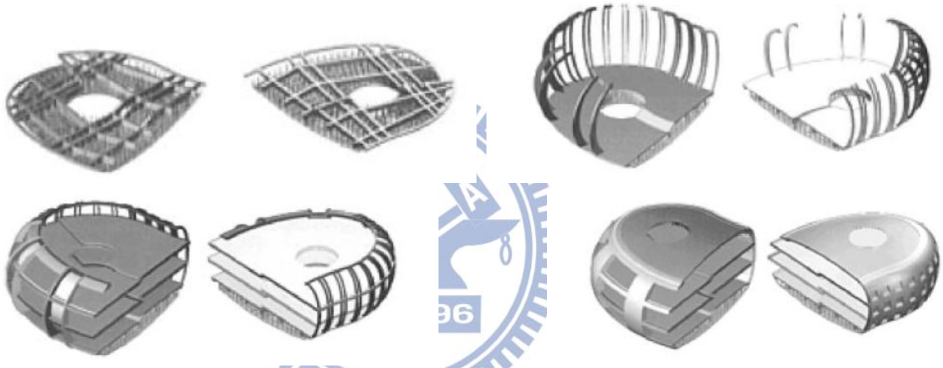


Figure 4-14. The Parametric Computer Models

3. Detail

The study of the curved form is engaged in mechanical, structural and environmental analyses, in which the windows are altered to wrap around the curved façade. These chamfered windows are aimed to maximize light penetration in the internal space, which represents traditional Swiss local building technique. In the project, the Swiss traditional, velux-like, doubled-glazed windows are reinterpreted with advanced computer technology, through which panoramic views of the surroundings are allowed and sustainable efficiency is promised, to ease the extreme weather conditions.

Figure 4-15. Doubled-glazed Windows

4. Fabrication / Construction

The advanced CAD/CAM machine of the Computational LIGNAMATIC CNC timber processing has an array of twenty tools at any angle (cut, drill, rout, bore…etc.) which allow the designer to shape a piece of laminated timber into every curvature for any unusually-shaped wooden structures (Figure 4-16). By producing the coursing lines as flat patterns, the model maker cut the timber shingles by CNC machine, and they are assembled by hand.

Figure 4-16. The Computational LIGNAMATIC CNC Timber Processing Machine

(2) Design Media

1. Generation

   The project demonstrates the digital possibilities of cantilever structure - computer-based structural analysis modeling, innovative engineering with traditional technique, and ecological materials. By using computational, fluid dynamics analysis of ventilation and air flow pressure, the digital simulations are applied to observe individual curvatures to ensure the greatest energy efficiency.

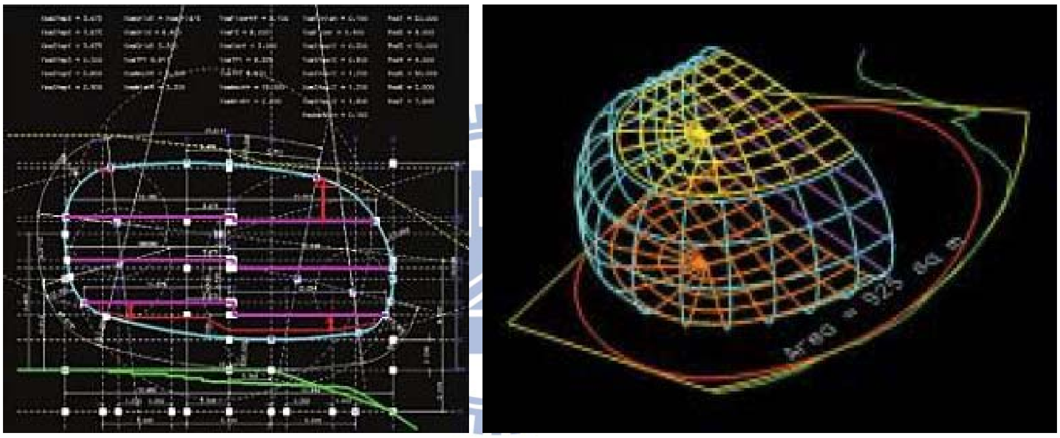


Figure 4-17. Parametric Computer Models

2. Motion

   Learning from an enduring tradition of Swiss mountain homes, the architect elevates the apartment off the ground to eleven-and-a-half feet high by eight steel piloti. The architects use 3D modeling and computer calculation to simulate the dynamic lifting of the building. The digital analysis helps test the structural stiffness during the process of automatic generation. The elevated height would keep the wooden shell from being rotted and damaged by the moisture in winter - a common situation caused by long-term exposure.

Figure 4-18. View of Steel Piloti

3. Structure

Though the construction site is located on the edge of a slope, the efficient superstructure is secured by the steel structural elements and two circular concrete cores (Figure 4-19). These two cores consist of an inner core for elevators and an outer core for spiralling staircase, which creates a vertical access and provides stability from the light-weight timber superstructure. The load-bearing structure of the cross-beams is supported by eight steel piloti and the outer shell perimeter of the project is protected by the edge beams. In addition, the prefabricated timber floor plates reduce the weight and allow an easier lift from the ground and simultaneously offer an integrated thermal wall to save the energy.

Figure 4-19. The Structural Elements

4. Material

The application of the larch shingles is chosen as a durable local resource and thermally efficient material for covering the curving surface of the building, which responds to the weather as color changing throughout the seasons. The hand-cut wooden shingles are a natural choice of sustainable, local resource of timber, which helps achieve the curving form of the apartment building (Figure 4-20). The raw materials clad the entire building's façade, which effectively curtails the carbon emissions and reduces energy consumption through hand-picked local materials from the local woods. The double-layer, glazing glass structure provides load-bearing structure and simultaneously fulfills the purpose of energy saving.

Figure 4-20. Prefabricated Timber Frame with Shingle Cladding

(3) Design Method

1. Envelope

The timber sheer wall serves as an outer-stressed skin for adding lateral stiffness and stability. In order to attempt a continuous yet strong shell of inner and outer stressed skin, the double curved panels are constructed by glue laminated elements with which materials are bent and cut into exact curves by using the parametric model of a five-axial CNC cutter. The curving form of the apartment is simulated using the natural factors, as the colder side of the building is shaped in a sharper curvature with chamfered openings, while openings in the south feature a wider curvature and larger windows.

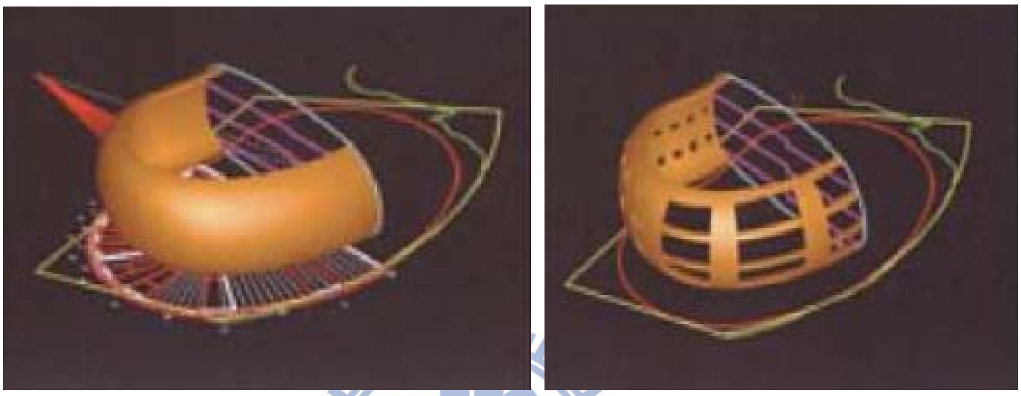


Figure 4-21. Parametric Computer Models

3. Form

   By using parametric model to explore the geometry, the form could be full of dynamic characteristics and energy-efficient. The round shape of this superstructure deflects the wind and reduces the amount of wind pressure for natural ventilation. During the preliminary scheme of the design process, software simulates air flow condition and calculates the surface pressure to the apartment's curvature of air volume, which aims for the generation of the overall design results to increase the sustainability of the building.

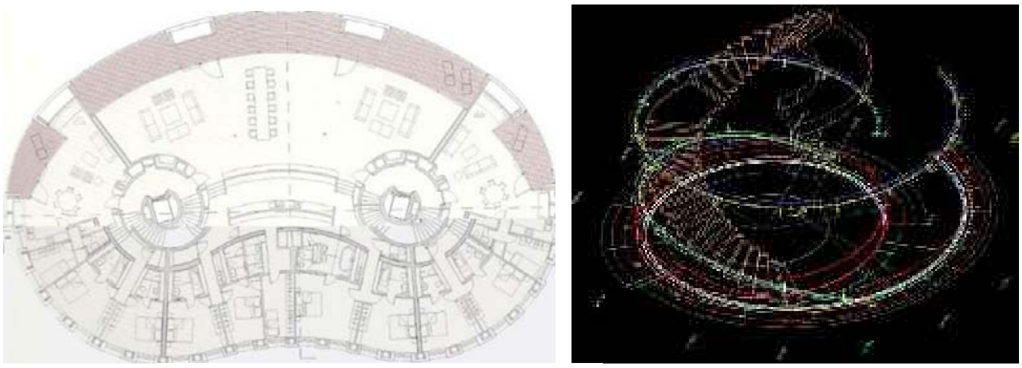


Figure 4-22. Wind Patterns around the Round Form

4. Energy

While the curving form of the building responds to the nature scenery and weather conditions; the colder, northern façade towards the weather-beaten mountain has smaller openings for the purpose of thermal mass side; the southern façade wider openings with spacious balconies for enjoying view and sunlight (Figure 4-23).

Figure 4-23. South and North Elevations

4. Interaction

Despite its small site, the Swiss building standing on stilts is reinterpreted as a more free-form yet lightweight structure, in which the curving form and its natural environment are integrated and calculated into a digital analysis process for energy efficiency.

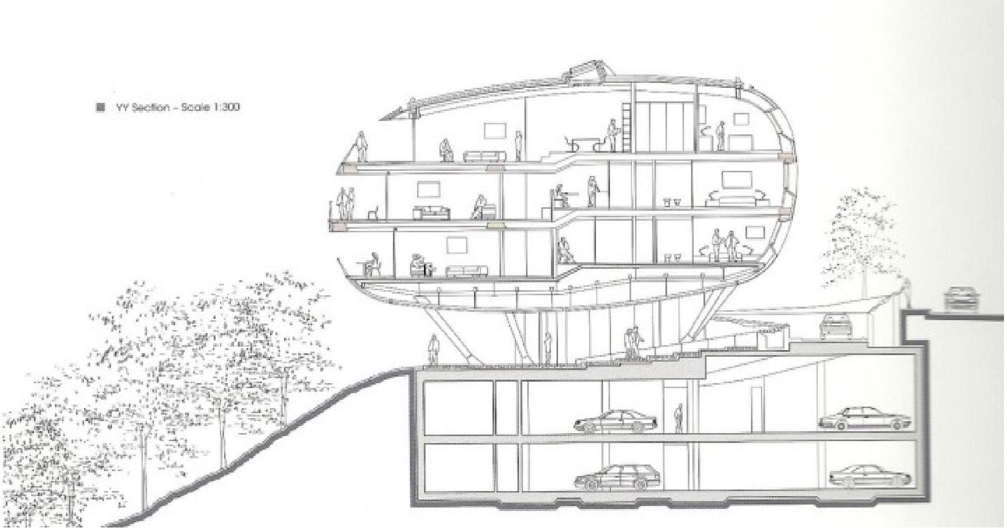


Figure 4-24. Section

4.3. ***Case 3:*** *Carbon Tower*

The tower, proposed by Peter Testa, is designed on the basis of using carbon fiber – inventive material. The research aims for combining traditional weaving techniques and digital/computational method, which multiply the possibilities of design methodology. The project analysis is based on the twelve Digital-Green design factors as follows.

(1) Design process

1. Concept

   The research of Testa's carbon tower focuses on material science of CAD / CAM technologies and materiality. Instead of applying traditional weaving technique, the research uses digital weaving calculation technology to make use of advanced structural materials in architecture, which suggests the concept of surface and structure in one. Without using traditional construction materials such as steel, concrete or glass in construction, the innovative means of employing carbon strands is recognized as a new design methodology of digital computation.

Figure 4-25. Traditional Weaving Technique vs. Digital Weaving Technology

2. CAD / Simulation

The development of the helicoids pattern is simulated with weaving algorithm in Maya within the design process. While the surface and structure of the entire building are made of continuous carbon strands, the weaving algorithms interface with CAD / CAM techniques which generates a method for the interweaving structural assembly and applies it to large-scale architectural design. The carbon fibre can be tested before being exposed to the site conditions with digital modeling and materializing by rapid prototyping machines.

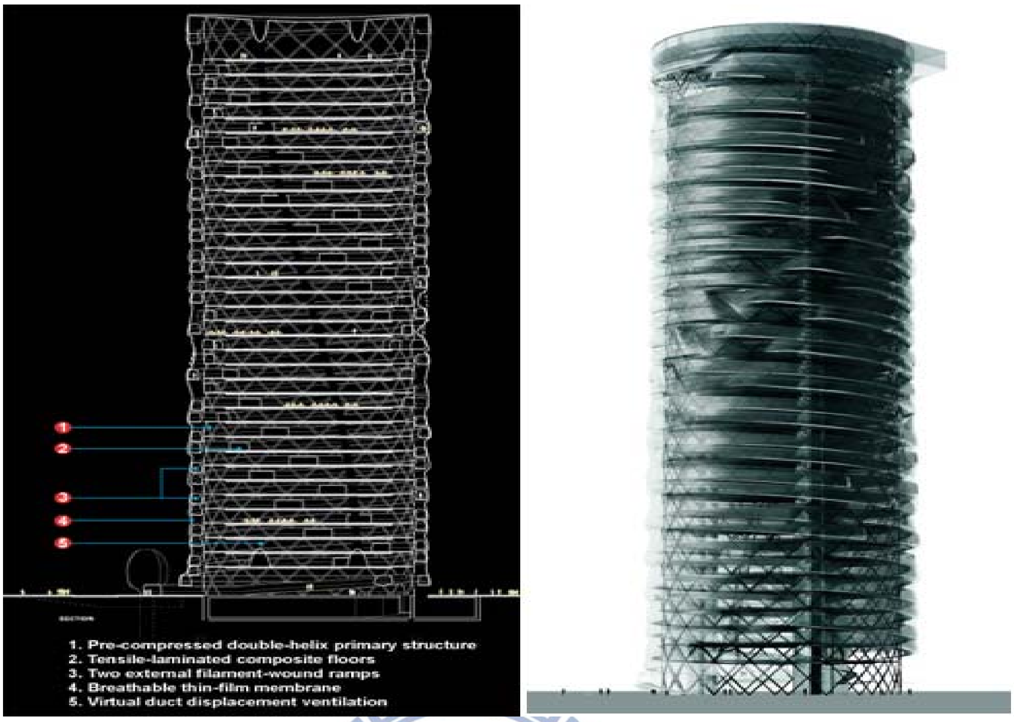


Figure 4-26. A Computer Model of a Carbon Tower Prototype

3. Detail

The forty-story high, cylindrical building is connected by forty pieces of one inch wide and sixty-five feet long carbon-fiber strands. By using digital weaving technique, the structure eliminates the requirement of joints for assembling different parts.

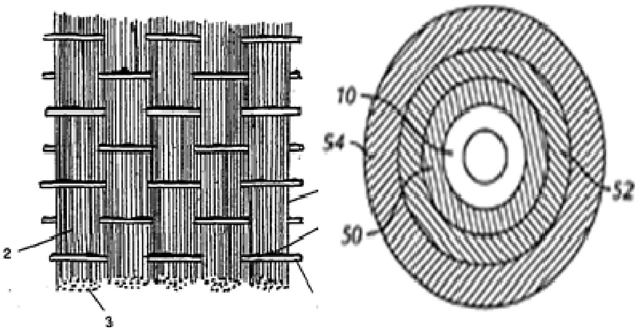


Figure 4-27. Carbon-Fiber Stands

4. Construction / Fabrication

During the design process, the designers consider materials as part of the engineering processes of fabricating and manufacturing. While the traditional technique of weaving and braiding coexists with the advanced computer-controlled process, a new construction method of Pultrusion is emerging in producing composite materials through continuous extrusions. By using a digital Pultrusion machine, the designer has the capability to fabricate a continuous interweaving structure and to fix twenty-four strands into shape. The fabrication process of twisting, braiding, or bundling the rigid rods and flexible fibers into cables becomes feasible and allows direct construction on site.

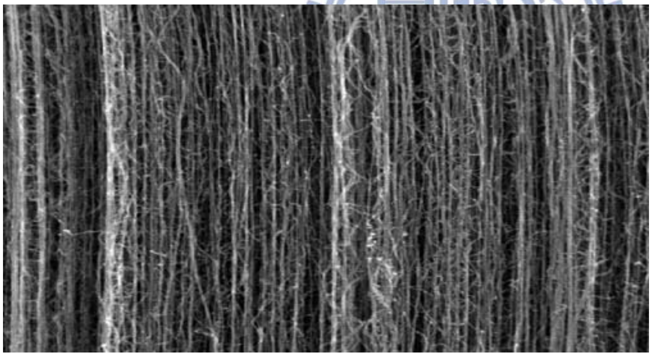


Figure 4-28. The Continuous Interweaving Structure

(2) Design Media

1. Generation

As shown in the figure, the development of the new material -- Carbon Fiber Reinforced Plastics (CFRP) -- is generated and tested by the computer calculation to ensure its stiffness and strength for a high-rise building. While the structural members -- circulation and ventilation -- act as one, Weaver, the computer program, helps visualize the structure. These techniques bring forth the evolution of surface morphology. Such an interactive program provides a virtual test of innovative materials, which generates parameters and structural analysis for a proper woven pattern.

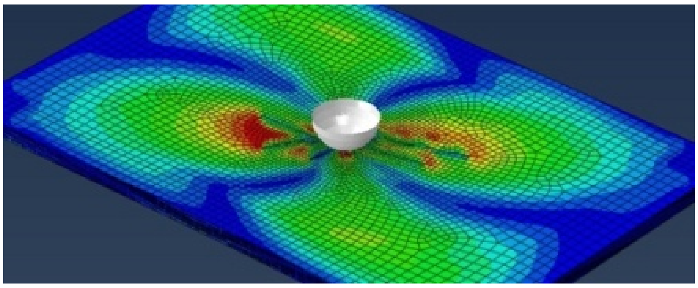


Figure 4-29. FLUENT Software Simulation

2. Motion

The use of ramps in the project functions not only as the circulation on the exterior, but also offers the structure overall stabilization. The exquisite structure is tied with the floor plates and woven, vertical strands. Moreover, the ramps form a lateral bracing around the helicoid structure which helps the building to cope with the external temperatures.

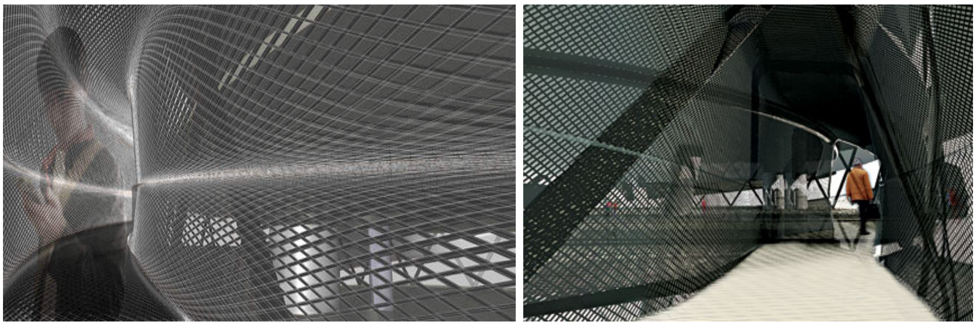


Figure 4-30. The Circulation on the Exterior

3. Structure

To support the floors with helicoid structure and tensile materials, designers connect the woven vertical strands and floor plates by binding the cables to tie across the helix for supporting the floor plates. The combination of both techniques makes it possible for the outer form to retain a continuous appearance without over-buckling on the helix structure. Thanks to the advanced textile technology, columns and vertical structural elements become scarce since the vertical compressive loads are taken. As shown in the figure, both grouping the one-inch, thin carbon strands into cables and constructing them into the building form a winding and continuous shape from the bottom to top in both directions. Therefore, the floor structure and surface cable networks are tied together with the external structure.

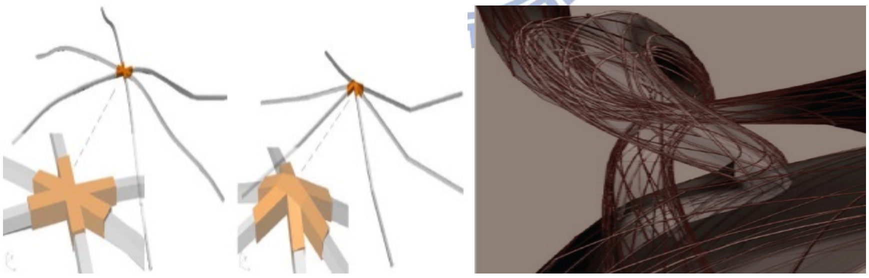


Figure 4-31. Thin Carbon are Stranded into Cables

4. Material

The design uses composite materials such as fiberglass and mostly carbon fiber. These fiber materials are not only chosen due to being lightweight and having durable strength, but also for a cost-effective construction. With high tensile strength, the structure is five times stronger than a steel one. Due to the high-tech innovation of extremely compressed materials, column-free floors become possible. Merging digital, weaving technologies and traditional, natural materials helps discover an avenue for greater structural performance and generates unlimited sophistication in the digital computational method for design process and thinking.

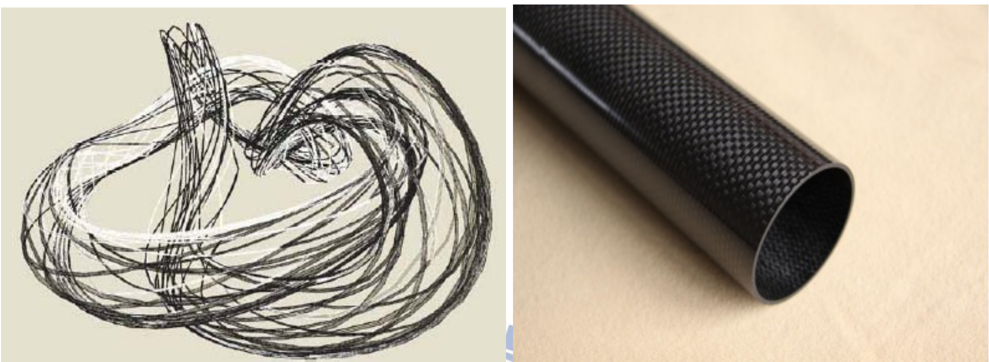


Figure 4-32. Carbon-Fiber

(3) Design Method

1. Envelope

The primary structure of the Carbon tower is made out of pre-compressed and double helix carbon fiber strands. The envelope is created by the weaving techniques of formable, light, and stable carbon fiber. The breathable woven materials layer and combine several kinds of materials with various membranes through digital computational process, which weave the envelope into a superstructure.

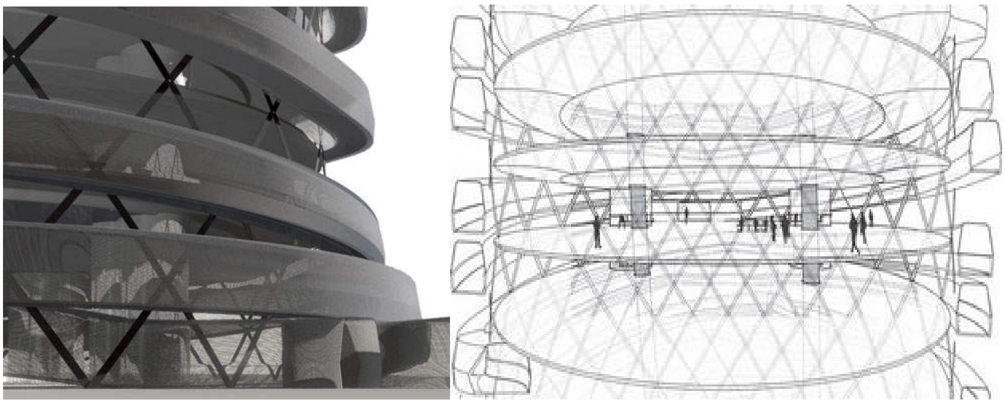


Figure 4-33. The Helicoid Structure

2. Form

   Carbon Tower is a double-helix tower with the round form and column-free structure. With the multiple layers of skin wraps around the contour of the distorted ramp for enveloping the structural matrix, the building allows air and light to flow, providing free and natural ventilation within the interspaces.

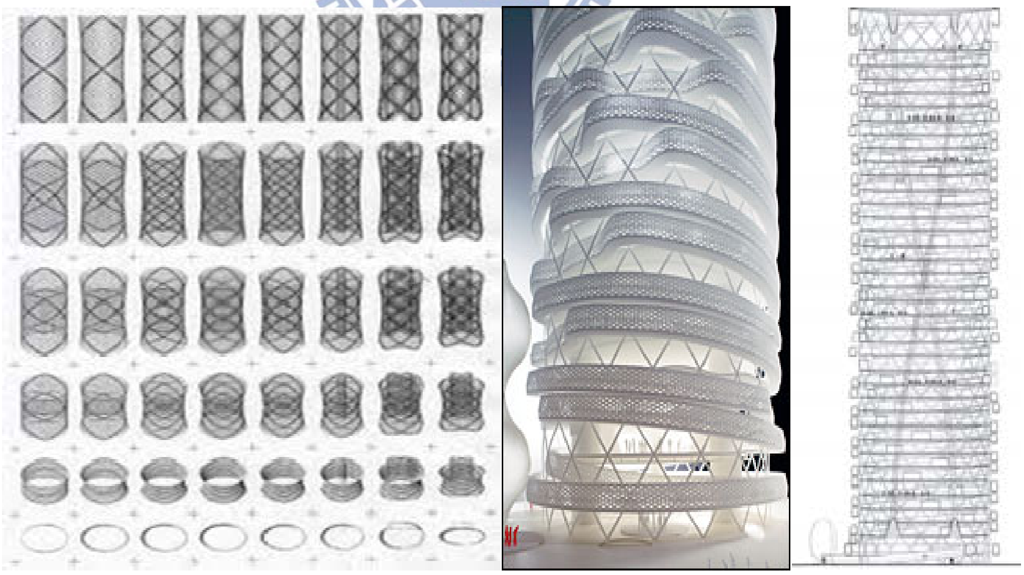


Figure 4-34. Spiral Geometry

3. Energy

Carbon Tower has the tensile, membrane skin for natural ventilation and the ability to adapt UV resistance. The outer skin is self-cleaning and pre-fabricated for energy saving. The fabrications of the exterior membrane involve the help of thermal, UV protection and fiber matrix technologies. Moreover, such a lightweight material can be easily transported to the site and manufactured on the site. That is essentially cost and energy-waste savings for a large constructing building project.

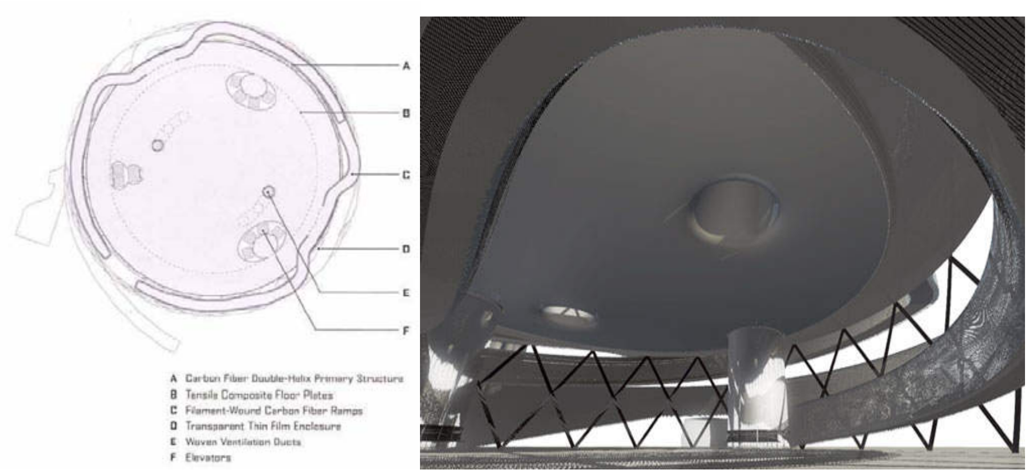


Figure 4-35. Tensile Material

4. Interaction

The complex interactions between elements and environment are provided by computing, simulating and analyzing the testing model during the design process. With the newly invented tensile membrane skin of the Carbon Tower, the continuous perspective provides a new interactive relationship between the internal and external phases of the building. The same dynamics occur in between the city and the architecture site.

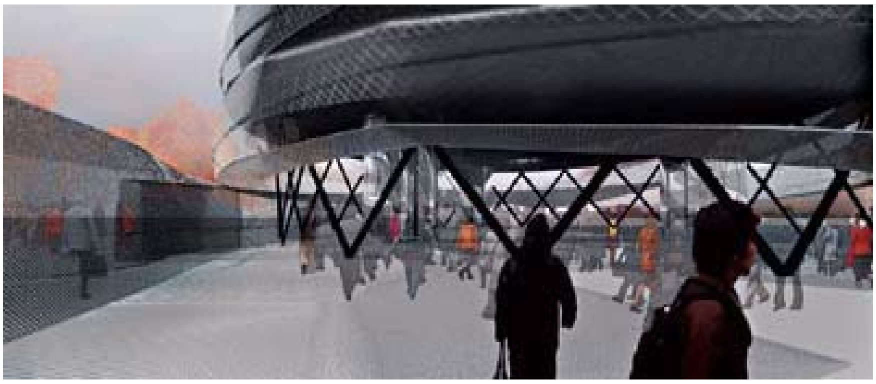


Figure 4-36. View of the Entrance

4.4. ***Case 4:*** *BMW WELT Munich*

The body of this project is unique by its twisting form with the semi-transparent structure, which is classified into five parts: Hall for the production of cars, Premiere for car exhibition, Forum for the restaurant space, Tower for shopping area, and Double Cone for a media center for exhibitions. The project analysis is based on the twelve Digital-Green design factors as follows.

(1) Design process

1. Concept

The concept of the project is more than exhibition facilities for BMW. The designers attempted to focus on energy saving through the project's technological building system and portray the continuity of topological surface by capturing the idea of Umberto Boccioni's sculpture - *Unique Forms of Continuity* in Space (Figure 4-37). The designer presents both the hovering structure of 'Cloud Roof' and the dynamic 'Double Cone' as the characteristics of the building, which blend function and aesthetics in one.

Figure 4-37. Umberto Boccioni’s Sculpture - *Unique Forms of Continuity* in Space

2. CAD / Simulation

The mesh topology of this 172,000-square-foot sculptural roof and a 43-foot-tall hourglass-shaped element, called Double Cone, are the two major elements, expressing the branding reputation of BMW and also functioning as the structural framework. In order to achieve the horizontal elements and diagonal bracing without a secondary structure, the parametric modeling of computer simulation is applied to the project. The digital technique is mainly completed with the scripting skill during design process. Using computer algorithms such as Grasshopper software to create the structure and generate the sustainable needs with better accuracy and less on-site efforts, designers actualize sustainable glass structures with the roof and Double Cone.

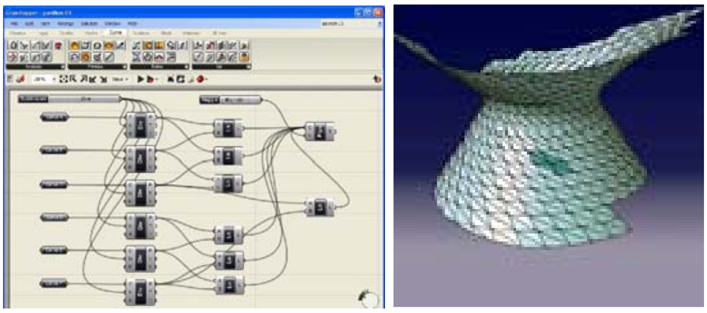


Figure 4-38. Computer Algorithms

3. Detail

Instead of using rectangular and square iron sections with the L and C profiles for the glazing supports, the architects make use of rubber in settling the glaze with corners, by which the frames are been strengthened. The triangular lattice prefabricated steel frame of Double Cone is formed by 900 different glass panels on the outer skin to fit in individual panel sizes in different dimensions. Moreover, the post-and-beam system for the façade leans vertically outward at a ten-degree angle, which allows the roof structure to function without extra movement joints.

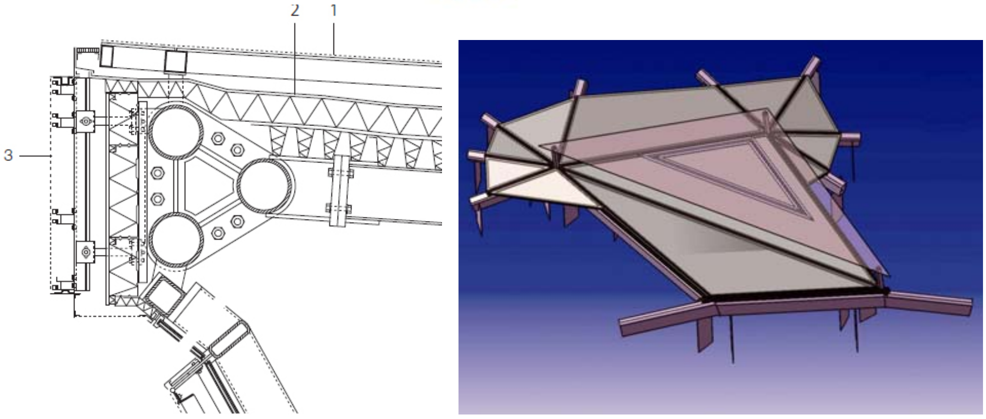


Figure 4-39. The Triangular Lattice Prefabricated Steel Frame

4. Construction / Fabrication

The metallic structure of this project is preassembled in the factory, transported in pieces and recombined at the site. By means of CNC milling machine and curtain wall supplier, a system of industrial production is employed in the procedure to reduced tolerance and consumption in the factory and on the site. As Figure 4-40 has shown, the roof structure contains a double-layered girder grid, which is differentiated from the upper and lower grids -- while the upper grid chambers function as a cushion to support the floating roof; the lower absorbs the load bearing scenario of the structure underneath.

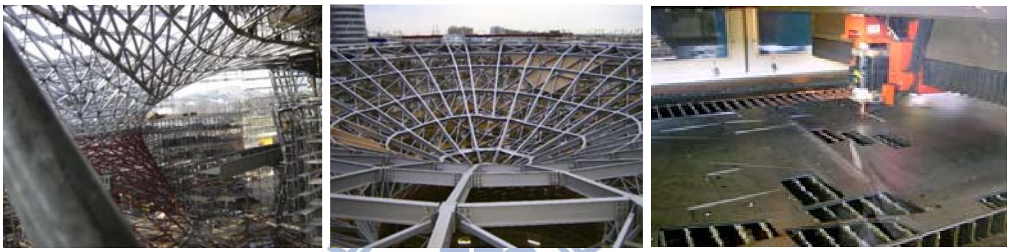


Figure 4-40. The Roof Structure

(2) Design Media

1. Generation

In order to make the roof float by the Double Cone and twelve hinged columns, the designers employ computer programs to generate the form and structure during the process. The complex structure can be precisely controlled and simulated by using the software Catia, which can also scale down the application of iron beams for the sake of structural and sustainable concerns. The use of 3D Rhino and SpaceArm are aimed for converting physical models into the surfaces, Nurbs (Figure 4-41), and for calculating the best surface solutions with the most effective form. The characteristics of diagrammatic simulation allow the direct implementation of a parametric, truss geometry, which presents the relationship between the force flows and behaviors of structural geometry under deformation.

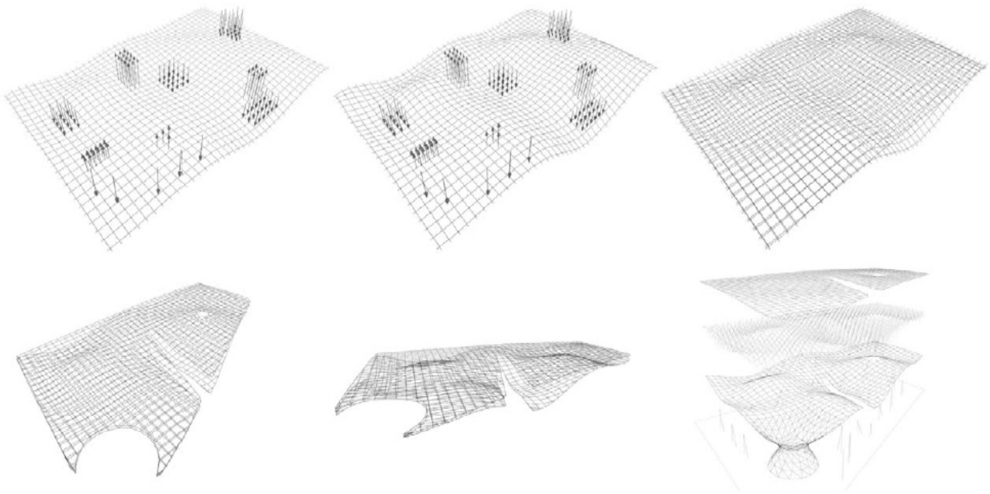


Figure 4-41. The Parametric Computer Models

2. Motion

With the dynamic simulation process via 3D software and flexible alternation of dynamic forms, the continuous overhanging tornado-like roof and the glass-and-metal-mesh, vortex-like Double Cone structure are generated to meet designers' aim. The success stirs up discussions over structural issues of freeform roof and the simulations of thermal currents and solar energy.

Figure 4-42. The Framework of the Steel Structure

3. Structure

Due to the sustainable concerns, the framework of the steel structure focuses on the expression of its extreme lightness in construction. The 16,000-meter-square roof structure consists of stainless steel cladding panels, which are incorporated into the morphology by a B-spline surface to form the innovative and dynamic characteristics of the building. While the typical steel framework contains horizontal, vertical and diagonal elements, the project conceives to twist the horizontal and diagonal elements for shaping a dynamic structure framework. Five load transfer points are designed to carry the entire structure load; while the ‘cloud-like’ roof and the Double Cone structure merge to share the bending behaviour of the roof structure.

Figure 4-43. The Continuous, Overhanging, Tornado-like Roof

4. Material

The BMW Welt is constructed by a semi-transparent glass structure with UV protection of the perforated surfaces. The outer cladding of the BMW Welt and the Bridge is made out of stainless steel and layered with laminated safety glass. Moreover, the glazed, stainless steel clad surfaces help to maintain optimal temperature, with low thermal transmission coefficients in the building.

Figure 4-44. The Glass-and-Metal Mesh

(3) Design Method

1. Envelope

The envelope of this glass-and-steel structure, containing an integrated façade heating system, provides a freeform yet sustainable glass structure for this project. The semi-transparent glass façade provides the interior space with natural lighting and proper indoor temperature. The unique Double Cone structure sustains the building as a load-bearing force, channels natural lighting building-wise, and generates the capability to carry the loads of the floating roof structure. In order to keep the Premiere levels from heating up and filling with exhaust fumes generated during car delivery, a ventilation system is combined with the wall structure to make the thermal flow through the roof, outside the building.

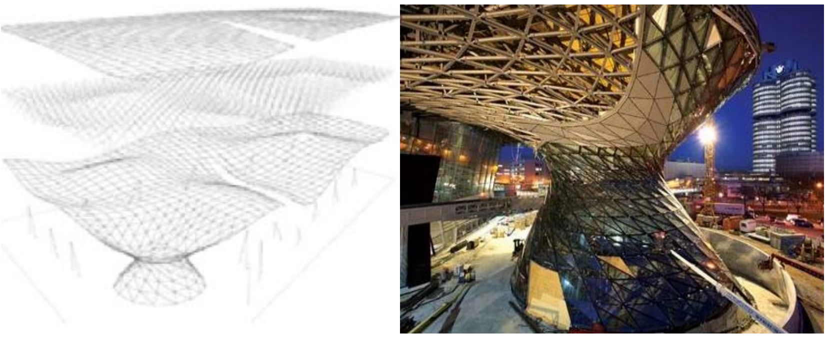


Figure 4-45. The Double Cone Structure

2. Form

The wavy pattern on the Double Cone structure near the top end makes the visual effect of the floating roof. The sculptural roof with its cloud-like floating form is placed on a Double Cone steel structure and some hinged columns. The Bridge becomes the access that connects the Tower, the Forum and the Double Cone together, but hangs from the roof structure without any supporting columns in the interior. In order to encourage the continuity of natural ventilation through the whole building in this project, the façade and the Double Cone column structure merge together with the roof with the solar modules integrated on the surface; the original architectural elements are replaced with a multi–functional, freeform structure.

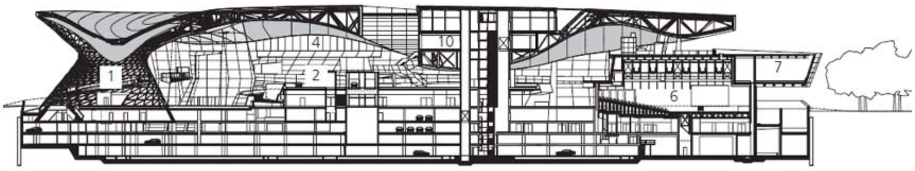


Figure 4-46. Section

3. Energy

The new additional function to the Munich BMW complex is to design with the techniques of solar heating and natural ventilation by generating the accumulated thermal currents or wind turbulences in the areas of the façade and roof. The roof top is equipped with flat roof-integrated PV system plus solar modules are installed. With the naturally ventilated system of the building and the solar modules on the roof top, the building is enabled to automatically provide air and heating without using extra environmental energy. The thermally efficient façade and glass surfaces help control proper room temperature and maintain a sustainable interior. The rotational, hyperboloid frame of the 28-metre high Double Cone has a triangular, hollow steel structure, which pump hot or cold water through the welded profiles for heating in the winter or cooling in the summer. Moreover, this project uses rectangular pipes to support the glass panes directly instead of traditional round pipes, which certainly reduces steel consumption in construction.

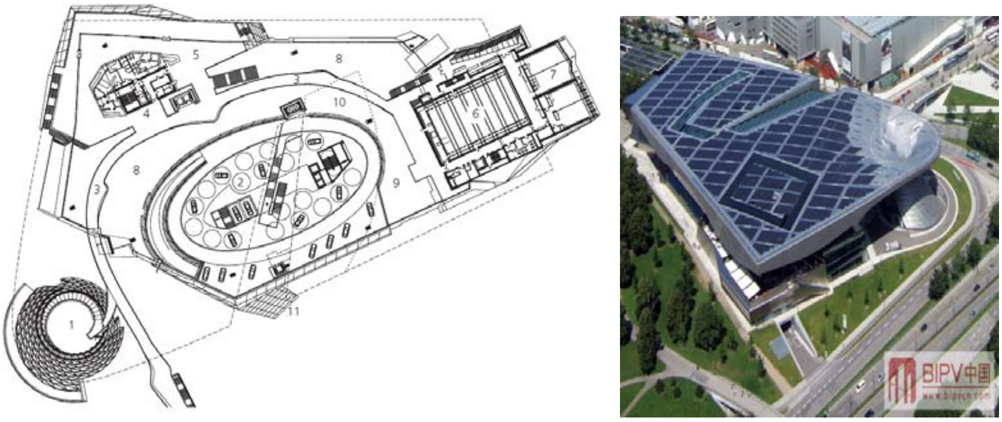


Figure 4-47. The Double Cone’s Hollow Steel Structure

4. Interaction

With the cloud-like floating roof and the sculptural whirling Double Cone, this project creates a visual connection between neighboring people and architectures. With the interaction between the site and architecture, there is vegetation planted around the building in order to provide a filtering system for seasonal dust particles. The semi-transparent glass façade also broadens the view for visitors and invites interaction with the natural energy such as bright sunlight. The Bridge in the project not only connects the building zones by resting on the structure of the Tower, Forum and roof, but also links the neighbors by extending the Bridge length to the opposite side of the street.

Figure 4-48. The Semi-transparent Glass Façade and the Bridge

4.5. ***Case 5:*** Whitney water purification facility and park

The design enlarges the existing wetland by minimizing site disturbance with the thin profile of the building. The inverted raindrop shape of the administration building was voted as the Top 10 Green Projects by the American Institute of Architects Committee on the Environment. The project analysis is based on twelve Digital-Green design factors as follows.

(1) Design process

1. Concept

At the beginning of the design process, the designer develops the concept by hand drawing. However, a series of tests with digital technology are used to simulate the possibilities of preserving the natural resources in the wetland. Compared to other case selections, the project is intended to explore the sustainability and environmental friendliness of the facilities plus the underground park. Instead of using computer calculations for form exploration, the digital technology is primarily focused on constructing underground green architecture. The designer intends to leave 90 percent of the building underground applying the concept of porosity to minimize the impact on the environment.

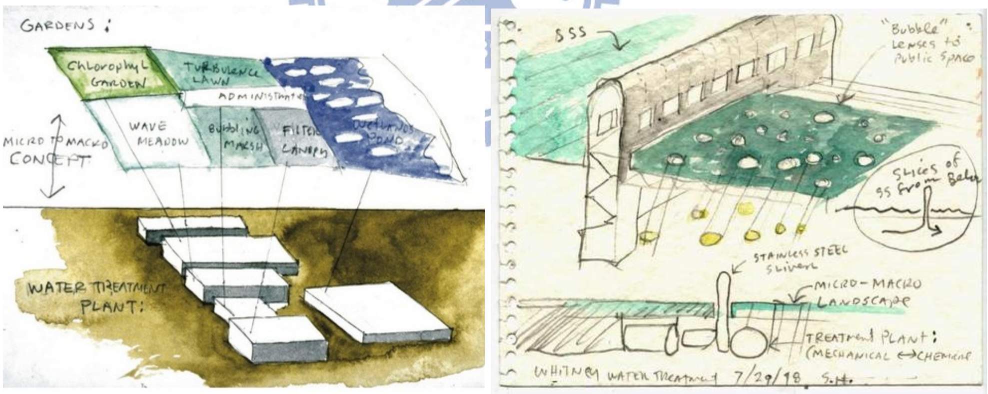


Figure 4-49. Early Conceptual Sketches

2. CAD / Simulation

The project employs a single continuous form with stainless metal shell to express a typical characteristic of a digital freeform object, which is the only part of this project on the ground. The CAD / CAM technology is employed to achieve the material continuity by developing the stainless steel clad surface. The computational surface of the convex arcs allows the metal envelope to open a topological space. The construction of the facilities demonstrates the process of water treatment where a public education classroom is automatically formed.

Figure 4-50. The Computational Surface of the Convex Arcs

3. Detail

As shown in Figure 4-51, the domed skylights in the green roofs protruding into the landscape allow not only the daylight to shine upon the water treatment plant, but also for visitors to learn about the water treatment process as a form of public education. The building surface is covered with cladding in thin, steel shingles to shelter it from heat gain and to ensure the semi-underground level with energy efficiency.

Figure 4-51. The Underground Water Purification Structure

4. Fabrication / Construction

The construction of this project is majorly generated by three-dimensional computer-aided technologies for the prefabricated structure and outer skin, which shapes a silver-drop building on the ground. With the aid of computer media, the construction of underground water purification facilities can be digitally calculated and the structure is constructed with greater efficiency on site. Moreover, the prefabricated techniques also minimize material and time consumptions. By selecting off-site prefabrication, the construction timeline is shortened with quality precision of structure forming.

Figure 4-52. Steel Structure

(2) Design Media

1. Generation

The designer employs computer drafting programs for the digital fabrication of the ribbed aluminum panels. The form of this project contours the outlines with the computer-controlled machine and the three-dimensional virtual wire-frame models so that it emerges as a geological extension of the landscape. With the logic of parametric design process, the assembling methods allow the prefabricated materials to be constructed precisely on-site.

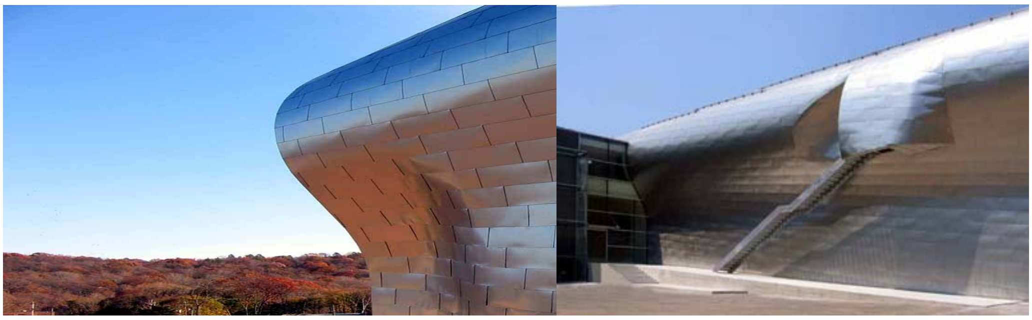


Figure 4-53. The Computational Surface of the Convex Arcs

2. Motion

While the water purification process takes place under the six different landscapes of the green roof, the sloped park also helps to filter storm water passing through the site. With a digital graphic analysis for the dynamic density variation of the environment, the growth of the green roof is generated by computational technology.

Figure 4-54. The Sloped Park Helps Filter Storm Water

3. Structure

The main structure is comprised of metal roofing and concrete. This linear structural system is calculated and simulated by automatic computer generation technology. The exterior cladding is made of a metal and glass curtain wall and the flat-lock stainless steel panels make up the angel-hair finished roofing. The cast-in-place and pre-cast concrete structure makes up the water treatment area.

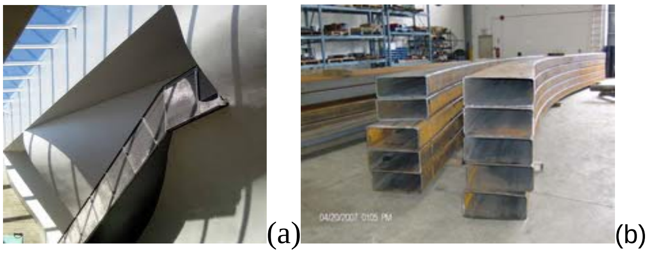


Figure 4-55. (a) The Installation of Extensive Concrete Walls Serves as a Thermal Mass
(b) The Flat-lock Stainless Steel Panels

4. Material

In this project, the prefabricated aluminum-ribbed panels on the exterior and the handcrafted techniques in the interior are constructed by non-toxic materials. It demonstrates how a digital freeform stainless steel building could also be sustainable with heat absorption reduction. Through this, the stainless steel proves to be recyclable and naturally-finished. By reusing materials such as recycled sand, soil and concrete for the building from the originally demolished facility, the designer saves energy.

Figure 4-56. The Stainless Steel Clad Surface

(3) Design outcome

1. Envelope

   This freeform building is composed with curved and stressed-skin panels. The prefabricated aluminum-ribs provide structural connections to the stressed-skin panels. The envelope of the galvanized aluminum shell is created by the ribbed panels. The green roofs and double walls of this project are incorporated with advanced mechanical systems such as the heat absorption reduction of the roof and the recycled aggregated glass floor.

Figure 4-57. The Computational Surface of the Convex Arcs

2. Form

   The form of this public park is composed by six sectors of underground facilities as the water treatment site. With the 360-foot stainless steel inverted drop building and the underground water purification below the park, the curve of the roof is also angled in order to perform as solar panels.

Figure 4-58. The 360-foot Stainless Steel, Inverted Drop-shape Building

3. Energy

   The angled green roof insulation of the project not only employs photovoltaic panels to gather energy from solar power, it also functions as the cistern for recycled water collection. The design of skylights in the green roof brings in sunlight for the below-grade planting locations. The installation of extensive concrete walls serves as a thermal mass, which minimizes the energy consumption. The application of solar power heating and geothermal cooling system on a ground-source also provides a comfortable interior temperature.

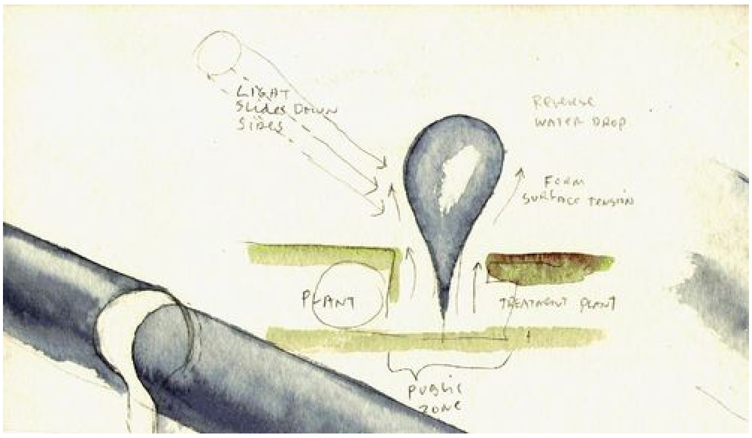


Figure 4-59. The Roof Functions as the Cistern for Water Recycling

4. Interaction

With the merging of high technology and green thinking, the ozonation bubbling system and green roof system on the rooftop brings natural light to the interior building and also corresponds to the surrounding site. The inverted water-drop shape of the building not only creates a flowing interior, but also leads the viewers to appreciate the surrounding landscape. The water purification building and the landscape co-exist in a way to preserve the wetland area and maintain biodiversity of the environment. The former also mingles with the landscape as an open-space sculpture.

Figure 4-60.   Green Roof and a Separated, Grey Water System

*4.6. **Case 6:** Zaragoza Bridge Pavilion*

Zaragoza Bridge Pavilion is designed for the Zaragoza Expo 2009 by Zaha Hadid Architects. This project addresses the importance of water resources for sustainable development. The Pavilion also functions as a pedestrian bridge to cross the river Ebro. The project analysis is based on the twelve Digital-Green design factors as follows.

(1) Design process

1. Concept

   The design is a harmonious combination of architecture, engineering and environmental concerns. With the earlier design concept, Hadid proposes a more building-like, scale architecture instead of a shell structure resulting from a series of heavy engineering. Based on the theme of “Water, a Unique Research,” the design concept of the Bridge Pavilion is focused on integrating the structural system of a bridge function-wise and the natural ventilation for an exhibition and its audience space-wise.

Figure 4-61. The Theme of “Water, a Unique Research”

2. CAD / Simulation

   While the project is an attempt to achieve the long span of 155-meter sections crossing the river, the intertwining, diamond cross sections are initially calculated via computer generation. The cladding strategy for the geometry of the perforated exterior shell turns feasible due to the applications of computer numerically cut (CNC) and modular steel slip.

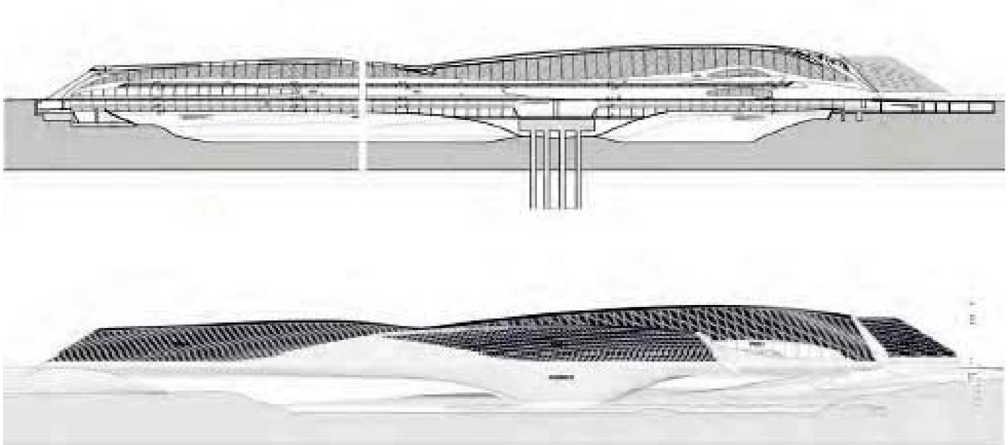


Figure 4-62. The Geometry of the Perforated Exterior Shell

5. Detail

During the process of structural analysis, the four separated ‘pods’ of the Bridge Pavilion are contained with stacking and interlocking, truss elements for optimizing the structural system. To perform as both structural elements and programming properties, the space-frame structure of the diamond section is designed for force-running over the surface. As shown in Figure 4-63, the intersecting truss elements, namely the “pods,” not only serve as joints of the bridge structure, but correspond to expanding the exhibition space. These intersecting pods brace one other to share the load with four trusses instead of a singular long span element.

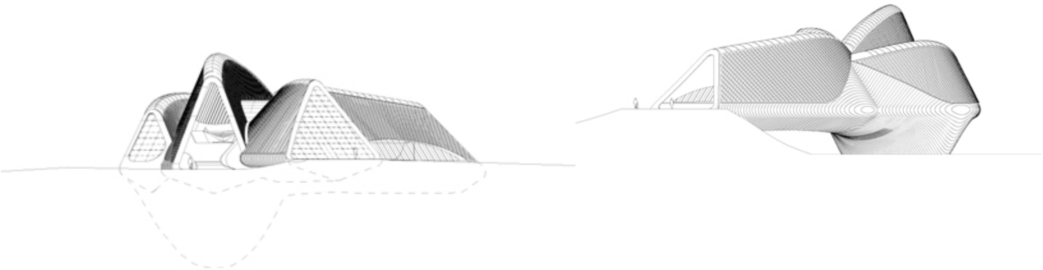


Figure 4-63. The Intersecting Truss Elements

4. Construction / Fabrication

Taking advantage of structural and technical innovations during construction, the curved façades of the bridge's primary structure and substructure are produced with the repetitive system of penalization by computer technology. By using CAD/CAM technologies, the organic form of these 62,500 steel structural elements is prefabricated through digital tools such as CNC, laser cutting, or water-jet cutters in nine metal-fabrication workshops. With a temporary peninsula built in the middle of the river, three prefabricated pods of the northern portion of the bridge structure and one part of the southern portion are assembled together on site by a 42-meter high pulling tower (Figure 4-64).

Figure 4-64. One of the Greatest Construction Challenges of the Entire Expo

(2) Design Media

1. Generation

Computer graphics are engaged to generate and simulate the form variation in the design concept. To achieve the concept of the design, the pods are the interlocking trusses, which function as the structural system and also the natural ventilated interiors. Making use of efficient parametric control, the four trusses (pods) across the river intersect through grafting the pods from one side of riverbank to the other side in order to share the loads with one another instead of relying on one horizontal bridge structure.

Figure 4-65. The Parametric Computer Model

2. Motion

The Bridge Pavilion has the pattern of shark scale skin around the body created by overlapping shingles to one another. By rotating shingles around pivots and varying the degrees of the aperture sizes, the Bridge Pavilion invites natural light and fresh ventilation into the space through the different sizes of aperture (Figure 4-66). The responsive building skin helps respond to the environmental and functional needs of the surroundings. The internal micro-environment is adapted to the responsive skin, which takes advantage of shade glazing to reduce heat gain and naturally offers direct connections to the river view with its ventilating shells.

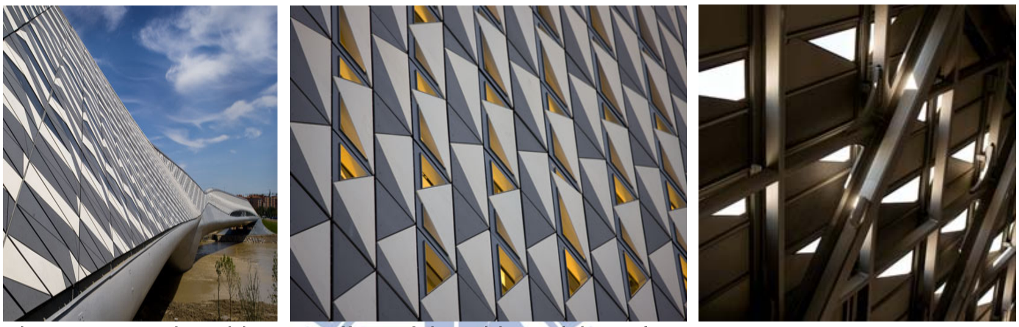


Figure 4-66. The Shimmer Effect of the Shiny, Fish-scale Patterns

3. Structure

The comprised 68-meter foundation piles of Bridge Pavilion are considered the deepest bridge foundation constructed in Spain. As shown in Figure d, the main pod intersects with other three adjacent pods, which is aimed to reduce the bridge weight as a diamond structure. The triangulating and interlocking steel structure with steel cladding is boldly visible to define the Pavilion’s exterior envelope for both structural and spatial principles.

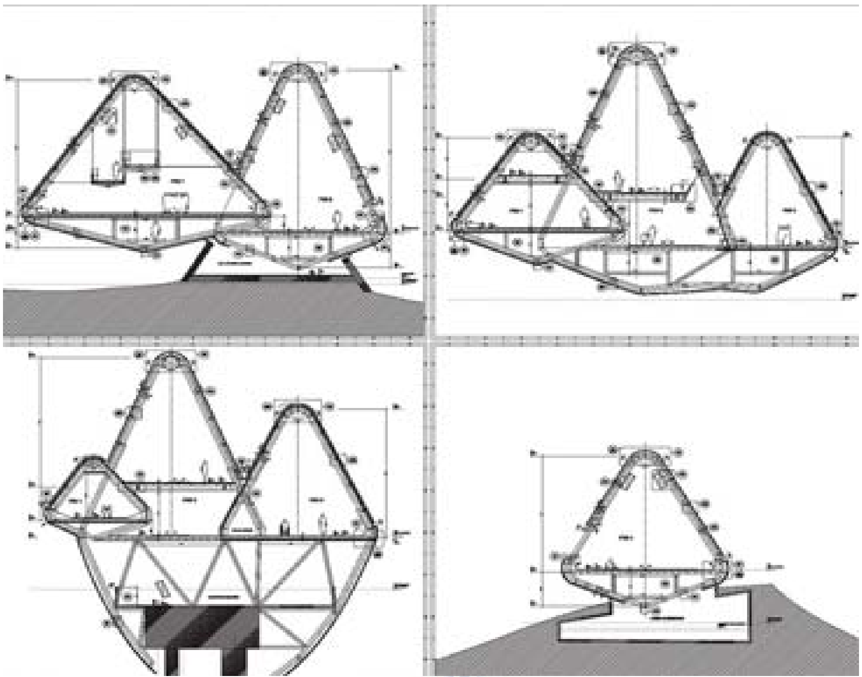


Figure 4-67. The Foundation Piles of Bridge Pavilion

4. Material

This project shows the consideration of using innovative, sustainable materials to envelop the outer skin of the building, which splits longitudinally into upper deck’s cladding system of glass-reinforced concrete (GRC) panels and lower deck’s structural metal plates. In order to clothe the outer curvature skin of the bridge building with 29,000 triangles, the designer chooses the environmentally-friendly material Fibre C as one of the raw materials. The glass fibre reinforced concrete (GRC) selected for this project, which is also known as Fibre C. The choice is made out of concern of sustainability and also for flexibility in précised process or freeform-making.

Figure 4-68. The Glass Fibre Reinforced Concrete (GRC)

(3) Design outcome

1. Envelope

The envelope of the Pavilion’s surface is enclosed to be the exhibition space yet visually connected to natural environment. The visual appearance of the shark-scaled patterns can be easily wrapped around the complex, curvature shape of the bridge structure. These envelopes with various sizes of the aperture also allow close relations between the interior space and the surrounding environment variations such as the wind and sunlight.

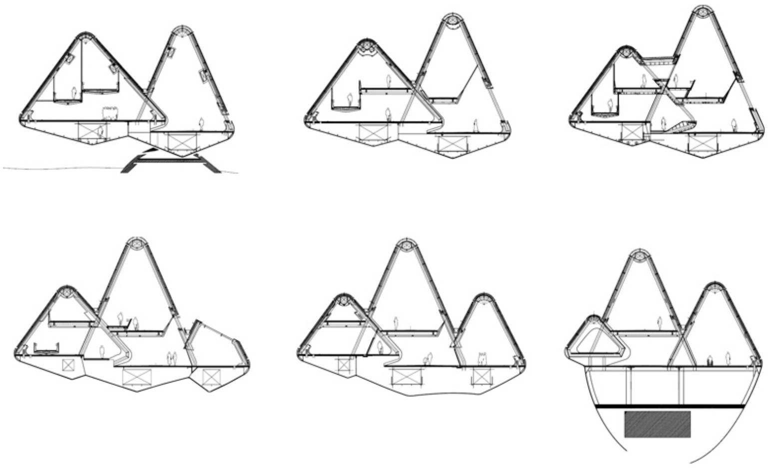


Figure 4-69. The Arch Structure

2. Form

The 275-meter bridge structure has a slightly curved form with four ‘pods’ resembling the exhibition space of the Bridge Pavilion, namely spatial arch bridge. With the arch structure, the bridge form is shaped to support the horizontal curved decks of the warped geometry. The arch-deck transversal relationship, shown in Figure 4-70, is constructed in an anti-funicular freeform, bending in an unsymmetrical shape.

Figure 4-70. The Horizontal, Curved Decks of the Warped Geometry

3. Energy

By using computer technology and simulation, designers could manipulate different kinds of materials and structure to achieve the dynamic form one desires to approach but also have sustainable value for the environment.

Figure 4-71. The Interior Space of Pods

4. Interaction

The shark-scaled envelope with its diversely generated shingles allow for leading natural light and visual contact with the river, which demonstrate its relationship to the surrounding environment visually and sustainably. The interior space of pods acts like space dividers, directing visitors from one exhibition space to another. Some exhibition zones are shaped by slightly enclosed pods, while others might have greater openings, allowing stronger visual connections to the outside such as a river view of the Expo with varied degrees of the aperture size. The shimmer effect by the shiny fish scale patterns brings about a strong visual contact with visitors surrounding the Expo and generates interactions between the reflections of the river waves and the exterior surface of the building.

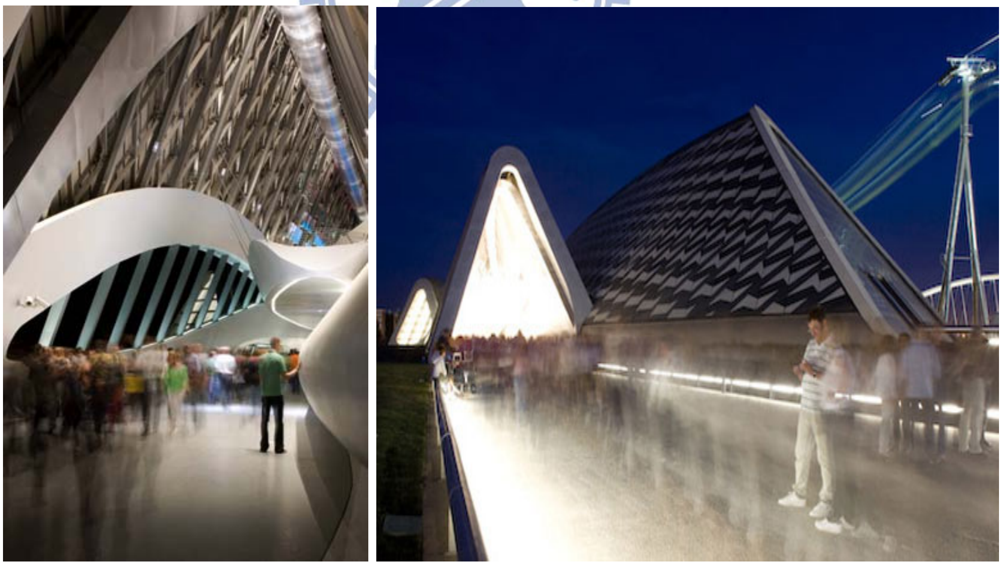


Figure 4-72. The Exhibition Zones

4.7. ***Case 7:*** CSET building designed by MCA

The Centre for Sustainable Energy Technologies (CSET) is designed by Mario Cucinella Architects, the MIPIM Green Building Award winner. The purpose of this building is for numbers of research laboratories to investigate sustainable technologies such as wind, solar power, and photovoltaic energy. The project analysis is based on the twelve Digital-Green design factors as follows.

(1) Design process

1. Concept

   The design adopts the idea of Chinese lanterns and a screen-printed curtain wall as the main elements for an energy-conscious enclosure, which allows natural ventilation channelled from the open rooftop (Figure 4-73). Advanced modeling software is used to simulate the lantern-like structure of the curtain wall to develop a stable structure.

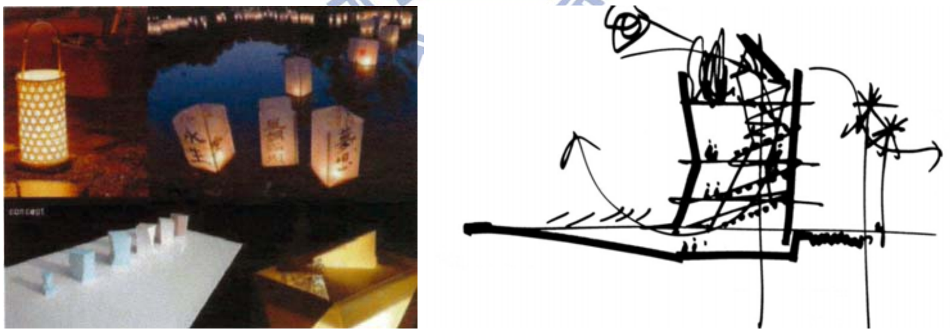


Figure 4-73. Early Conceptual Sketches

2. CAD / Simulation

   During the process of design, new computer modeling techniques are introduced to simulate the structural and environmental systems for energy efficiency. While shaping the lantern form of the CSET building, Computational Fluid Dynamics (CFD) was employed to test the impact of the sun path by calculating the environmental considerations (Figure 4-74).

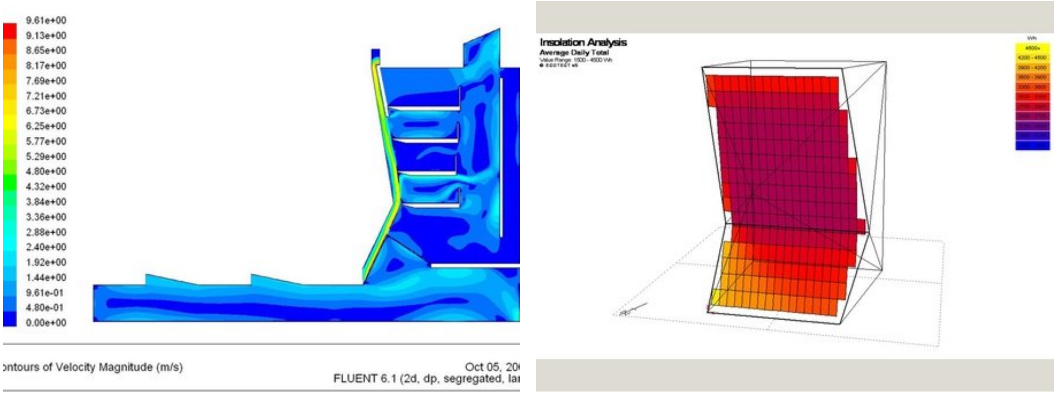


Figure 4-74. The Computational Fluid Dynamics (CFD) simulations

3. Detail

As a part of the sustainable strategies of the project, the double glazing units are spun from two slabs which are directly fixed to the concrete wall for thermal insulation. The steel bars fixed to the steel structure support the system of silk-screen laminated, glass modules on the concrete wall. Filling the gap between glass modules with metal profile creates a decorative pattern to the façade of the building (Figure 4-75).

Figure 4-75. The Folded Curtain Wall

4. Construction / Fabrication

With CAD/CAM technology structuring the screen-printed curtain wall, the digital tools are necessary for assembling each panel with exact precision for the angled and tilted forms. Therefore, the whole tower is built entirely from prefabricated parts that are made digitally for speedy construction and energy saving.

Figure 4-76. The Folded Curtain Wall

(2) Design Media

1. Generation

To manage a cross ventilation system, a series of openings are positioned in the concrete wall and the folded curtain wall, which were structured by computerized calculation. The digital approach aims for simulating proper space and angles to simultaneously create a dynamic building form and promote efficient natural ventilation.

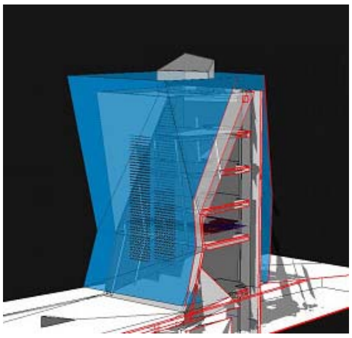


Figure 4-77. The Parametric Computer Model

2. Motion

As shown in Figure 4-78, the dynamic bending gesture of the design in twisting and tilting offers different facades for the tower. By the tilted tower back of a total sealed surface on the north side, the building is protected from the cold wind. The other sides of glazed screen with diagonal textures help to provide the building with daylight. With the digital and interactive system of the aluminium shading panels, the direct sunlight and the heat are deflected. The carbon emissions of the building are effectively decreased by these installations.

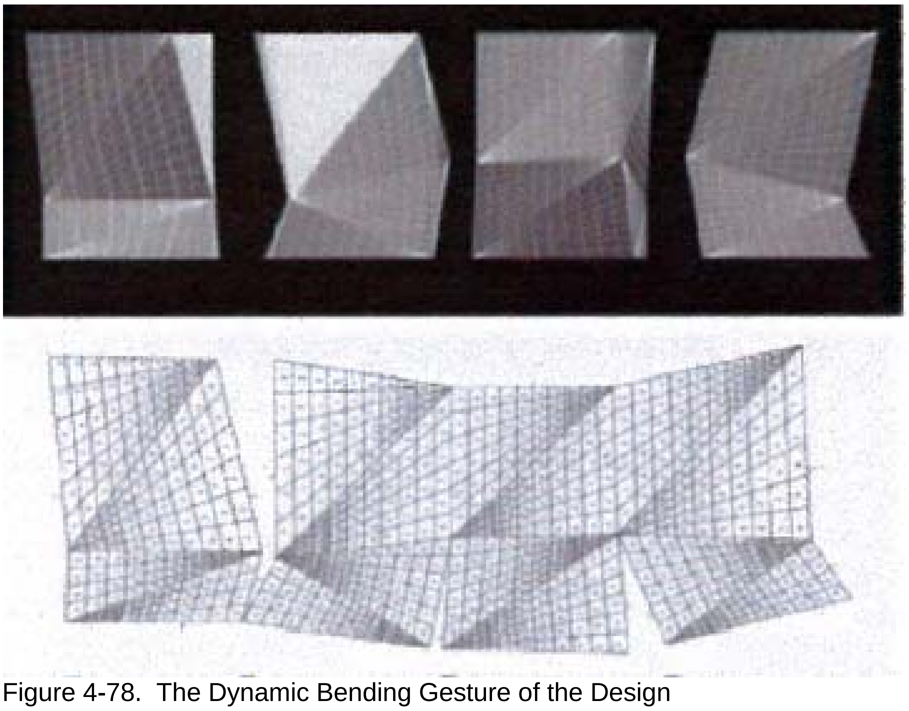


Figure 4-78. The Dynamic Bending Gesture of the Design

3. Structure

The duel wall system consists of concrete wall with openings and structural curtain wall. The former extends up to 150 mm thick, forming the insulation panels. The latter, double-skin glass with printed aluminum panels, is directly installed on the concrete walls for almost total coverage to protect the tower from cold wind in winters and sunlight radiations in summers. In between these two façades, natural ventilation enters the interior space from the openings of the concrete wall without further installation of cooling or heating facilities. The interior concrete staircases also function as the structure for the stability of the tower.

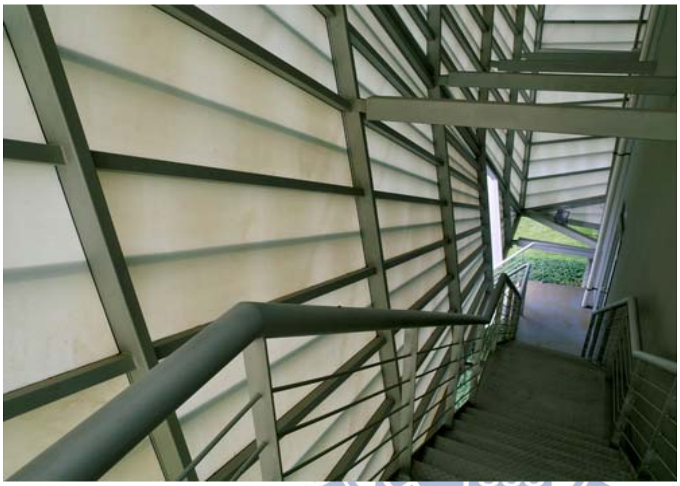


Figure 4-79. The Concrete Staircases Function as the Structure

4. Material

The tower features numerous green elements: using locally available materials from renewable sources, promoting curtain wall system and also merging ground heat pump system and photovoltaic panels for cooling and heating purpose. By cladding with double-skin glass and evoking decorative screen-printed patterns, the printed glazing envelope of the building is not only shaped like a Chinese lantern, but also transformed into a transparent structure at night in the façade, though it glimmers in the daytime.

Figure 4-80. The Decorative Screen-Printed Pattern

(3) Design Method

1. Envelope

The envelope of the building functions as a double glazing unit that provides thermal insulation and ventilation space. This double-glazing envelope wraps the building surface entirely, which is directly connected with the interior concrete slab structure and also serves as a structural curtain wall. The three sides of the external envelope structure slightly open for the penetration of natural daylight but are sealed on the northern side.

Figure 4-81. The Curtain Wall for the Penetration of Natural Daylight

2. Form

The system is developed via a detailed 3D model. The parametric approach and scripting interface allow the design team to rapidly generate several lantern shapes and complex geometric models. Adopting inspiration from Chinese lanterns with the echo of traditional wooden screens, the atmosphere of the tower has dual characteristics from day to night. As shown in Figure 4-82, the four tilted triangular skylights above are located to face the northern side for channeling adequate natural light into the basement. As for the semi-basement floor areas, the clever design ensures the direct sunlight is avoided.

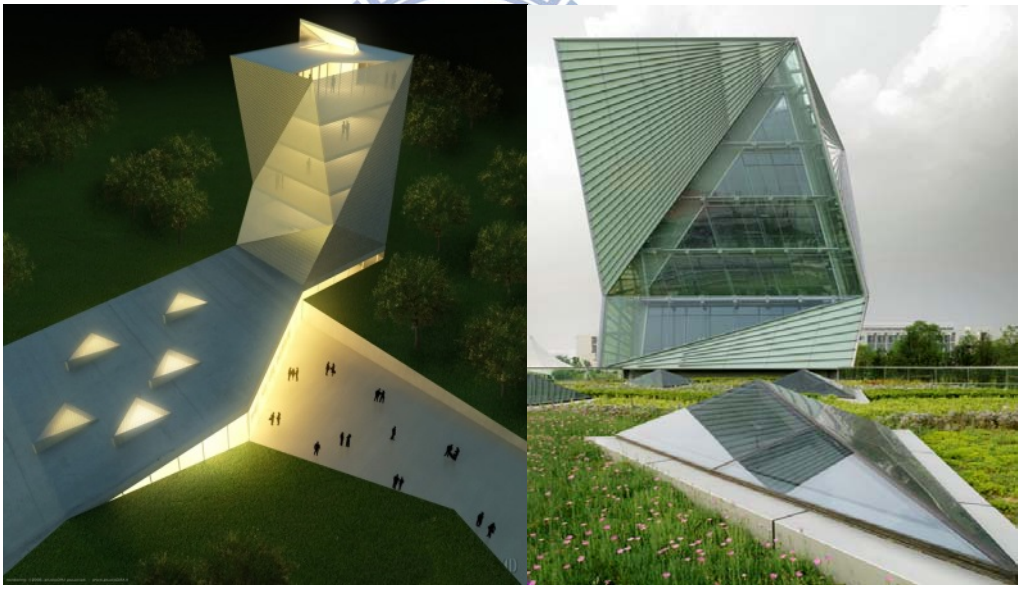


Figure 4-82. The Semi-basement Floor Areas

3. Energy

By responding to the daily or seasonal temperature differences in the Ningbo, the floor slabs are ventilated naturally and heated with geothermal energy while the opened rooftop and the internal light well cross vertically to bring natural light to all floors for the flue effect. Therefore, the building could minimize the needs of heating energy by merging the photovoltaic thermal capacity to the internal floors and walls, or cooling by natural ventilation from the partly glazed façade on the south side. The tower with the laboratory and workshop in the semi-basement are also designed for natural cooling underground in order to avoid the use of an air-conditioning system for such a busy working area (Figure 4-82). By re-using grey water, storing rainwater, and renewable sources on site, the building creates a self-reliant system and self-sustaining ecology.

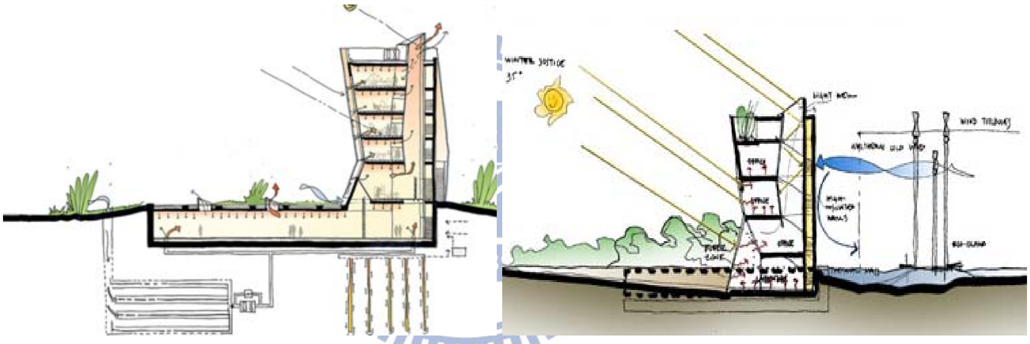


Figure 4-83. The Self-reliant System and Self-sustaining Ecology

4. Interaction

This project adopts its own energy from using renewable sources such as reusing grey water and providing an underground energy system in order to balance its own biodiversity and the natural energy (Figure 4-84). The building, with its screen-printed patterns, also creates visual connections for the historical buildings of the surrounding Ningbo area, and the tower.

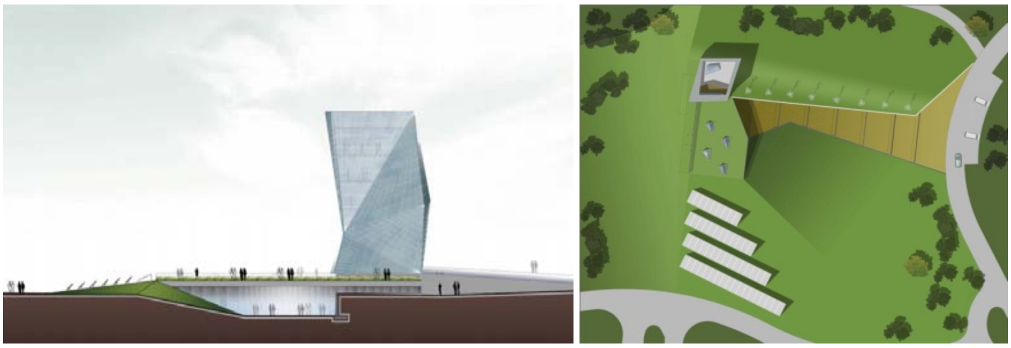


Figure 4-84. The Underground Energy System

4.8. **Case 8:** Japan Pavilion 2010

Japan Pavilion, proposed in the Shanghai Expo of 2010, is designed on the basis of eco-breathing architecture. The pavilion, with three floors mounting 24 meters high above ground, is the largest building in Shanghai Expo 2010. The project analysis is based on the twelve Digital-Green design factors as follows.

(1) Design process

1. Concept

In order to develop the pavilion in an invented biomorphic form with the shape of silkworm larva, the designers use innovative material with tensile architecture and computational technology for energy efficiency.

Figure 4-85. The Shape of Silkworm Larva

2. CAD / Simulation

The Computational Fluid Dynamics (CFD) simulations help calculate the virtual prototype of the membrane structure and simulate with a physical model to consolidate the building's geometry. The techniques also compare experimental data to result in the best-performing parameter variations for the pavilion. With automatic generation of the structure, the double-layer pillow construction in an organic PV membrane is simulated for both structural and ecological purposes.

Figure 4-86. Interior Space

3. Detail

The lightweight amorphous silicon photovoltaic (PV) films help cover some electricity load of the Pavilion. As shown in Figure 4-87, the ***ETFE,*** filled with a flexible PV film placed inside, is inflated to form a pillow and supported by the steel frame. The use of PV solar cells with the ETFE cushion protects the architecture from extreme environmental conditions and reduces the energy consumption in the construction.

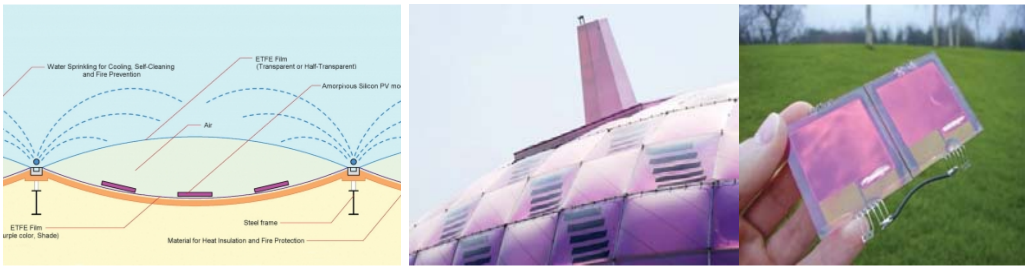


Figure 4-87. Organic Photovoltaic Cell

4. Construction / Fabrication

The ETFE materials work as pneumatic panels for assembling the upper exterior surface of the steel-framed structure, which requires innovative fabrication techniques. Based on both digital and green concerns, one could see the definitions of basic architectural elements such as roof, façade, column or window becoming vague because of the comprehensive functions and roles. With the assistance of CNC controlled machines, the cushion elements are scaled down due to their geometrical form and joined by high frequency welding techniques. By fabricating in the factory and assembling on-site, the process of simple and efficient construction helps reduce the environmental impacts.

Figure 4-88. The Steel Frame Structure

(2) Design Media

1. Generation

To fulfil the need for lightweight materials, the pavilion is erected with a light ETFE cushion. The application of computer simulation helps to calculate the innovative materials through load-bearing tests and wind-force test. The construction of the eco-tubes is also generated by computer analysis with the structural and environmental factors.

Figure 4-89. The Eco-tubes

2. Motion

Japan Pavilion employs advanced ecological technology to create the “breathing” elements such as the functional antennae and caves, plus solar energy cells over the membrane. The ‘Eco tube’ employs six vertical apertures, an innovative energy generating concept, which accumulate rain water to the rooftop sprinklers in order to reduce the temperature of the building and moderate environmental concerns. As shown in Figure 4-89, the system functions as a chimney directly connecting to the interior. That is, the roof collects rainwater for cooling mist and redirects the sunlight for heating. The generation of mist spray from the exterior body also creates the interaction between the visitors and pavilion.

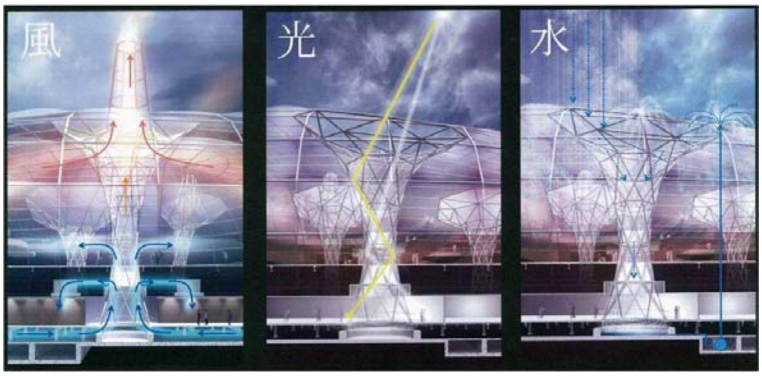


Figure 4-90. The Eco-tubes Function as a Chimney Directly Connecting the Interior

3. Structure

The architectural fabric structure is composed by membrane material with high tensile strength. The internal air pressure helps support the tension structure, which resists external wind forces and snow loads. The high strength membrane material helps apply a tension stress on the surface of the membrane and carries loads of tensile stresses.

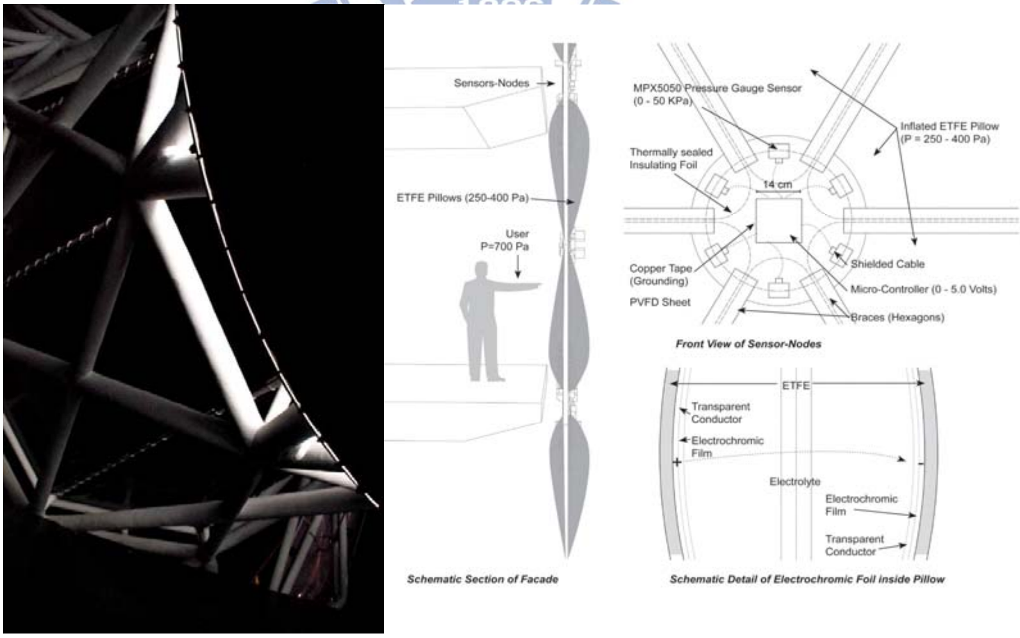


Figure 4-91.   Section through Double-layer ETFE Pillows

4. Material

The material of the pillow-like membrane helps to exhaust heat and provides natural ventilation for interior comfort. At the same time, this material also has a reflective effect to block sunlight. These purple membrane materials covering the semi-circular structure share similar material, ETFE, as the Water Cube in Beijing. Compared with other materials such as glass, ETFE is a resilient light-weight structure with self-cleaning capability due to its nonstick surface. This recyclable material also transmits light to interior space, simultaneously blocking solar radiation.

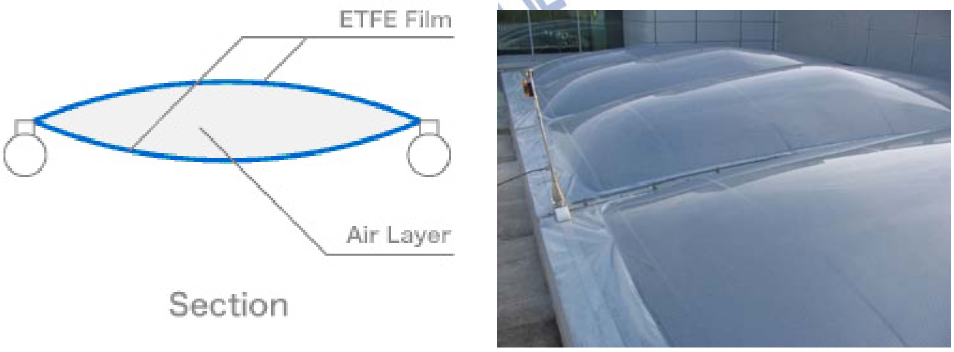


Figure 4-92. ETFE Pillows Perform like a Greenhouse Enclosure

(3) Design Method

1. Envelope

The envelope is made of the steel frame structure, covered with the ETFE double-layer pillow construction. The caves on the rooftop are inverted to the interior as the vertical hollows, which function as the eco-tubes. The eco-tubes bring in sunlight, provide natural circulation of air quality, and spray mist from the stored rainwater in order to cool down the envelope surface. The pillow membrane envelope has a built-in solar cell installation that collects solar energy and filters the sunlight.

Figure 4-93. The ETFE Double-layer Pillow Membrane Envelope

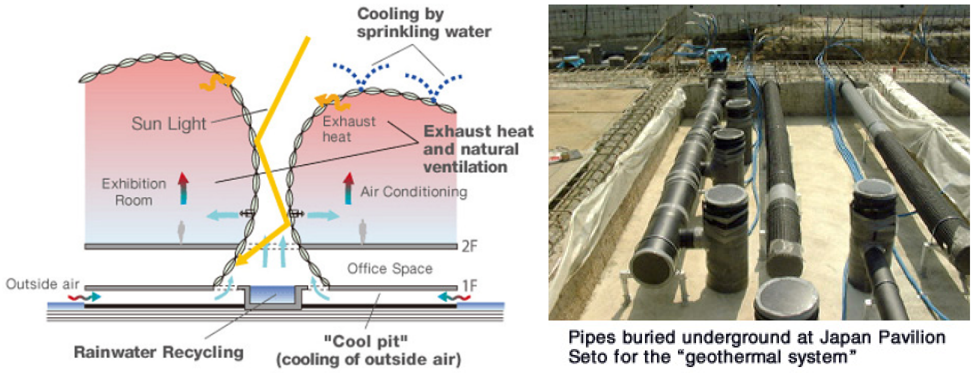
2. Form

The form of the pavilion is made of an egg-shaped structure with some antennae and caves on the rooftop. The elements of antennae and caves on the roof structure help the pavilion to inhale and exhale as an organism. Most of the pavilion surface is covered by a large, pillow-like roof structure that leaves the lower part with semi-openness, which provides good ventilation for the interior.

Figure 4-94. The Lower Part with Semi-openness

3. Energy

The building weight is reduced by the lightweight membrane systems for less steel construction. The ecological materials and structural selections reduce the environmental impact by minimizing the alterations on-site. With the hidden amorphous solar energy collection batteries under the double-layer membrane, this pavilion has the ability to filter sunshine and generate solar power to achieve a comfortable and sustainable interior condition. The caves on the rooftop of the exterior not only function as the rainwater collector, but also spray the “cool mist,” from the collected water, to the building exterior surface for cooling the temperature. The Eco-tube system under the floor space or under the roof helps to reduce the interior temperature by natural ventilation from the circulation of air, water, and sunlight. There is also the energy system of photo-catalysts called “cool pit” for purification and heat exhaustion.



Pipes buried underground at Japan Pavilion Seto for the “geothermal system”

Figure 4-95. The Energy System of Photo-catalyst

4. Interaction

   The reddish violet color of the Japan Pavilion exterior expresses the symbolic natural colors of sun and water. The ETFE surfaces have dual interaction with the surroundings by projecting different atmospheres from day to night. The functional antennae and caves of the roof create interactions between nature and the pavilion.

Figure 4-96. The ETFE Surfaces have Dual Interaction with the Surroundings

4.9. ***Case 9:*** Haesley Nine Bridges

Haesley Nine Bridges club house is a wooden architecture completed by Shigeru Ban Architects in 2009. The research is aimed for experimenting with traditional timber materials using computational technology, which explores the invented tree-like timber column with a height of three stories. The project analysis is based on the twelve Digital-Green design factors as follows.

(1) Design process

1. Concept

   With the need for both structural support and natural ventilation, the innovative pattern of the hexagonal gridshell unlocks the potential of the wooden material via the application of digital technology. As shown in Figure 4-97, the concept of the shell roof composed of hexagonal grids is inspired by the summer pillow of Korea, a traditional technique for weaving bamboo.

Figure 4-97. The Summer Pillow of Korea

2. CAD / Simulation

As shown in Figure 4-98, computer graphics are employed to simulate the funicular forms of arches and net-like form. The project is an attempt to obtain an efficiently woven timber structure with intersecting girders. With advanced computer technology and CNC fabrication process, the digital assembly process helps minimize the quantity of timber used and automatically reduce material waste.

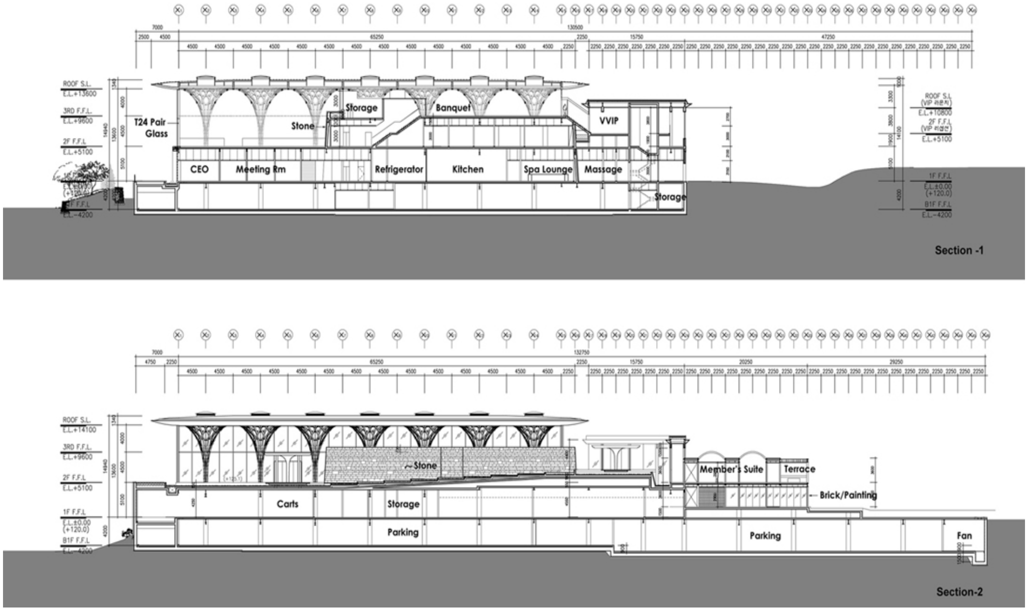


Figure 4-98. Sections

3. Detail

With the auxiliary of traditional weaving technique and digitalized process, the timber structure in hexagonal gridshell automatically generates a detailed model, projected in a parametric system as a new construction method. By defining a curved surface, the roof structure contains 3,500 curved timber components which create almost 15,000 lap joints, allowing girders to be expanded in three directions.

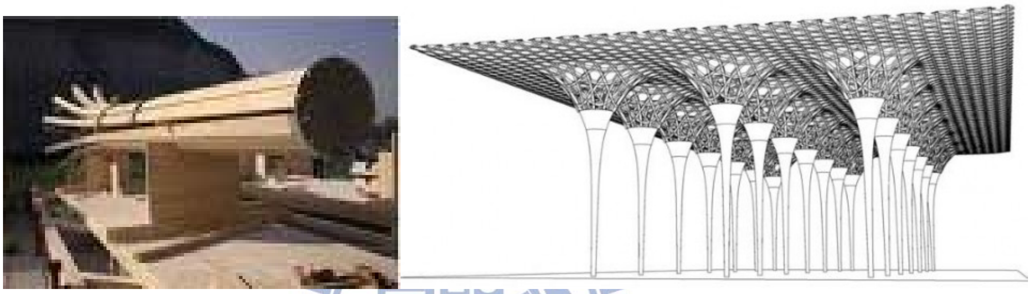


Figure 4-99. The Timber Structure

4. Construction / Fabrication

With the complex roof construction and glue-laminated timber columns, the structural system can only be constructed by means of digital fabricated technology. The approach promises an effective and accurate construction (Figure 4-100). The timber roof in prefabricated gridshell structure and curved surface is installed in fixed-end, funnel-like timber columns. As shown in Figure, the large roof surface is composed of a sequence of prefabricated grid arches. Given the fact that the CNC-machined components of the roof structure are prefabricated in Switzerland and shipped to Korea, plus the timber materials are produced by computer-controlled machines, the entire process is considered green due to its low carbon dioxide emissions. This environmental-friendly aspect is highly valued in comparison with other structures built from reinforced concrete.

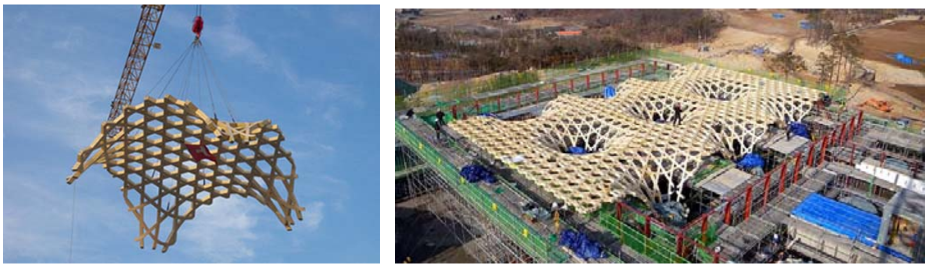


Figure 4-100. The Roof Construction

(2) Design Media

1. Generation

Applying computer algorithms for calculating the gridshell ensures a rigid shell structure that shares loads efficiently. To make possible the highly complex, freeform roof structure, the building is automatically generated by parametric modeling. By rendering and testing the curved surface of the roof, the simple and accurate computer modeling generation also showcases a resource-saving construction by curtailing material waste (Figure 4-101).

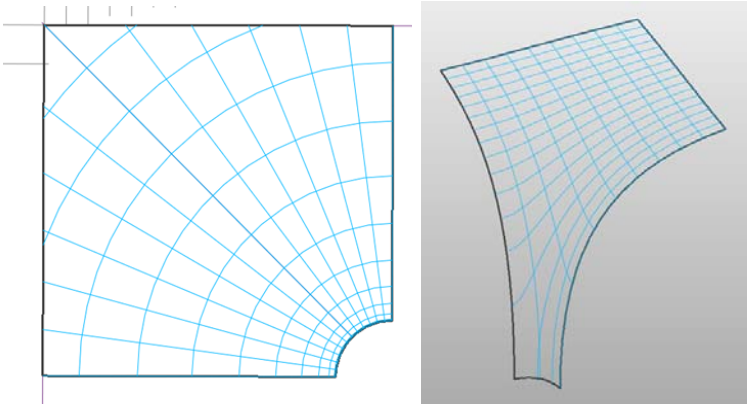


Figure 4-101. The Curved Surface of the Roof

2. Motion

In the virtual design model, the tectonics of digital timber construction for undulated roof structure are arrayed with the techniques of bending, weaving and folding, namely parametric design tools, which develop and test a form and/or structure for economical value.

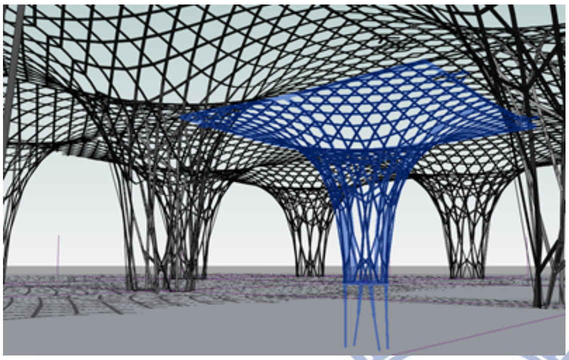


Figure 4-102. The Parametric Computer Modeling

3. Structure

The main structure is supported by funnel-like timber columns reaching to the roof plane of the atrium, which are curved to form the hexagonal grid components horizontally (Figure 4-103). While combining the function of the beams and columns, the thickness of the wooden structure is increased in order to achieve increased protection against fire.

Figure 4-103. The Hexagonal Grid Components

4. Material

The materials consist of timber columns with steel, glass curtain wall, concrete and stone podium area. These renewable timber materials are not only chosen for the purpose of their elastic quality of curving, but are applied for lowering energy consumption and CO2 generation. (Figure 4-104).

Figure 4-104. The Computational LIGNAMATIC CNC Timber Processing Machine

(3) Design Method

1. Envelope

The glass envelope façade directs sunlight to the interior reception zone and the stone podium, on the other side, is reserved for the service areas. The transparent curtain wall not only provides the interior space with natural lighting and proper indoor temperature, but bridges a visual connection to the outdoor scenery along with tree-like timber columns in the atrium.

Figure 4-105. Front Elevation

2. Form

Computer generation is employed to simulate the design form and automatically calculates the mesh geometry in triangle and hexagonal shapes (Figure 4-106). While increasing the strength of the roof structure yet conducting natural ventilation and light through the space, the consumption of material and energy is scaled down. Taking advantage of the hexagon gridshell successfully demonstrates a harmonious combination of structural aesthetics and ecological function.

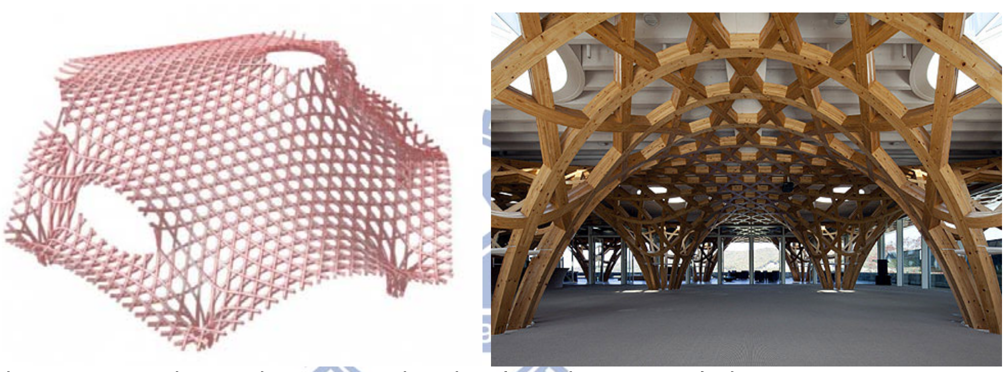


Figure 4-106. The Mesh Geometry in Triangle and Hexagonal Shapes

3. Energy

The roof construction of hexagonal gridshell is an integration of energy savings and natural ventilation where daylight infiltration and heat reduction are both accomplished (Figure 4-107). To eliminate the constraints of wind load, the building form is dynamically simulated with advanced computer modeling techniques to test the hexagonal gridshell system in different weather conditions.

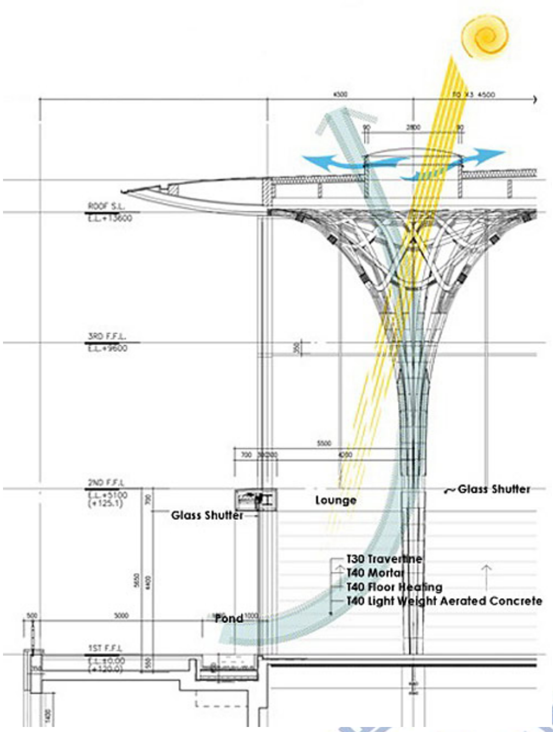


Figure 4-107. The Roof Construction of Hexagonal Gridshell

4. Interaction

As shown in Figure 4-108, the flowing grid roof and tree-like timber columns are contained in a rectangular box through which an intimate connection with the nature is bridged through the transparent curtain wall. The direct view also provides a smooth contact and interactions with the reflecting pool outdoors.

Figure 4-108. The Transparent Curtain Wall

4.10. ***Case 10:*** EEA and Tax office

The Education Executive Agency (EEA) and Tax office is an undulating building designed by UN Studio for the National Tax Offices and the Student Loan Administration. This 92-meter tall complex is also known as one of most sustainable office buildings in Europe, with a digital appearance and energy efficiency. The project analysis is based on the twelve Digital-Green design factors as follows.

(1) Design process

1. Concept

   By integrating sun shading, wind control, daylight penetration and freeform appearance in one concept, the project is an attempt to achieve architectural sustainability and innovation. Without additional structural modifications, the office building could be transformed into residences for future use.

Figure 4-109. Section

2. CAD / Simulation

According to Arup mechanical engineer Verwer's speech, the soil and well-grown trees, located at the large public city garden and in front of the office complex, tend to dry out if some direct wind were to sweep through the building. Using computer calculation to generate the wind direction and energy performance, the aerodynamic form and fins are employed for wind control. The design highlights the value of protecting forest ecology surrounding the complex.

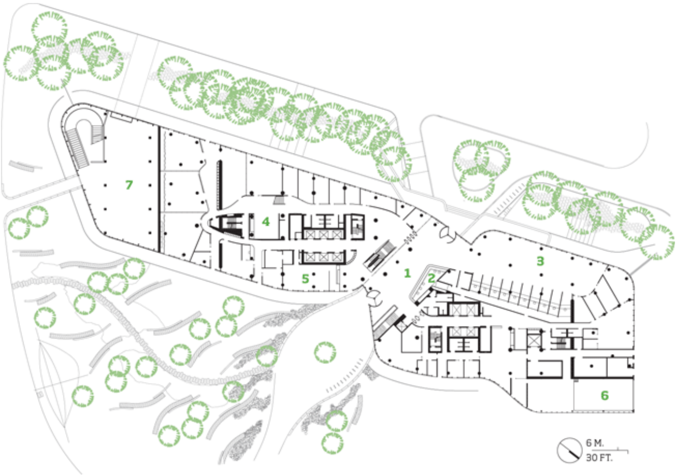


Figure 4-110. The Large Public City Garden in Front of the Office Complex

3. Detail

The fin-shaped terrace functions as a tool of wind control. The fin placement and shape around the building vary based on their locations. The said concern is calculated via automatic computer generation. As shown in Figure 4-111, the fins shade the building from direct daylight in summer and absorb the sunlight to heat up the office in winter. The architectural response of this detail reduces energy consumption by calculating ventilation efficiency and façade design in one approach.

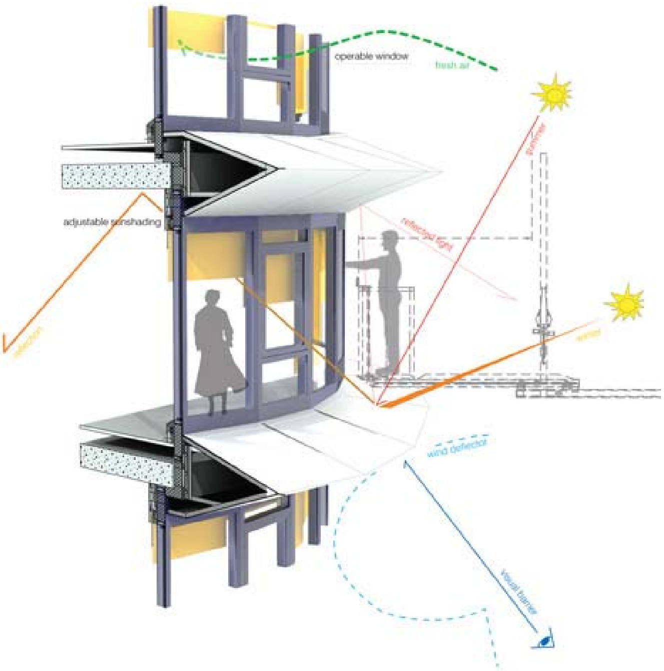


Figure 4-111. The Fin-shape Terrace Functions as a Tool of Wind Control

4. Construction / Fabrication

In order to construct the fluid form of this project, the designers employ computer fabrication and use digital tools for an effective and accurate construction. The horizontal fins around the building are installed on the exterior façade after the construction on the masonry of the lower tower.

Figure 4-112. The Horizontal Fins around the Building are Installed after the Construction

(2) Design Media

1. Generation

In order to fulfil the purpose of a flexible aerodynamic form, the building is automatically generated by parametric modeling in the conceptual design process. By using computer algorithms to calculate sun path and wind regulation around the building, the computer modeling technologies assist the designers to achieve a speedy and accurate sculpting approach. The simplified and accurate manufacturing process also produces less material waste by the new technique of computer modeling.

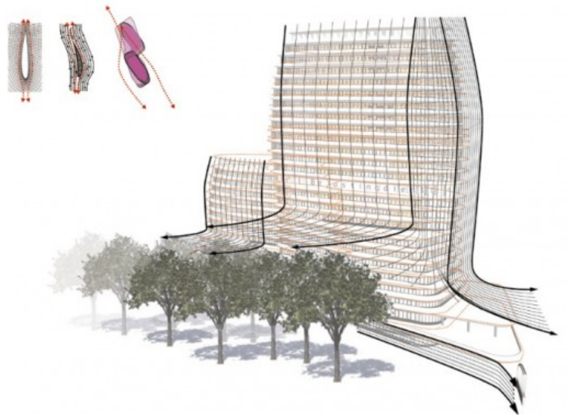


Figure 4-113. The Aerodynamic Form and Fins for Wind Control

2. Motion

For the need of natural ventilation, the parameters of the curving form are calculated with computer generation to obtain the vertical-motion ventilation technique. The fresh air moves vertically from the ground floor to roof and escapes from the punched holes, where the inflow and outflow of natural air takes place via a sustainable chimney.

Figure 4-114. High-performance Facade

3. Structure

The structural grid is deployed to 1.2 meters instead of the common 1.8 meters for an office building. The purpose is to leave the space with a potential be reused for residential apartments in the future. To lower the floor heights from 3.6 meters to 3.3 meters, the downsizing approach automatically scales down the energy and material consumption. The service areas are embedded in the concrete core. The structure is carefully constructed for architectural recyclability without major structural modification.

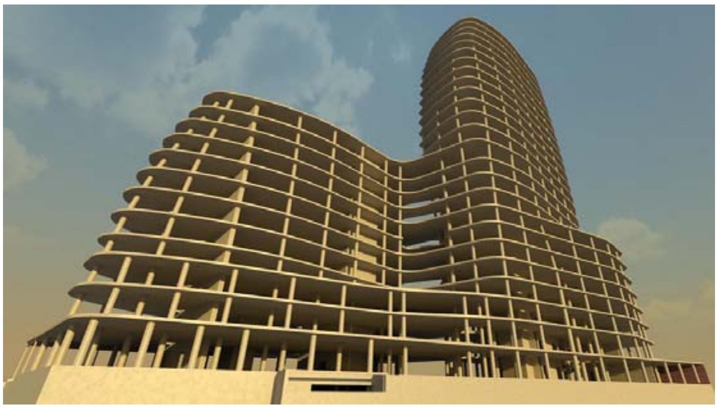


Figure 4-115. The Structural Grid and the Architectural Recyclability

4. Material

To meet the building requirements of fluid forms and integration of natural ventilation principles, sustainable materials are applied for lowering energy consumption and for ecological cause. In order to achieve aerodynamic form, easy-shaping materials are chosen for the transparent glass walls and the smooth surface of the fins.

Figure 4-116. The Transparent Façade

(3) Design Method

1. Envelope

This design employs continuous fin structure as the characteristics of terrace, roof, and floor. These fins limit the artificial lighting needed by fencing off the direct sunlight. The façade with the fin feature also provides sunshade for natural cooling. The length and size of the fins are designed to accommodate the heat and sunlight throughout the day.

Figure 4-117. The Corner-less Fluid Form

2. Form

The building with its aerodynamic form is produced by the sun and wind analyses. With the motif of the rounded corner façade, the construction of the form is integrated with the concepts of energy saving by daylight infiltration, sun shading, and wind coordination. The terrace design minimizes the microclimate disruption of the surrounding green area (Figure 4-118).

Figure 4-118. Circulation Diagram

3. Energy

With the freeform appearance, this project makes use of less material and less energy by taking advantage of its round corners. The innovative concept of this aerodynamic project is not only integrated with easy-maintenance and building lifespan, but also with consideration of reusable resources for reducing construction waste during the design process (Figure 4-119).

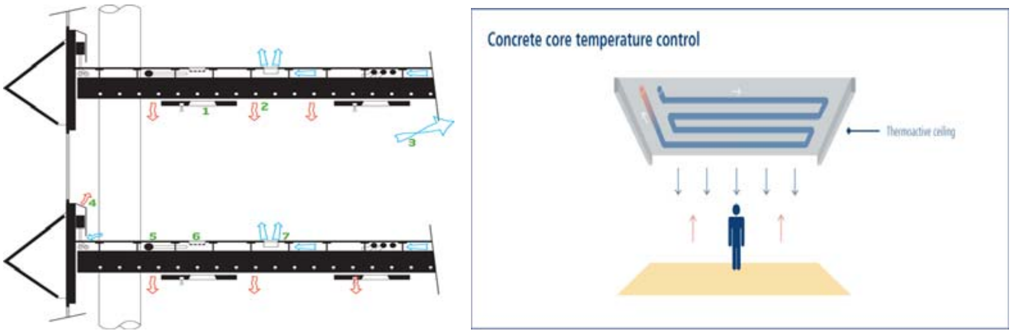


Figure 4-119. Concrete Core Temperature Control

4. Interaction

The urban garden on the ground level is constructed with a large-sized water channel. With an open view of the transparent façade and the corner-less fluid form, the personnel in the office building have a closer visual interaction with the city and the surroundings. By generating the fluid form with the analyses of the wind and sun influences, the architecture itself has an intimate connection with nature. The fluid circulation of the interior provides a smooth contact and interaction between the personnel and space.

Figure 4-120. The urban garden at the ground level

Chapter 5 Conclusion:

New design process involving the digital and the sustainable

5.1 Modeling the Design Process of Digital-Green Architecture

This research points out the need for a higher-level coordination between the digital design process and sustainable concepts in the Digital-Green age. The digital-green evolution in architectural design has been supplanted not only in the design manipulations, but also in the evolution of merging digital technology and sustainable aspects. As mentioned previously in Chapter 3, the ten cases selected need to be re-examined in a more systematic framework. Therefore, the twelve factors are proposed to streamline a new design process where digital technologies and sustainability merge. With the twelve factors, ten cases are analyzed (cited in Chapter 4) and the logic of the design processes are clarified. In the process, the new Digital-Green factors are coordinated and the new framework, with its five suggested phases, is clustered through the analysis of the case features. The five phases are Design Development, Computational Analysis, Digital Modeling, Manufacturing, and Assembly Method.

TABLE 2 Digital-Green Design Factors

		Design Development	**Analysis**	**Digital Modeling**	**Manufacturing**	**Assembly Method**
Design Process	Concept	V				
	CAD / Simulation			V		
	Detail		V			
	Fabrication / Construction				V (Fabrication)	V (Construction)
Design Media	Generation			V		
	Motion			V		
	Structure		V			
	Material		V			
Design Method	Envelope			V		
	Form			V		
	Energy		V			
	Interaction	V				

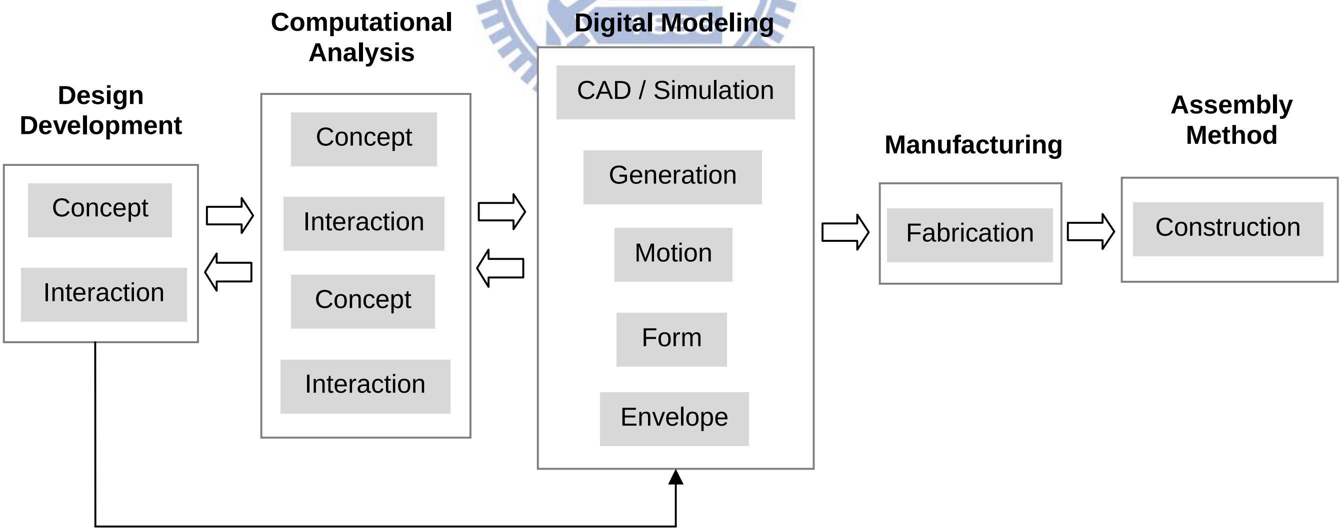


Figure 5-1. The Digital-Green Design Process

With the increasing demands for the integration of digital technologies and sustainability, a preliminary framework for a new design process is proposed. In the new framework, the five phases and the twelve factors interact to form a new design process. The first phase is focused on the factors of Concept and Interaction, which is conducted in Design Development. The second phase engages the factors of Detail, Structure, Material, and Energy, which are clustered under Computational Analysis. The third phase of the Digital-Green design process consists of the factors of CAD / Simulation, Generation, Motion, Form, and Envelope, which are suggested as the process of Digital Modeling. The fourth phase proceeds with Manufacturing and interacts with the factor of Fabrication. The new methods of assembly are explored by using the CAD/CAM fabrication technology such as CNC milling machine or rapid-prototyping (RP). Finally,, the last phase of the process is suggested as Assembly Method with the factor of Construction. The first three phases are organized as a looping system that allows for re-examination. By merging the digital design technique and green thinking through the ten case studies, a new method of design process is formed and offers an innovative way to explore different possibilities in design thinking. It is essential to emphasize a broader range of issues in the design process, bonding digital architectural and sustainable applications.

5.3 Limitations

The development of design process is moving from a micro to macro level. Whether the marriage of digital fabrication technologies and form-evolutionary calculation could effectively minimize the environmental concerns, the impact is still too fresh to be re-examined in a systematic research methodology. The initiatives of employing new materiality for sustainable and structural purposes help produce creative ideas during the design thinking process. However, in many cases, budget constraints curtail many aspects of a construction process. A tendency to focus on digital-green projects may result in a more cost-effective process over time for energy saving.

5.2 Heading toward Digital-Green Architecture

Along with the analysis of the ten cases, digital technologies not only reflect the development of sustainable materials but also explore a new territory of form-finding. This research could extend the design process to a more general and comprehensive level by integrating four components - computer calculating technology, sustainable design thinking, freeform finding and experimenting with structural materials. This might advance the establishment of a prototype to automatically test the potential energy-efficient forms by computer simulations or modeling, with the examination of new factors and the new design process. Through the process, an understanding of the relationships between the new Digital-Green architecture and sustainable analysis is articulated. By examining a new design process, future studies are given the direction of exploring diverse freeform by applying innovative materials and structural systems. The results might influence the generation of future work and deliver levels of change through a freshly-integrated perception of new technology and sustainable design thinking.

The evolution of design factors in the digital era deserves a comprehensive investigation to establish and clarify the connection between social development and construction factors. Such a study can define and clarify the linkage between advancing technologies and rapid societal needs such as the advantages of digitalization, aspiration of free-form aesthetics, and requirements of energy efficiency. In the area of digital materials, architects are provided with innovative tools of merging sustainability and digitalization. Currently, most structures are erected with the focus on either digitalization or sustainability. An adventurous attempt toward digital-green materials can be broadly encouraged instead of applying merely passive and recyclable materials.

References

Addis, Bill. *Building: 3000 Years of Design Engineering and Construction.* Phaidon Press, 2007.

Beukers, Adriaan and Hinte, Ed van. *Light-ness: The inevitable renaissance of minimum energy structure*. Rotterdam Publishers, 2005.

Beylerian, George M. and Dent, Andrew. *Ultra Materials: How Materials Innovation is Changing the World.* Thames & Hudson Inc., 2007.

Booth, David W. *Mathematics as a Design Tool: The Case of Architecture Reconsidered*. The MIT Press, 1996.

Braun, Hugh. *An Introduction to English Mediaeval Architecture*. Faber and Faber, London, 1951.

Burry, Jane and Burry, Mark. *The New Mathematics of Architecture.* Thames & Hudson, 2010.

Brawne, Michael. *Architectural Thought: The Design Process and the Expectant Eye.* Architectural Press, 2003.

Carlson, Wayne. *A Critical History of Computer Graphics and Animation*. Ohio State University, 2003.

Chan, Yenna. *Sustainable Environments: Contemporary Design in Detail.* Rockport, 2007.

Chick, Anne and Micklethwaite, Paul. *Design for Sustainable Change: How Design and Designers Can Drive the Sustainability Agenda.* AVA Publishing, 2011.

Cook, Peter and Webb, Michael. *Archigram*. Princeton Architectural Press, 1999.

Cooper, Ian and Symes, Martin. *Sustainable urban development*. Routledge, 2008.

Delanda, Manuel. *A Thousand Years of Nonlinear History*. Zone books, 2000.

Deleuze, Gilles. *A Thousand Plateaus: Capitalism and Schizophrenia*. University of Minnesota Press, Minneapolis, 1987.

Deplazes, A., ed. *Constructing Architecture: Materials, Processes, Structures.* Birkhauser Verlag, Basel, 2008.

Emery, Marc. *Innovations Durables Appropriate Sustainability: New Ways in French Architecture.* Birkhauser, 2002.

Farmer, Graham and Guy, Simon. *Conditional Constructions: Environmental Discourses on Natural Ventilation*. International Journal of Environmental Technology and Management (IJETM), Vol. 2, No. 1/2/3, 2002.

Fitzgerald, Eileen, McNicholl, A., Alcock, R., and Lewis, J. O. *A Green Vitruvius: Principles and Practice of Sustainable Architectural Design.* James & James Science Publisher, 1999.

Fletcher, Banister and Cruickshank, Dan. *Sir Banister Fletcher's a History of Architecture*, 20th edition. Architectural Press, 1996.

Frampton, K. *Studies in Tectonic Culture.* MIT Press, Cambridge, 1995.

Fuller, Buckminster. *Inventions: The Patented Works of R. Buckminster Fuller*. St. Martin's Press, New York, 1983.

Fuller, Buckminster R. *Operating Manual for Spaceship Earth*. Carbondale, Southern Illinois University Press, 1969.

Gissen, David. *Subnature: Architecture's Other Environments*. Princeton Architectural Press, 2009.

Guy, Simon and Moore, S.A. (eds). *Sustainable Architectures: Cultures and Natures in Europe and North America*. Spon Press, New York, 2005.

Guy, Simon and Farmer, G. *Reinterpreting Sustainable Architecture: The Place of Technology.* Journal of Architectural Education, 54(3): 140-8.

Gao, W.P. “Tectonics? A case study for digital free-form architecture.” Proceedings of Computer Aided Architectural Design Research in Asia (2004): 519-534. Seoul: Yonsei University Press, 2004.

Haggard, Kenneth. *Passive solar handbook*. California Energy Commission, 1980.

Himmelb(l)au, Coop *and* Kwinter, Standford. *Dynamic Forces: BMW Welt Munich.* Prestel, 2007.

Hull and Jacobs, P.F.. *Rapid prototyping and Manufacturing: Fundamentals of Stereolithography*. Dearborn, MI: Society of Manufacturing Engineers, 1992.

Holzman, Malcolm. *Bruce Goff: 3 Houses*. View Productions, 1998.

Iwamoto, Lisa. *Digital Fabrications: Architectural and Material Techniques.* Princeton Architectural Press, New York, 2009.

Jodidio, Philip. *Green Architecture Now. Taschen, 2010.*

Kaltenbach, Frank (Ed.). *Translucent Materials: Glass, Plastic, Metals.* Detail Praxis, 2004.

Kaufmann, Hermann and Nerdinger, Winfried. *Building with Timber: Paths into the Future.* Prestel, 2011.

Koleravic, Branko. *Architecture in the Digital Age: Design and Manufacturing*. Spon Press, 2004.

Koleravic, Branko and Klinger, K. *Manufacturing Material Effects: Rethinking Design and Making in Architecture*. Routledge, 2008.

Krauel, Jacobo. *Contemporary Digital Architecture Design & Techniques.* Link International, 2010.

Lancaster, Lynne C. *Concrete Vaulted Construction in Imperial Rome*. Cambridge University Press, 2005.

Le Corbusier. In *Towards a New Architecture*. The Architectural Press, 1923.

Lim, C.K. “Digital CAD/CAM media realize Chinese Calligraphic aesthetics in architectural design.” In Proceedings of Computer Aided Architectural Design in Asia (CAADRIA 2009), 225-234. Yunlin, Taiwan, 2009.

Lim, C. K. “From concept to realization.” In Proceedings of Association for Computer Aided Design in Architecture (ACADIA 2006), 386-391. Louisville, Kentucky, 2006.

Lim, C. K. “Towards a framework for digital design process: In terms of CAD/CAM fabrication.” In Proceedings of Computer Aided Architectural Design in Asia (CAADRIA 2006), 245-252. Kumamoto, Japan, 2006.

Liu, Yu-Tung and Lim, C. K. *New tectonics: Towards a New Theory of Digital Architecture: 7th Feidad Award.* Birkhauser, 2009.

Liu, Yu-Tung. "Creativity or novelty? A model of design creativity and its implications to computer." Design Studies, Vol.21: 261-276, 2000.

Lynn, G. *Architectural Curvilinearity: The Folded, the Pliant and the Supple.* AD Profile 102: Folding in Architecture, Academy Editions, London, 1993.

McDonough, William and Braungart, Michael. *Cradle to Cradle: Remaking the Way We Make Things.* North Point Press, 2002.

McDonough, William. *Big & Green: Toward Sustainable Architecture in the 21st Century*. Princeton Architectural Press, New York, 2002.

Melet, Ed. *Sustainable Architecture: Towards a Diverse Built Environment*. Germany: NAI Publishers, 1999.

Meisel, Ari. *LEED Materials: A Resource Guide to Green Building.* Princeton Architectural Press, New York, 2010.

Mendler, S., Odell, W., and Lazarus, M. A. *The HOK Guidebook to Sustainable Design. John Wiley & Sons, Inc.,* 2006.

Mitchell, William J. *A. Tale of Two Cities: Architecture and the Digital Revolution*. In *Science*, Vol. 285, no. 6, 1999, pp. 839-841.

Mitchell, W. J., Inouye, A. S., and Blumenthal, M. S. *Beyond Productivity: Information Technology, Innovation, and Creativity.* The National Academies Press, Washington DC, 2003.

Mori, Toshiko. *Immaterial / Ultramaterial: Architecture, Design, and Materials.* George Braziller Inc., 2012.

Mori, Toshiko. *Textile/Tectonic: Architecture, Material, and Fabrication.* George Braziller Press, 2005.

Panofsky, Erwin. *Renaissance and Renascences in Western Art*. Harper and Row, New York, 1960.

Pawley, Martin and Foster, Norman. *Norman Foster: A Global Architecture.* Universe, New York, 1999.

Porteos, Colin. *The New Eco-Architecture: Alternatives from the Modern Movement. Spon Press, London,* 2002.

Ritchie, Adam and Randall, Thomas. *Sustainable Urban Design: An Environmental Approach.* Taylor & Francis Group, 2009.

Roth, Leland. *Understanding Architecture: Its Elements, History, and Meaning*. Westview Press, 1993.

Ryder, G.J., McGown, Ion, A., W., Green, G., Harrison, D., and Wood, B. *Rapid Prototyping Feasibility Report, Rapid Prototyping Group*. Glasgow School of Art, 1998.

Sadler, Simon. *Archigram: Architecture without Architecture*. MIT Press, 2005.

Scully, Vincent. *American Architecture and Urbanism.* Holt Press, New York, 1988.

Segal, Walter. *Learning from the Self-Builders.* World Microfilms Publications Ltd, 1983.

Sekler, E. F. *"Structure, construction, tectonics."* In Structure in Art and in Science, edited by G. Kepes, 89-95. New York: George Braziller, 1965.

Semper, G. *The Four Elements of Architecture and Other Writing.* Cambridge University Press, New York, 1951.

Spaargaren, Gert and Arthur, P.J., Mol. Sociology, Environment and Modernity: Ecological Modernisation as a Theory of Social Change. Society and Natural Resources 5, 1992.

Stiny, G. and March, L. *Design Machines*. In *Environment and Planning B: Planning and Design* Vol. 8. London: Pion, 1981, pp. 245-255.

Streich, B. *Creating Architecture Models by Computer-Aided Prototyping*: Proceedings of the International Conference for computer Aided architectural Design: Education, Research, Application. Swiss Federal Institute of Technology, 1991.

Terranova, Antonino, Spirito, G., Leone, S., and Spita, L. *Eco Structures: Forms of Sustainable Architecture.* White Star Publishers, 2009.

Thompson, Rob. *Manufacturing Processes for Design Professionals. Thames & Hudson Inc.,* 2007.

Vale, B. In *Towards a Green Architecture*. RIBA Publications, London, 1991.

Wang, Y and Duarte, J. P. *Automatic Generation and Fabrication of Designs*. Automation in Construction, 11(3) 291-302.

Weston, Richard. *Plans, Sections and Elevations: Key Buildings of the Twentieth Century*. Laurence King, London, 2004.

Williamson, Terry, Radford, A., and Bennetts, H. *Understanding Sustainable Architecture.* Spon Press, 2003.

Wine, James. *Green Architecture.* Taschen, 2000.

Wright, F. L. *The Natural House.* Horizon Press, New York, 1971.

Zellner, Peter. *Hybrid Space: Emergent dimensions*: *information technologies and evolutionary architectures*. Rizzoli, New York, 1997.