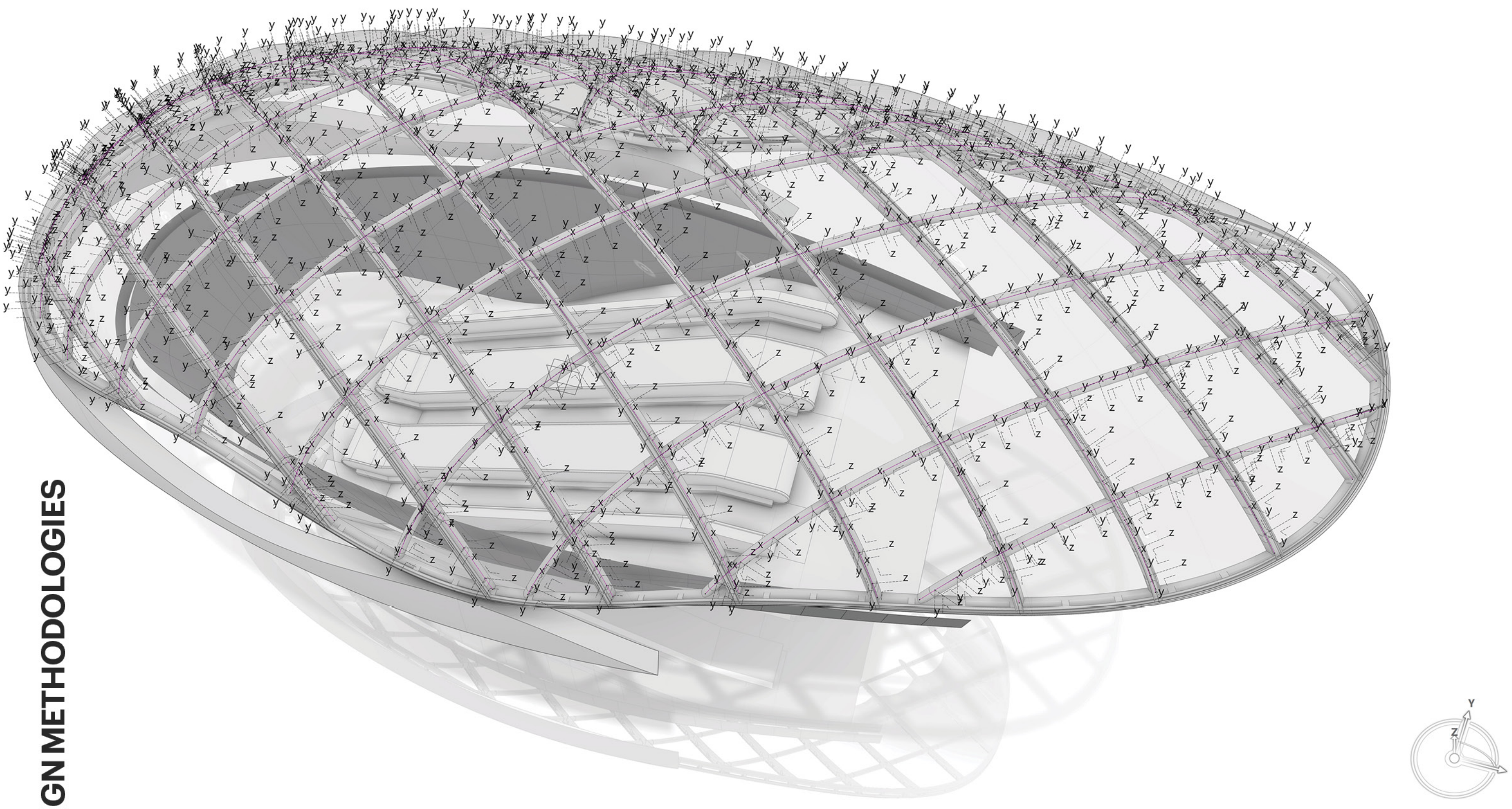
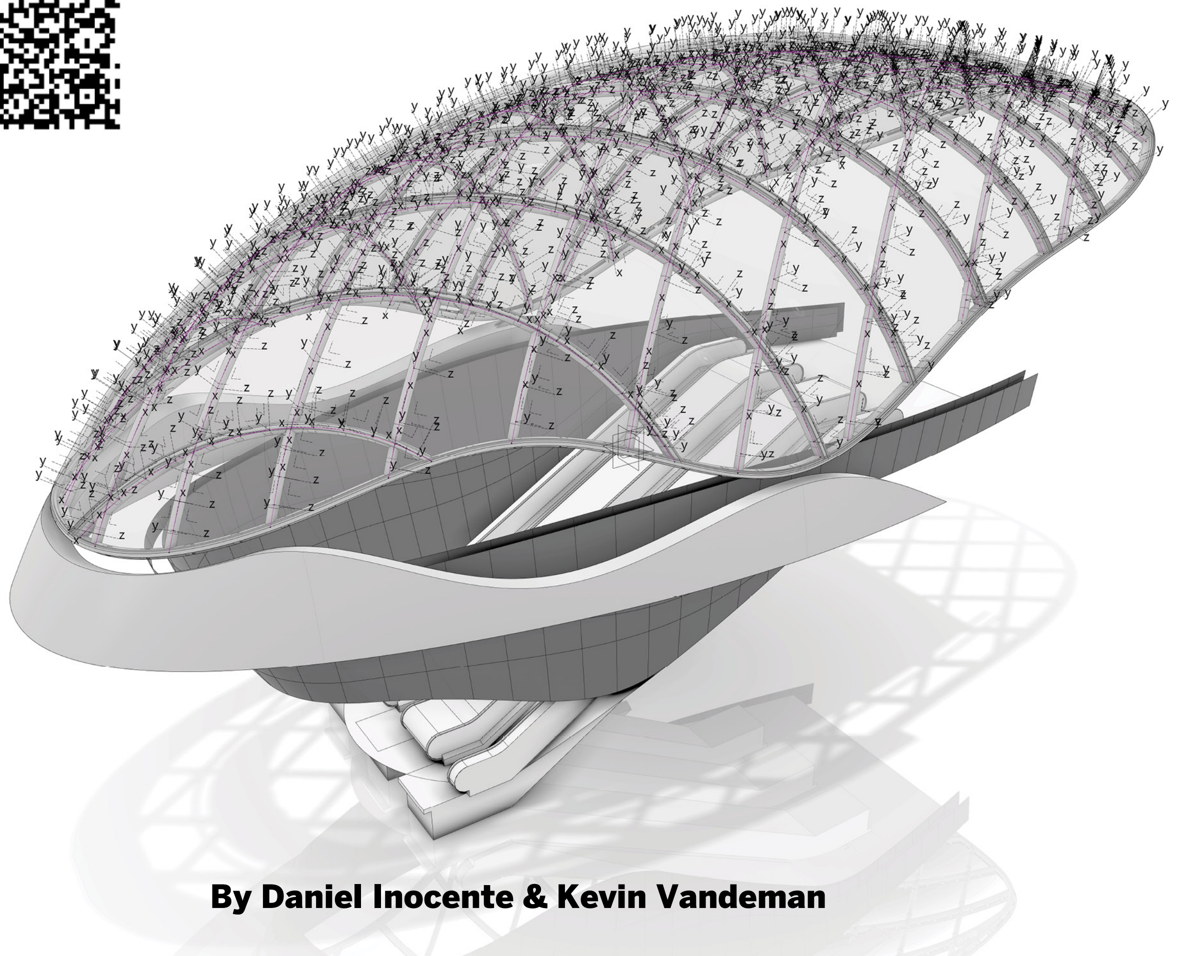
HOLISTIC WORKFLOWS

DIGITAL INTEGRATIONS, MATERIAL INVESTIGATIONS & DESIGN METHODOLOGIES

PART 1





By Daniel Inocente & Kevin Vandeman

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TRANSFORMING DIGITAL INTEGRATIONS & METHODOLOGIES

The implementation of advanced digital technologies has the potential to transform the AEC industry and produce innovative solutions at all levels. Design processes can be made increasingly effective, from geometrical explorations to material intelligence. They encompass a large range of focus areas, from energy conservation, fabrication techniques and computational design, to collaborative relationships, construction methods and end of life strategies. The availability of digital integrations challenges us to drive developments in technologies into our work-flows, manifesting higher quality designs and richer cross disciplinary experiences.

EXECUTIVE SUMMARY

HOLISTIC WORK-FLOWS

DIGITAL INTEGRATIONS, MATERIAL INVESTIGATIONS & DESIGN METHODOLOGIES

Science and technology are closer than ever ... and the progress in information techniques promise to change our lives in a radical way.
-Illya Prigogine

In his "Order out of Chaos," Ilya Prigogine who won the Nobel Prize in 1977 for his work on the thermodynamics of non-equilibrium systems, established the idea that all systems and their sub-systems exist in constant flux, a condition in which an instance of amplified disruptive energy is capable of shattering an established organization. A moment when it becomes impossible to determine the direction of change and whether this sudden break will turn into disorder or a more differentiated higher order which Prigogine referred to as a dissipative structure. This notion of spontaneous disorder and self-organizational systems has been applied to economics, biology, and technology as a way of understanding the complex processes of indeterminate change. In particular understanding the dynamics between economic growth, technological advancement and the non-growing finite ecosystems we exploit for material production. How each affects one another is a line of study that continues to be at the center of modeling methods we use to understand relationships between systems today. Using this kind of thinking, there is now evidence that economic growth and energy waste is something that technology is capable of disrupting in a positive way. We are moving into an age of accelerated change and growth, internationally and in the U.S., which leads to studies on how economic indicators can give us a glimpse into how technology might play a role in the way we conceive of design and production.

By 2030; global construction will increase by 85%, from $7.2 trillion today to $15.5 trillion worldwide. The US, China, and India will account for $4.5 trillion or 57% of this projected growth. A cumulative sum in construction reaching $212 trillion between now and 2030. The US construction market will be responsible for a playing a pivotal role in this surge and is predicted to grow faster than China by an average of 5% annually. The leading studies show that this is stimulated primarily by the housing sector and the economic upturn beginning to ascend along the pulse of the market.[1] The result, as is starting to be recognized by the building industry, is that much of this economic growth will depend on manufacturing advancements and technological competitiveness. These drivers will be responsible for catalyzing transformation across the AEC industry moving into the next decade. We are in the midst of seeing the impacts that technology and its ubiquity will have towards new levels of productivity and innovation but the challenge remains, that the industry as a whole is still primarily focused on preoccupations of dated models of design to production and common economic metrics. Perhaps the most critical distinction between conventional and emerging methodologies is that the latter focuses more on utilizing existing knowledge instead of acquiring new forms of knowledge. Growth is imminent for the entire building industry, making it imperative that new forms of exchange between specialized areas rapidly evolve we move into the next technological revolution. This work offers a lens for addressing the need for major strategic implementation of technological advancements and computing methods that will drive the near future of technologies role in building.

In the US alone $120 billion annually will be lost due to material waste and process inefficiencies. In response to this, a profound transformation is now taking place in the AEC industry. With major companies rapidly adopting technologies in the hopes of offering better services and innovative solutions. Design and engineering firms worldwide are implementing new digital technologies into both the value and supply chain. The ecosystem of emerging digital technologies will gradually begin to revolutionize how we operate at each level of business and design models which rely on change. We must also point out that the adoption of new technologies alone will not solve the challenges of delivering innovative solutions, but the thinking which binds these cross-disciplinary developments can drive a higher understanding of how digital technology can help us steer our industry toward better results.

To make this transformation, companies across the AEC industry have to rethink the use of digital technologies horizontally and vertically. Through both business operations and the value placed on architectural design. This deeply affects design thinking and the process of bringing ideas to production. Rethinking the role of technology in design, engineering and communication will enable how we transfer information from the creative stream of thought to the process of making. Our investments into digital technologies and integrations will also affect how we design toward larger and more global demands.

We have seen many breakthroughs in the AEC industry since the introduction of digital technologies into manufacturing processes in the 1960's. Adopting new methods for the exchange of information directly into the production process affected the tools we used to describe construction. Taking our ideas from analog to digital techniques became a leap in the design process. The relationship between descriptions of architecture and production were fundamentally changed. Going from 2D to 3D within the digital environment was a major shift for the industry, with manufacturing and construction having to adapt by implementing new ways of reading digital information. These adaptations have increased since then but even now face tremendous challenges. Inefficiencies in the integration of design methodologies within the production process continue to exist.

A major component of this challenge is the way in which we design and arrange information. Since design information is essential to validating an idea through production and performance, looking at how it is produced and managed needs to be understood fundamentally. Information arranges and forms the material in ways that are underestimated. As designers, we have the ability to control the way we build information. Constructing information about our designs in a way that extends its intelligibility through the production process makes for more efficient workflows.

The topic of information and the way it structures material extends far beyond the scope of this investigation but is of vital importance. Acknowledging that there is a fundamental link between order, structure and the way information is created enframes the challenges confronting our industry. In architecture, the relationship between information and material is more visible than in any other field, with buildings being the largest component of every major city.

Buildings not only make up the largest part of our cities but are also the largest consumers of resources globally. Buildings consume about 40% of global energy, 25% of global water, 40% of global resources, and they emit approximately 1/3 of C02 emissions worldwide. With the construction industry accounting for 6% of all U.S. industrial CO2 emissions or 80 million metric tons of CO2. An estimated 20% of the latter is due to inadequate production processes including material selection, manufacturing, distribution, construction and design redundancies. All of which can be made increasingly effective by establishing an integrated approach to working with a higher level of understanding of the material, manufacturing and digital processes of delivering information. In a research report on the US construction industry's efficiency conducted by Stanford University Civil and Environmental Engineering Research, Professor Emeritus Paul Teicholz states, "If you can put the proper design content for prefabrication into the design from the beginning, you can achieve a very

MetLife facade design based on environmental performance and material strategies for developing solutions to the 2030 challenge .

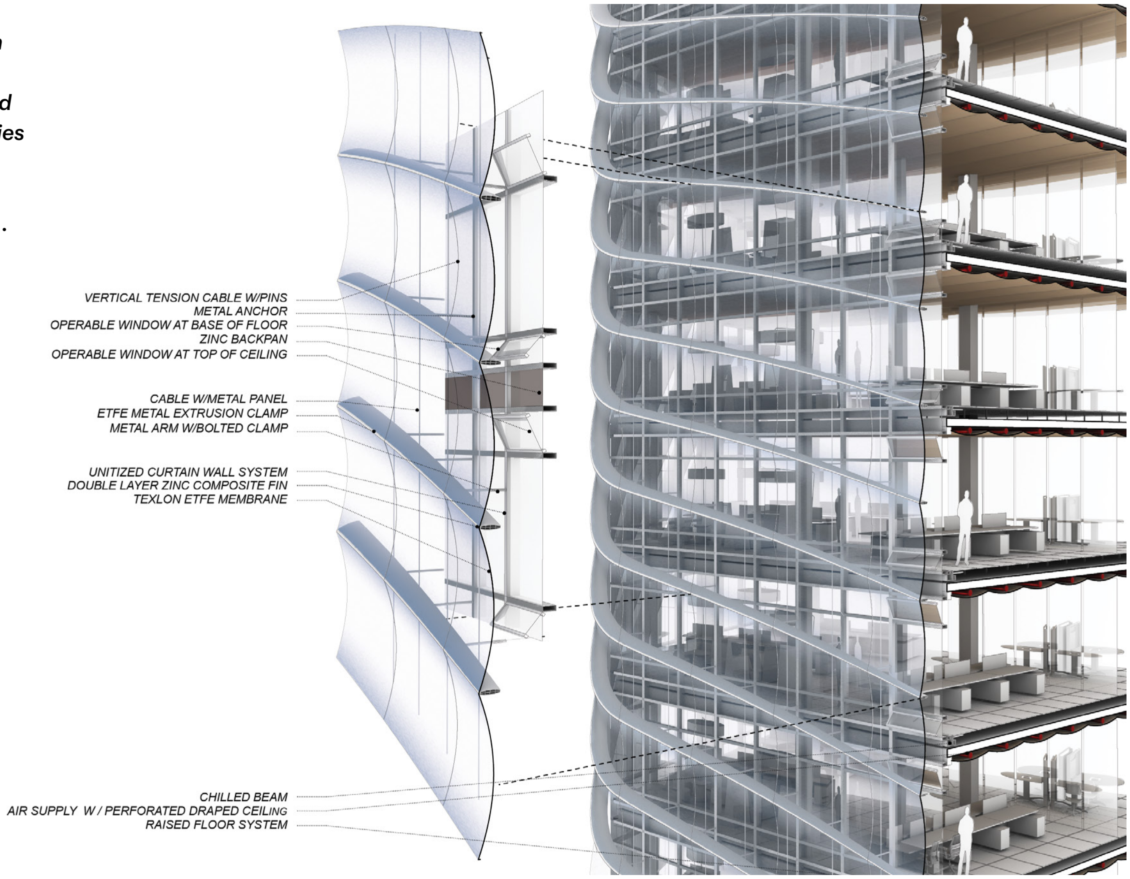


Figure 4: Metals In Construction design by HKS LINE, Facade Detail Axon

significant improvement." This underscores the importance of thinking holistically through design and delivery mechanisms. Digital technologies offer us the tools necessary to lead how the AEC industry affects change.

ADVANCED DIGITAL TECHNOLOGIES

Architectural design has seen some major paradigm shifts enabled through the application of advanced computational methodologies. The adoption of advanced technologies and methods makes possible an increased discovery of efficiencies and innovations for building systems. Without the introduction of certain computing techniques by the AEC as a whole, certain divisions of process and techniques become increasingly difficult to overcome. These challenges can be met by driving the integration of design methods into the design process. Methods where the design and fabrication techniques are informed by the delivery methods of building systems.

By developing ways of integrating new methodologies through computational and manufacturing methods, we can transform how architects engage other disciplines at every stage of the design process. This integration has the potential to reinforce interdisciplinary overlap, bringing higher intelligence into the entire development of building systems. These investigations will look at advancements in computation, engineering, and technology with the goal of developing more efficient and significantly richer cross-disciplinary experiences. Through the utilization of specific computational methods that drive higher levels of information into modeling techniques, we illuminate the benefits of using advanced

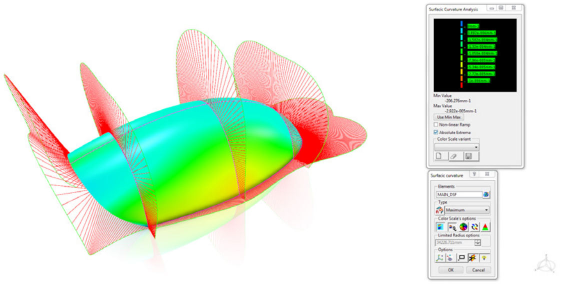


Figure 5: Gaussian Curvature Analysis of Pavillon de L'eau

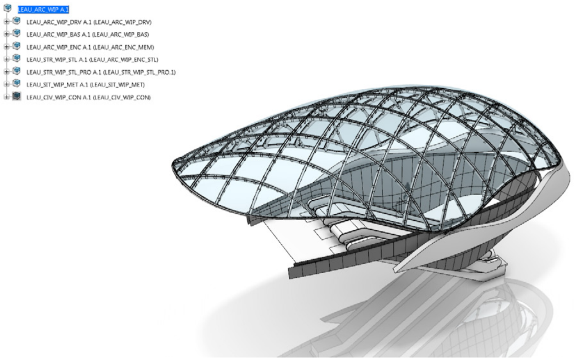


Figure 6: Pavillon de L'eau CATIA Model

design methodologies. These methods are informed by interdisciplinary knowledge and constructability constraints, allowing designers to bring higher fidelity to their work earlier in the process. A higher integration of constructability knowledge from the initial design phases promises to yield more creative and innovative solutions. Resulting in design approaches which capture and synthesize the complexity of relationships between computing, fabrication and holistic thinking.

Exploration comes at a cost, and one of the primary challenges in Architectural design has to deal with describing and translating design complexity into constructibility. Taking geometry and building systems from the digital environment to the field can be a tremendous feat to accomplish and even made impossible by the many contingencies that need to be resolved. For many buildings, the process can be simplified by adhering to conventional designs strategies and industry standards, but for this work, we will look at designs which deal with complexity outside of conventional practice. We explore designs which exploit the possibilities offered by advanced digital methodologies and take the design to fabrication workflows to new levels.

Complexity in architecture did not emerge with the development of software but thanks to digital design applications, we have seen an acceleration of complex geometries and systems which continue to push the limits of the building industry. These advancements in design technologies will only continue to provide designers with the capacity to create increased complexity, but as they are presently used, often fail to capture the realities of building systems and the limitations of manufacturing capabilities.

Although manufacturing technologies have evolved greatly since they were first developed, they require continuous integration. The early adoption of computer-aided manufacturing (CAM) which was first adopted in the commercial application by the automotive and aerospace industries has contributed significantly to the building industry. Manufacturing technologies together with computer aided design (CAD) software has made possible the tooling of robotics and machinery to be controlled through the translation of design representations into automated systems. While these advancements of computer aided manufacturing have evolved greatly since the first generations of CAD/CAM systems, there are numerous challenges and demands produced through advanced design software.

It becomes increasingly necessary for designers to utilize design technologies using new and novel methods so that designs can meet constraints of constructibility and cost. Computational technologies including, analytical methods, geometrical rationalization, and manufacturing integration have been primarily investigated to make complex designs manufacturable. These types of designs often take place separated from the realities of material constraints and building systems. This is in large part due to the limitations of design software and the capacity

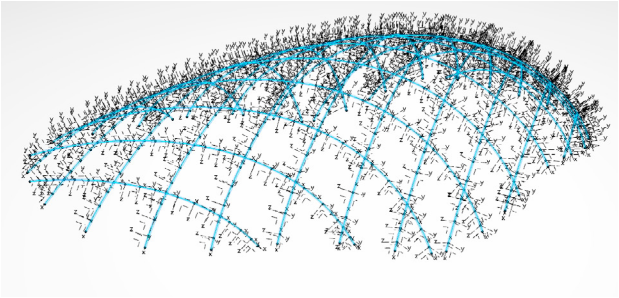


Figure 7: Pavillon de L'eau CATIA Scripted Construction Geometry

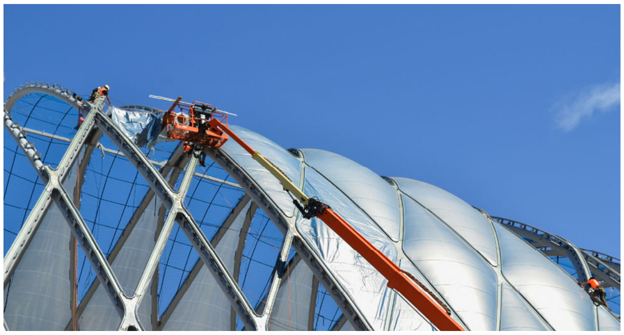


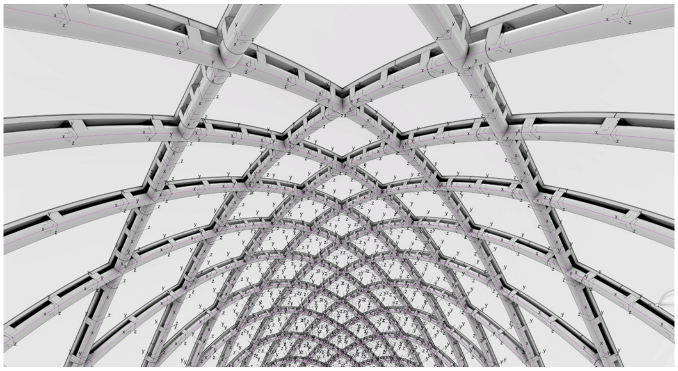
Figure 8: ARTIC Construction Photo, Installation of ETFE

to integrate manufacturing processes within the digital domain. This challenge can be met with a computational framework which embeds intelligent building systems into the modeling process. Together with the application of automation and algorithms for generative design, the design process is made highly dynamic. Providing the capacity to generate complex assemblies and structures out of complex geometry. In contrast with computer-aided techniques, specific computational methods can maintain associations across systems and provide detailed information about each element within an entire building system.

Defining parametric components that can be generated through automation is made effective by adding constraints of manufacturing and material capacities. Information about a building system and standard methods can be defined as parameters and adaptation constraints so that if a generated element is outside of certain requirements, it can be identified and resolved. Rationalization techniques further the constructibility of these building systems by providing geometrical optimizations through mathematical routines producing geometrical approximations that fall within limits. These kinds of considerations create a system of informed elements which empowers the designer with constructibility techniques and enables an iterative design process.

Working together with specialists in the construction and manufacturing industry while driving computational techniques into the collaboration process means adopting communication strategies which can translate design information directly into constructibility logics. As a part of the delivery process, we can make the delivery of information increasingly efficient by adopting product structure information management strategies, a strategy widely used in the automotive and aerospace industry. Managing large quantities of information by discipline, systems, components and their relationships, so that each collaborator can extract relevant data from the building context. The data structure together with the computational process can also generate information specific to manufacturing technologies with minimized translation effort. Translating geometrical data into proper formats for manufacturing and tracking of individual elements during assembly becomes critical in assembly and construction logistics. Organizing complex assemblies in this way make possible the translation, manufacturing, and coordination of multiple systems without disconnecting the modeling process from the process of construction. This computational methodology provides a process of developing and generating relationships holistically with a focus on execution.

Tooling as a part of this holistic approach also requires investigation by the designer, since behind every complex project a high degree of engineering and mathematics is involved. Developing unique techniques and tools requires having a basic understanding of descriptive methods and differential geometry. With the use of more advanced design tools for investigating and exploring architectural ideas, constructibility becomes critical. The designer's creative agency is not limited to the design of a building



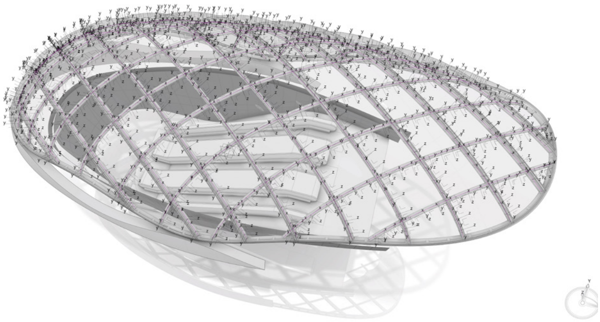


Figure 9: Engineered Model of Pavillon de L'eau Design Proposal

but can extend into other fields such as the designing of computational tools and fabrication processes. By establishing an intimate relationship with the digital processes, we can identify necessary tooling requirements which lead to innovative design strategies.

Tooling becomes as much a part of the design process as the conceptual phases. We are comfortable with technologies ready made for use, but some of the most creative solutions come out of devising unique tools for achieving complex ideas. Most CAD packages come with the ability to tap directly into the application programming interface and language for developing unique tools. Each application is having a finite number of discrete routines designed to perform specific tasks. With some providing more access than others, the programming language behind these applications provides the ability to code automation and generative routines. Coupled with algorithms for generating the fittest possible solution, whether regarding performance, cost or aesthetics. Designers can achieve results that become a part of a generative process.

Ultimately these brief illuminations only touch the surface of the global behaviors associated with designing architecture. If we increase the level of sophistication in our design methodologies through technology, then we have the ability to drive innovation into the building industry. It is clear that no single part of any system can be isolated and treated in conventional methods. They should be understood through the collective intelligence of all building systems, and their interactions and performative qualities.

ABSTRACT

HOLISTIC WORKFLOWS

DIGITAL INTEGRATIONS, MATERIAL INVESTIGATIONS & DESIGN METHODOLOGIES

There is an accelerated shift in architecture taking place today which is characterized by the infusion of evolving digital technologies and interdisciplinary knowledge. Information is the foundation on which this change takes place and its transformability is what enables us to communicate with other professional fields effectively. Architecture is known for its ability to absorb subjects and techniques occurring across disciplines. This encourages the infusion of methodologies from a wide range of specialized fields and is in large part responsible for much of the transformation that is occurring within the Architectural discourse and profession. The ensuing results indicate that there is a paradigm shift occurring which is made progressively possible through the discoveries in disciplinary exchange. The transfer of knowledge produces discoveries while simultaneously making it possible for the AEC industry to exploit novel solutions. Many of the effects that computer technologies and computational techniques are responsible for have already been demonstrated in achievements of the 21st century. In highlighting how these leaps have taken place, the techniques and methods behind them can be understood, adopted and advanced. Building on the evolutionary progress of pervasive technology and driving its potential effects on architecture and its discourse.

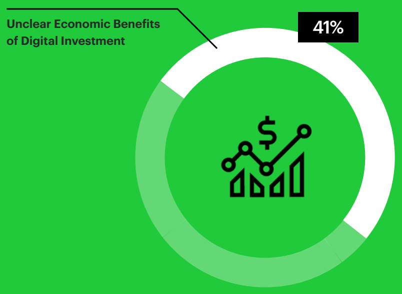
A large part of this research will study how computational technologies have influenced architectural production leading up to insights toward establishing holistic design methodologies. The opportunities described will go beyond descriptive functions, integrating knowledge of materials, manufacturing processes, analytical methods, computational methods and the transformation of data. Altogether, attempting to demonstrate the underlying mechanisms we will rely on.

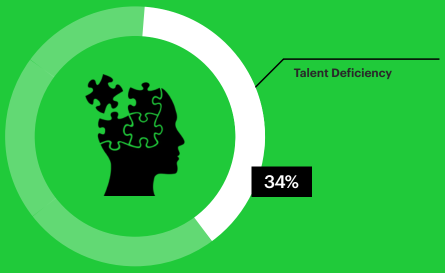
This study is manifold, from descriptive to analytical and generative processes in design, we will emphasize the value in going beyond conventional practice and moving toward new performative qualities. The synthesis of computational technologies with physical processes during the early phases of design, will promote an awareness of constructability through design exploration, driving new relationships into design methodologies. Bridging the divisions in our industry and promoting interdisciplinary experiences will be the outcome and Architects are integral to leading this shift. Integral to this study, we will look at how the AEC industry has overcome major challenges in the design and engineering of complex projects as project teams have attempted to produce novel solutions through digital integrations and methods. This research ultimately serves to inform the development of a pilot project, Pavillon de L'eau, in order to discover new opportunities for advanced design methodologies by placing the design process in parallel with digital technologies, engineering, analysis and the prospect of holistic thinking.

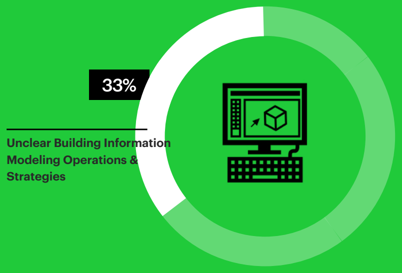
DIGITAL CULTURE

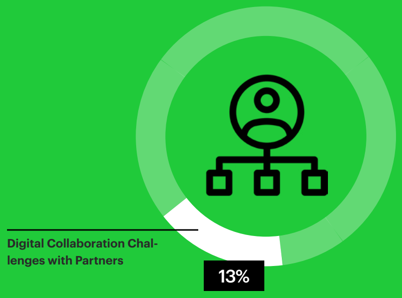
Establishing a digital culture and proper knowledge transfer mechanisms continues to be one of the biggest challenges for the AEC industry.

With proper leadership and a vision for digital integration, companies can execute more sophisticated designs.









TRANSFORMING DIGITAL CULTURE

Digital culture is a major component of delivering higher quality design and achieving efficient execution processes. A survey conducted by PwC with over 2,000 companies in the construction industry highlighted the need to drive advanced digital methods for enabling competitive services. Digital technologies are having a major impact on the AEC industry but failures to lead and nurture a higher level of knowledge and clarity on the possibilities of digital workflows can stifle engagement and productivity. The level of digital literacy for streamlining design to construction has major leaps to make. The opportunities to adopt new technologies such as building information modeling, parametric modeling, digital manufacturing, life cycle analysis, virtual design construction and evolving methodologies can only be captured by clearly defining goals for a companies design culture. Open exchanges between leadership and the community can propel increased knowledge and interest in driving advanced technologies. Inspiring new ideas and intelligent process.

INTRODUCTION

The AEC industry is experiencing transformational change, accelerated by the demands of growing societies, economies, and evolving technologies. This change has begun to manifest itself through the effects of emerging technologies and cross-disciplinary partnerships. According to a recent report by GCP, global construction will increase by 85%, from $7.2 trillion today to $15.5 trillion worldwide by 2030. The US, China, and India will account for an estimated $4.5 trillion or 57% of the total projected growth, a surge in construction that will reach a total sum of $212 trillion between now and the year 2030. This global assessment of growth is an indication that future societies will be predicated on what is being called the fourth industrial revolution. Companies are beginning to apply an increased digitization of process workflows across the board, enabling them to make leaps in efficiency and performance. In the United States alone, the construction market is predicted to grow faster than China by an average of 5% annually, stimulated by the housing demand and economic rise stemming from a desire to reclaim self-reliance and productivity. [1] The AEC industry will realize this resurgence at various levels, many of them unknown and some directly influenced by manufacturing developments and technological competitiveness. These critical elements will serve to catalyze much of the transformation that will take place across the AEC industry. The conversion from present activities to future developments today seem far from actualizing potential advances in productivity and innovation but will be necessary if we are to drive the industry's capacities. Achieving measures beyond efficiency will determine how we step into the future and advancing our technologically enabled problem-solving capacities will reveal how shifts in technology can be adopted in the AEC industry. Other industries dealing with complex material processes and technological integrations are currently adopting advancements in design and development methodologies. Industries related to engineering, material science, computer science and manufacturing are taking on advanced technologies and processes with the promise of offering improved solutions and better services. The adoption of emerging technologies across industries dealing with design, production and the processing of materials promises to bring new problem-solving mechanisms into the AEC industry. These mechanisms can lead to enhancing the design process and innovative capacities within the field of architecture but also integrating knowledge from other disciplines. Ensuring the continuation of this progress will require technological integrations to be strategic, focusing on design intelligence, information technologies, and materials innovation. Unless the AEC industry becomes amenable to these subjects, it will continue to see inefficiencies both vertically and horizontally, across the value and supply chain.

On a global scale, efficiency gain through increased digital integrations have significant potentials. In a report by pwc, a predicted efficiency gain of approximately 3.6% annually or nearly $420 billion globally for the industrial sector if digital technologies are infused into the heart of digital culture throughout industries. The AEC industry also has the potential to exploit these developments with the promise of major gains that arent being seen today. The United States will see nearly $2 trillion spent in construction every year from now until 2030. Out of this, 16% or nearly $120 billion per year will be lost due to material waste, design redundancies, lack of interoperability, disputes, and digital process inefficiencies. While economic waste is a significant indicator of the shortfalls associated with conventional approaches in the

PWC INDUSTRY 4.0 DIGITAL INTEGRATION SURVEY

"Behind the scenes of the world's leading industrial and manufacturing companies, a profound digital transformation is now underway.... Companies are digitizing essential functions within their internal vertical value chain, as well as with their horizontal Partners along the supply chain. In addition, they are enhancing their product portfolio with digital functionalities and introducing innovative, databased services."

- 2016 Global Industry Survey

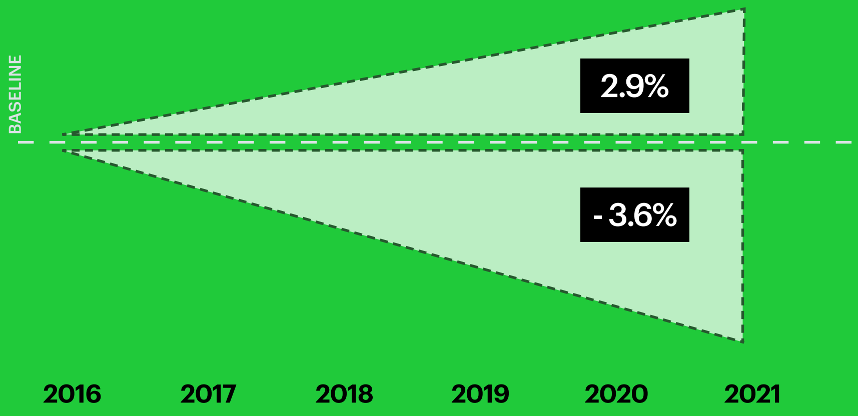
Digital Technologies Performance Impact

2,000+
Participants

26
Countries

72%
Expect Reaching Advanced Digitization Levels by 2020

33%
Indicate Advanced Digitization Levels



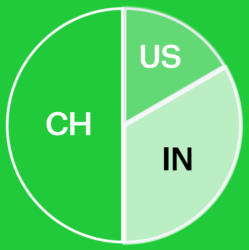
Survey by PwC indicates that over the next five years out of 2,000 companies they expect to reduce cost by an average of 3.6% and an increase in annual revenues by an average of 2.9% due to advanced digitization technologies.

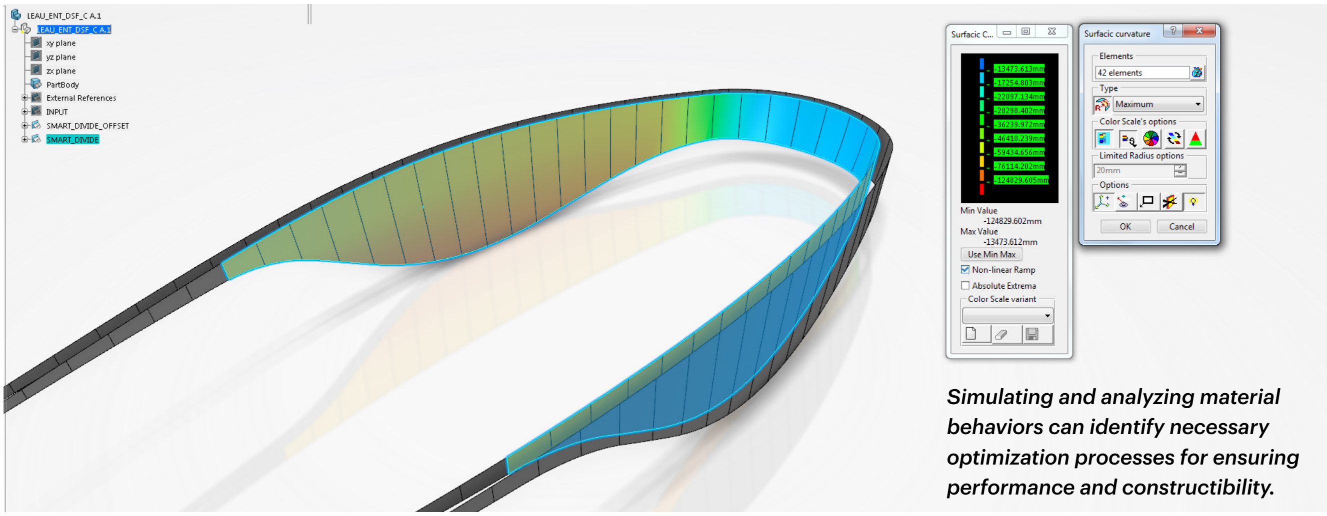
GCP & OXFORD ECONOMICS REPORT

Global Construction Increase by 2030

GCP predicts that global construction will increase by 85% to $15.5 trillion worldwide by 2030. with three countries, China, US and India accounting for 57% of all global growth.

85%

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xy plane
yz plane
zx plane
PartBody
External References
INPUT
SMART_DIVIDE_OFFSET
SMART_DIVIDE

Min Value -124829.602mm
Max Value -13473.612mm
☑ Non-linear Ramp
☐ Absolute Extrema
Elements: 42 elements
Type: Maximum
Limited Radius options: 20mm

Simulating and analyzing material behaviors can identify necessary optimization processes for ensuring performance and constructibility.

Figure 10: Gaussian Curvature Analysis of Pavillon de L'eau Curved Metal Panels

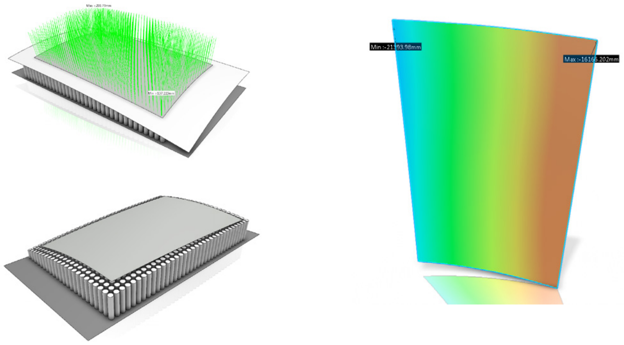


Figure 11: Pavillon de L'eau Panel Forming Simulation

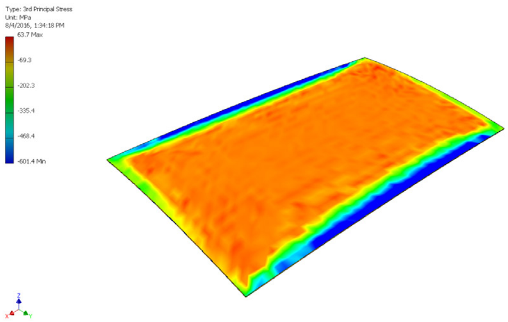


Figure 12: Pavillon de L'eau Panel Forming Stress Analysis

AEC industry, the effects of improving economic output through technology will translate into matters of even greater importance.[2] These are issues directly related to the pursuit of design innovation and the empowerment of practitioners to be both creative and rigorous problem solvers. Solving problems of design and engineering requires an understanding of the dynamic behaviors of information exchange, materials and processing systems. The problem-solving approach emerging in other fields promising to advance how we think through complex systems is that of computational design thinking. Now that technology and computing have pervaded all aspects of how we build our urban environments, embracing next generation processes is even more critical. This line of thinking involves processing and formulating solutions for matters of concern through understanding system behaviors. Using abstraction, computation, thinking algorithmically and understanding consequences across scales can significantly affect how problem-solving evolves in design.

The fourth industrial revolution relies on various technological developments, many of which emerge out of industries and disciplines outside of the AEC industry. Technologies that will be embedded into the digital ecosystems of business and industries are primarily focused on data and analytical technologies. These capacities are applied across disciplines and actualized in industry applications. Cloud computing, data analytics, robotic manufacturing, human-machine interfaces, ioT platforms, computational programs, analysis software and mobile devices are just a handful of the technologies that will be responsible for a shift toward the next industrial revolution.

With the prospect of transformational change, adopting new problem-solving approaches and techniques will continue to occur in the AEC industries. AEC companies are embracing new technologies stemming from other fields in science. Companies are investing in newly established technologies and at the same time venturing into emerging technologies that are in the nascent stages of development. These technologies are also made viable through early adoptions and validation. This stewardship, confirms the profession's duty to discover ways of staying at the forefront of design and innovation. The increased integration of digital technologies into both the value and supply chain is revolutionizing how companies in the AEC industry operate.[3] Technological integrations blur the boundaries between design, engineering, material science and construction. Adopting new technologies alone will not solve all the challenges of delivering better-performing designs and more efficient development processes, but the thinking behind this synthesis can drive a higher understanding of how digital technology can help us steer our industry toward better results.

The shift from an analog mode of production to a digital mode has made leaps since its inception. The first graphical interfaces to digital design were developed in the 1960's. Sketchpad, created by Ivan Sutherland at MIT in 1963, was a significant leap in computer graphics for human-computer interaction. This invention led to the evolution of future digital systems during the following decades, resulting in many of the sophisticated design interactions systems we use today.[4] Design interfaces allow users to explicitly describe geometries in multiple dimensions, establish parametric relationships and the integration of meta-information about designed systems. Most designers appreciate the digital interface as the design environment. It prompts us to approach design in unique ways but also constrains us to techniques often undermined. The interaction between the user and digital environment has a profound effect on how the designer approaches problem-solving. The digital interface is the actuator of technique and method during the problem-solving process. It provides us with discrete tools, but also frames the possibilities that digital interactions can offer while giving form to design ideas. Computer application systems provide opportunities that are not always visible through the interface, but being cognizant of the limitations within each system brings an awareness of the impacts they have on our ability to work through design problems. For this same reason, being knowledgeable of the evolution of these applications gives us insight into how other disciplines bring ever changing capabilities.

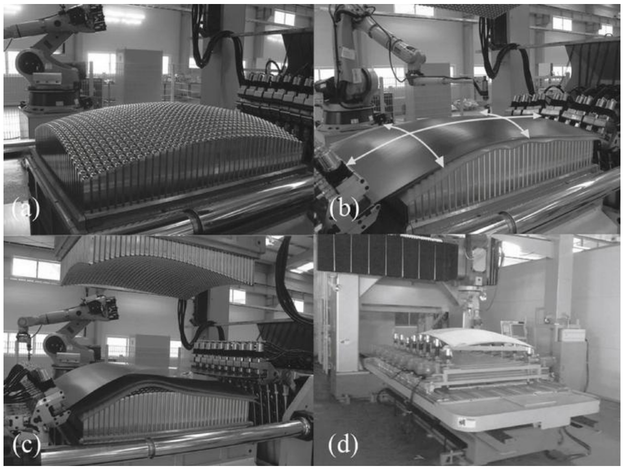


Figure 13: Multi-point Stretch Forming Technology (SteelLife)

Digital technologies evolve in parallel with multiple disciplines, transforming at various levels, emerging in disciplinary isomorphism. The changes taking place in digital integrations affect discoveries in science. In turn, those findings affect computing, hardware, software and eventually transfer these developments across disciplines. They lead to interdisciplinary synthesis, establishing new relationships between the digital and the accumulation of knowledge outside of design applications. Computer applications are now capable of taking the physical properties of materials and manufacturing constraints directly into the digital environment, providing designers with the ability to specify material behaviors and anticipate constructability limitations through computational modeling, simulation and analysis. These integrations allow users to drive external data and physical behaviors into the design process, maximizing the potential of progressive computing capabilities.

The effect that computation has on architecture spans across disciplines. Mathematics and the sciences embrace computational methods, with the possibility of bridging knowledge across disciplines and into the digital domain of design. The result is the progressive involvement of the sciences within the practice of architecture and the building industry. With the integration of engineering, manufacturing, computational technologies and other knowledge into shared digital environments, we have seen developments in design that attempt to simulate physical processes from simulated performance to digital construction.

This evolving capacity to take interdisciplinary knowledge into the design process is a key indicator of the paradigm shift supported by computational techniques. These techniques have been theorized, advocated and patronized with increased effect on the whole of the AEC industry. As leaders in these sectors, architects and designers are in the position to lead these developments through the value and demands placed on digital integrations. By setting a high value on achieving and producing higher performance into design solutions, the industry will challenge how technologies bridge disconnected processes of design and development. Finding novel ways to bridge these processes places the architect in a position to drive one of the world's largest industries into the future.

This paradigm shift is enabled through the application of advanced computational methodologies. The adoption of advanced technologies and methods makes possible an increased discovery of efficiencies and innovations for building systems and material processes. Without the adoption of technologies and computing techniques by the AEC industry as a whole, divisions of process and methods become increasingly difficult to overcome. Overcoming these challenges is manifested by establishing relationships that integrate knowledge across domains using digital environments involving multiple disciplines. Engineers use state of the art analytical tools to understand physical patterns of behavior across structural systems, rates of change and integrated mathematical methods for assessing the effects of quantitative intensities on qualitative changes. These types of analysis provide scientific insight based largely on understood mathematics and material properties. The analysis of structural entities for example involves organizing prevalidated element types (sectional profiles, variable changes, constraints) with associated material properties into a structural network and iteratively solving for best possible performance strategies. Structural analysis in practice was once a rigorous manual process, involving manual calculation, similar to how architects worked with pen and paper. In current applications, engineers can solve through a spectrum of possibilities beyond performance including the specification of innovative material applications, economics and life cycles. Designers use similar iterative solving methods to arrive at novel solutions computationally. Parametric automation allows designers and engineers to take complex design abstractions, make them adaptive systems and iterate through possible solutions. While these methods exist, the level of resolution incorporated into the solutions is rarely fully investigated. The problem of taking designs into the digital environment with increased fidelity and integrating the effects of material properties into the design process remains a major challenge. We are gradually finding effective ways of achieving this because of opportunities to communicate construction logics and building systems of high complexity.

Design exploration produces many challenges. One of the primary challenges in architectural design has to deal with describing and translating complexity into constructability. Taking geometry and building systems from the digital environment to the field can be a tremendous feat to accomplish and made increasingly difficult by associated constraints. For many buildings, the process is simplified by adhering to conventional design strategies and industry standards, but with advanced methods and technologies, we can go beyond convention and into high degrees of complexity. Complexity itself is not a goal, but it is how we deal with the effects of growing demands and technological change which presents us with countless contingencies. In this work, we will look at designs which have to deal with complexity outside of conventional practice.

Complexity in architecture did not emerge with the development of computer systems, but thanks to design technologies, we have seen the emergence of multiple discrete geometrical techniques and their logical systems. The techniques responsible for generating various unique geometrical types owes much to the integration of mathematics into computing systems. Digital computation produces architectural forms that go beyond Euclidean types, including the non-Euclidean, procedural, parametric and others. These geometries resulted in the acceleration of complex designs and systems which continue to push the limits of the building industry. The implications mathematical and computational developments have on geometry can be better understood by looking at the epistemology of form. Tracing geometry back to core functions and algorithmic expressions responsible for complex geometry is increasingly necessary when attempting to rationalize complex forms.[5]

The advancements in design technologies today continue to provide designers with the capacity to design and create high degrees of complexity in the computer. Design complexities in the digital environment might seem harmless but can result in many unforeseen complications. Many of these complications have to deal with the arrangement of information and the integration of it. Information arranges and forms materials in ways that are often misunderstood or underestimated. Without properly describing geometries and materials by means that communicate with production processes, construction can be made difficult and even impossible. Design information is essential to validating ideas through production processes and the verification of performance goals. The generation and management of information should be critically analyzed so that we can resolve issues of design and production at the origin. We are challenged to rethink the way we inform the production of information for building systems. Informing design decisions that tie into the manufacturing process yields higher quality information and better performing building systems. This is made increasingly possible through the combination of strategies for producing intelligent information and establishing proper channels for the sharing of information.

If we consider how information flows from one phase of a design process to the production stages, we find that there is a constant need to re-engineer how systems work. The redundancies caused by conventional information transfer processes have major time and cost implications throughout the life of a project. It is one of the reasons why most designers simplify their design intentions throughout the development of a project. Without having the proper protocol for establishing transfer mechanisms from design to construction, we will continue to miss opportunities afforded by new technologies.

By informing the work, using tools that can analyze geometry and material properties simultaneously, we can arrive at solutions that ensure production down the line. Some of these analytical methods include FEA or Finite Element Analysis, which simulate the effects of real-world forces, loads, temperatures, velocities, displacements, pressures and structural properties. Bringing a high level of external information into the initial stages can lead to minimized redundancies and the discovery of potential solutions. Using analytical tools like FEA brings us closer to finding strategies that make the manufacturing and fabrication process more efficient. Understanding the limitations of materials allows us to push the limits of manufacturing and processing materials. With this level of embedded knowledge, designers can appropriately identify novel solutions uncommon in practice.

The integrations of digital technologies and production processes additionally have the potential to reinforce interdisciplinary overlap, extending into the entire development of building systems. Our investigations will look at advancements in computation, engineering and technology with the goal of developing more efficient and significantly richer cross-disciplinary experiences. Through the utilization of specific computational methods that drive higher levels of information into modeling techniques, we can point out the benefits of using advanced design methodologies. This means identifying ways with which to inform design by investigating the production process. We then inform design through specific optimizations extending the use of particular manufacturing techniques to pursue novel solutions.

Informed by interdisciplinary knowledge and constructability constraints, our work advocates for enabling designers to integrate a higher level of fidelity into their work earlier in the process. A greater integration of real-world variables from the initial stages can reinforce creativity and innovation. It will enable us to exploit the flexibility that computational methods provide and the assurances that designing for material processing can bring to projects.

Manufacturing technologies have evolved significantly since their inception. Computer-aided manufacturing (CAM), initially adopted into commercial applications by the automotive and aerospace industries, was one of the first digital to manufacturing systems. UNISURF, developed by Pierre Beziers during the 1960's, was significant in establishing numerical control programming systems or CAD/CAM used for the design and tooling of automotive bodies. This technology made a major contribution to several industries including the building industry as it evolved and adapted more sophisticated instruments. These tools relied on standardizing information for communicating digital models. The translation of design geometry to G-Code became the common language used to communicate with many of the instruments developed for manufacturing.[6] Manufacturing technologies together with computer aided design (CAD) systems made possible the tooling of robotics and machinery, controlled through the translation of digital representations by computationally automated systems. Even with CAM/CAD systems advancing considerably, there are numerous challenges that these same technologies pose. The degrees of freedom in typical manufacturing technologies are limited, with limitations in how more advanced materials can be processed at larger scales. Robotics in design and manufacturing are beginning to explore possibilities provided by new materials and digital design techniques. This technology most widely used in automotive and aerospace manufacturing has been making progress into the domain of building design and structural components. Some advances in this domain include deterministic methodologies, where user-robot interfaces are explored as control mechanisms, enabling customized manufacturing techniques. More advanced methods push these relationships between robotic fabrication and generative techniques, where computation is exploited to establish generative ontologies and feedback loops. With these techniques, we can then unify the digital with customized additive manufacturing, including laser deposition technologies where digital information is translated into tooling paths, and a focused laser beam melts the targeted material. LDT can be used with various metals including steels, aluminum and exotic materials. Other additive methods include the deposition of composite and polymer materials using robotic systems, which has been studied and explored by organizations including Robotic Fabrication in Architecture. Current research and examples in robotic fabrication are attempting to blur the boundaries between digital environments and material knowledge, where information about material behaviors, generative design and parametric modeling inform robotic production. The integration of simulated behaviors and design descriptions within a production methodology extends into multiple machine technologies. Many of these technologies are unique to industries, but we have proof that even sophisticated machines find their way into the pedagogy of design in the building industry.[7]

Taking advantage of manufacturing technologies like those used in the aerospace or automotive industries is made possible by understanding how computational tools have been used to enable new methods in these industries. There are many examples of using CNC manufacturing technologies developed in other sectors. These include technologies such as CNC multi-point stretch forming, which are used in conjunction with surface curvature and FEA analysis methods. Other examples include the use of CNC cylindrical glass bending or robotic 5-axis milling. The combination of these tools also provides numerous workflows for fabrication of complex building systems.

When working with complex design problems, it becomes increasingly important for designers to utilize design technologies to bring novel methods into practice. Computational techniques including analytical methods, geometrical rationalization and digital fabrication are in large part responsible for enabling digital investigations that take complex designs through manufacturing. These kinds of designs often take place separated from the realities of material constraints and building systems due to the limitations of design software and capacity to integrate manufacturing processes within the digital domain. This challenge can overcome with a computational framework which embeds intelligent building system components into the modeling process. Together with the application of automation algorithms for generative design, the design process is made dynamic and responsive. Providing the capacity to generate complex assemblies and structures out of complex forms. In contrast with computer-aided techniques, unique computational methods can maintain associations across systems and provide detailed information about each element within an entire building system.

Parametric components generated through automation are made increasingly intelligent by adding constraints of manufacturing and material capacities. Information about a building system and standard methods can be defined as parameters and adaptation constraints, so that if a generated element is outside of certain requirements, it can be identified and resolved. Rationalization techniques further the constructability of these building systems by providing geometrical optimizations through mathematical routines producing geometrical approximations. These kinds of considerations create a system of informed elements which empowers the designer with constructability techniques and enables an iterative design process.

Working together with specialists in the construction and manufacturing industry, while driving computational techniques into the collaboration process, means adopting communication strategies which can translate design information directly into constructability logics. As a part of the delivery process, we can make the delivery of information increasingly efficient by adopting specific product structured data management strategies. An approach widely used in the automotive and aerospace industry. It manages systems information by discipline, systems, components and their relationships, allowing each collaborator to extract relevant data from the building context. At the same time, the data structure together with the computational process can also generate information specific to manufacturing technologies with minimized translation processes. Translating geometrical data into numerically controlled manufacturing and tracking individual elements for assembly becomes critical in assembly and construction logistics. Organizing complex assemblies in this way makes possible the translation, manufacturing and coordination of multiple systems without disconnecting the modeling process from the fabrication stages. This computational methodology provides a process of developing and generating relationships holistically, maintaining a focus on execution.

Tooling as a part of this holistic approach also requires investigation by the designer. Behind every complex project, a high degree of engineering and mathematics is involved. Developing unique techniques and tools means having a basic understanding of descriptive methods and differential geometry necessary for execution. With the use of more advanced design tools for investigating and exploring architectural ideas, ensuring that designs can be built becomes critical. The designer's creative agency is not limited to the design of a building but can extend into other fields such as the designing of computational tools and processes. By establishing an intimate relationship with the digital processes, we can identify necessary tooling requirements which lead to innovative computational strategies. Tooling is as much a part of the design process as the ideation of spatial qualities. We are now comfortable with technologies readymade for use, but some of the most creative solutions come out of devising unique tools for achieving complex ideas. Most CAD packages come with the ability to tap directly into the application programming interface and language for developing unique tools. Each application has a finite number of special routines designed to perform specific tasks. With some providing more access than others, the programming language behind these applications provides the ability to code automation and generative routines. Algorithms for generating the fittest possible solution, whether it concerns performance or aesthetics, brings design tools to a higher level intelligence.

These brief investigations only touch the surface of the possibilities that computational methodologies and manufacturing technologies can provide. We try to emphasize the importance of synthesizing real-world and digital methodologies but also understanding the ontologies which constitute them. Gradually becoming increasingly necessary components of achieving holistic design methodologies toward solving complex problems in Architecture and Engineering. Increasing the level of sophistication in our design methodologies will bring new capacities into the fields of design, driving innovation in the building industry.

SECTION 01 |

COMPUTATIONAL & ANALYTICAL METHODS

“The system problem is essentially the problem of the limitations of analytical procedures in science” – Bertalanffy[8]

The simulation centered design method has progressed greatly through the support of several applications with embedded analytical methods. Utilizing simulation and analysis technologies in specific applications has made possible analytical techniques to establish integrated relationships with the iterative design process. We will continue to see the development and integration of simulation and analytical tools into design environments but with major improvements to be made. The biggest obstacles are those of system boundaries. The limitations of system boundaries exist due to limited knowledge of how complex systems interact and are computationally defined, which will take decades to overcome. For this reason, most analytical tools, will provide analytical data and models at a specific phase only. The capabilities of certain methods currently contain limitations in how associations between design models and analytical models are conserved. The capacity for a single model to contain both design and analytical information is a major challenge, which is why analytical techniques such as FEA, LCA, and CFD are typically divided and defined by analytical boundaries.

LCA (Life Cycle Analysis) is a systems approach to assessing the environmental impacts associated with materials processes and production. It is a scientific methodology that looks at a variety of products across disciplines throughout their entire life cycle. LCA includes three distinct components beginning with the Life Cycle Inventory (LCI) that establishes a continuum from the natural state of materials to a product. The product system creates a detailed inventory of information about processes and their outcomes. This data-based inventory quantifies energy, raw material requirements, air emissions, waterborne effluents, solid waste, and environmental discharges for a product, process or life cycle. The second component is the Life Cycle Impact Assessment (LCIA), following LCI and focused on evaluating the effects of the environmental findings discovered by the Life Cycle Inventory processes. This step addresses ecological, economic, health, social and cultural impacts but always with exact measures that are categorized. For example: manufacturing a product will consume a quantifiable volume of gas or energy which is a part of the inventory, and the global warming impact from the use of that energy can be calculated as C02. This information is then used to determine what the overall impacts are by any given process. This analysis can also include multiple processes and is often a complex system involving the supply chain, production process, transportation, use, recycling potential and end of life potential. The third component we look at here is the Life Cycle Improvement Analysis, where opportunities are identified for mitigating the environmental impacts globally or through the entire life cycle of any given product, process or action. There are qualitative and quantitative measures taken into consideration during this step through optimizations

01 Advanced digitization of architectural design methods will lead to more efficient and richer cross disciplinary experiences.

TRANSFORMING AEC

INTEGRATED SOLUTIONS REINVIGORATES DESIGN CREATIVITY AND PERFORMANCE.

toward meeting goals established during the initiation of the study.

Life Cycle Analysis is used to generate a holistic understanding of a product at various life-cycle stages, but also for distinct phases including raw material extraction, manufacture, transport, use, maintenance and recycle potential. While a product may require high energy consumption in production, it may also have a considerable life span and recycle potential. Conversely, a product with a low environmental impact in use may have a high energy requirement for manufacturing and distribution or have a relatively short use period. By quantifying the impacts at each stage, strategies can be implemented to target waste reduction in specific areas and achieve environmental impact goals. A life-cycle analysis can also give valuable data to assist in selecting between two options with similar cost and performance. Improvements with this information can be made through changes in the design, material selection, material use, processing, industrial processes, product use, waste protocol, and end of life strategies.

Energy and C02 are major factors when conducting an LCA. The embodied energy of a product considers the energy consumed at system boundaries but can also assess an entire lifecycle when combined. The boundaries range from raw material extraction to recycling or disposal. The typical method for expressing embodied energy is by calculating the megajoules of energy required to create one kilogram of product (MJ/kg) and by describing the carbon footprint by tons of carbon dioxide created producing one kilogram of product (tCO2). The carbon footprint of a product varies depending on the source of energy used in the manufacturing process. Energy, emission, water and resource impacts are cataloged for thousands of materials in databases, accessible through multiple software applications. These technologies use the same phasing of conducting an LCA, delivering information for each phase. The information about products and their processes is continually changing, which means that as technologies and methods evolve so do the impacts of products. LCA is not a precise science and this is why there are numerous methods for quantifying the flow and impacts of products. [9]

The limitations in collecting precise information lead to the separation of material processes between sourcing, processing, manufacturing, use and end of life phases. It is challenging to address all of these stages holistically; an attempt to capture an entire analytical lifespan within a single domain reduces the accuracy of the analysis output. Material processes are not monitored sufficiently or efficiently standardized at a global scale. Channels for sharing information about industry methods are slowly evolving as well as processing methods. As they are recorded and shared, other world factors begin to affect them as well. Technological advances, economic fluctuations and environmental impacts also play a role in processing mechanisms. Information about materials currently exists in databases consisting of categorized data sets. Datasets have to undergo continuous updating and quality control before being plugged into computing applications. These applications incorporate information about specific material phases and deliver results pertaining to each system boundary. Divisions of system processes are not unique to LCA; it will come up again and again as we look at other computational and analysis techniques. Dividing up a complex problem into multiple sub-domains is deeply embedded within any problem-solving mechanism. Later we will take a closer look at specific methods that can only be resolved through subdivision and iterative solving.

Maintaining data richness across modeling environments is also a major challenge in maintaining feedback loops. Translation processes are a part of any design methodology, where information from one platform must cross over to continue developing specific descriptions of any system, especially when it comes to analytical models. It means that the analytical data is often generated in an independent model and disconnected from the design model. Losing associations between design elements and their analytical results leads to a loss of fidelity in the analysis as a design progresses. If designs could somehow be made associative with analysis, then added layers of design resolution would provide additional information which would significantly impact efficiencies in design.

The wide range of engineering analysis techniques and simulation technologies go beyond the scope of this paper, but are covered as they relate to validating architectural designs. The topics analyzed further include descriptive geometrical methods, structural forces related to geometry and material parameters for constructability. These kinds of analytical approaches also point out the need to drive associative or parametric design strategies as a major part of the design process. Only through making design elements associative or parametric, can a higher degree of fidelity be combined with simulation-based design to have a greater impact on how we analyze and verify performance goals.

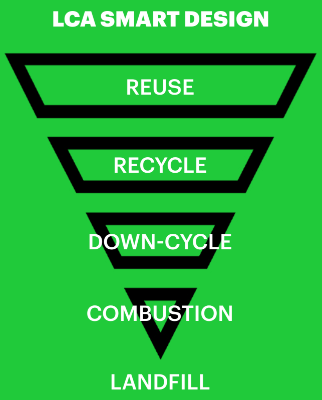
Finite element analysis or the finite element method has been used in solving many architectural issues of structural performance and integrity. The finite element method, first developed for solving mechanical engineering issues associated with the aeronautical industry, has seen a wide range of applications. The first funded development of this technology came from NASA, resulting in NASTRAN, which was used in the design of the Space Shuttle. This technology was eventually released to the public resulting in many of the commercial uses we see today in the automotive, engineering, aerospace and building industry.[10]

FEA can be described as using numerical methods for approximating solutions to continuous domains (complex assemblies or complex geometry). Using differential equations to describe multiple physical processes by subdividing the problem into finite or smaller elements. FEA takes an entire domain (complex geometry or assembly) and discretizes it into subdomains (smaller parts) which represent a set of element equations in relation to the whole, then reconstituting all of the element equations into a global calculation. This entire system of sub-equations then produces results from an initial state. Converting complex assemblies and geometry to mesh geometry is a method used for dividing continuous domains into smaller subdomains. It is also known as the discretization of a complex system and has been a term applied to many subjects including climate, organisms, ecosystems and chemistry. For this work, a complex problem is solved with FEA using a series of equations including, Euler-Bernoulli beam Equation, heat equation, Naiver-Strokes equations or integral equations. The Euler-Bernoulli beam method provides a way of calculating loads and deflections from an initial state, while the heat equation is a method for calculating the rate at which heat is distributed over time. The Naiver-Stokes equation provides a method for describing the motion of fluids such as the dynamic flow of fluids through pipes. Integral equations are much like differential equations, providing functions for taking physical quantities, calculating the rates of change and their relations. [11]

FEA tools are found in several PLM applications, including Siemens NX Pro, Dassault Systemes Simulia and Autodesk's NASTRAN which all use the NASTRAN solver (NASA Structure Analysis) developed by NASA. [12]Although there are many available sources for these tools, these are just a few of the available channels for using FEA. The increased availability of FEA within common applications requires knowing how and when to use it, providing us with the ability to make informed decisions about the physical behavior of

LIFE CYCLE ANALYSIS

LCA provides us with the means to understand energy and waste in design.



Environmental indicators are produced by analyzing detailed and quantitative information of natural resources and energy requirements for processing.

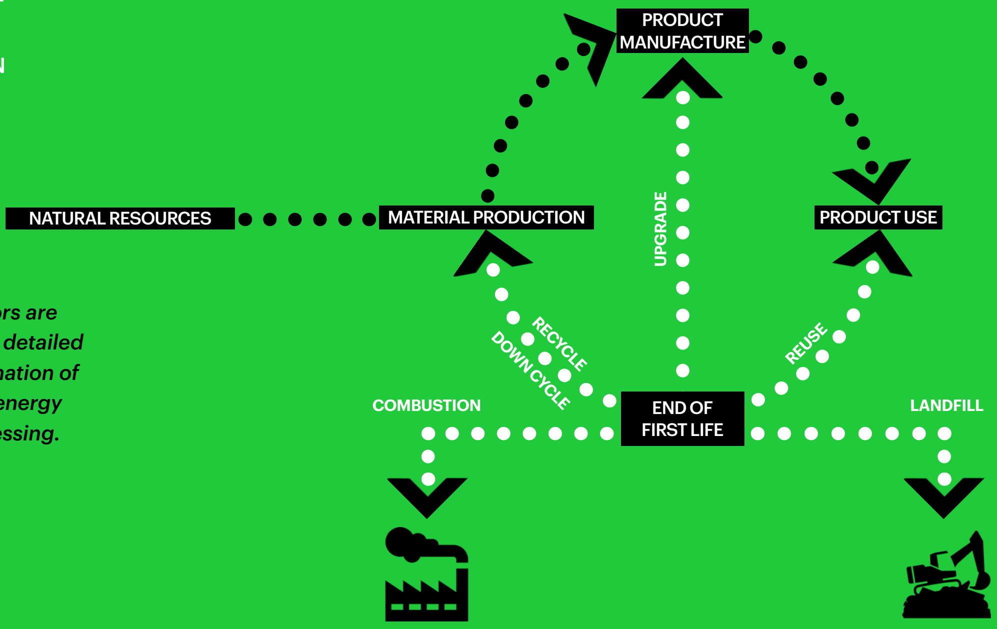


Figure 13: Material Life Cycle Process Diagram

PROCESS

MATERIAL PRODUCTION

MANUFACTURING OPERATIONS

MATERIAL MANAGEMENT
EOL POTENTIAL

MEASUREMENTS

EMBODIED ENERGY
MJ/KG

EMISSIONS
CO^2

WATER USAGE
LITERS

END OF LIFE PROCESSES

IMPACT REPORT

MATERIAL SELECTION
REUSE STRATEGIES

TOTAL ENERGY

TOTAL CO^2

EOL POTENTIAL

our designs. Since architectural design necessitates an iterative response to problem solving, the capacity to use analysis applications and comprehend their results is a major part of using simulation to inform design.

CFD or computational fluid dynamics methods have been applied in a wide range of applications within the AEC industry but can be traced back to some of its first uses in weather prediction. The basis of all CFD problems are solved using Naiver-Stokes equations, which describe the motion of fluids in multiple dimensions. The methodology behind CFD includes defining an initial analysis volume and the discretization that set volume into cells or finite volumes which can be defined at various resolutions. The boundary conditions are then defined, specifying inputs, fluid behaviors, and properties of the fluids. The simulation has an initial state and is calculated through iterations for transient problems taking into account pressure, mass flow rates, heat, and reactions. The domain in CFD can be understood as the model geometry which is then discretized into a finite number of cells. This discretization results in a large number of equations that are then iteratively solved until convergence is achieved. Convergence is achieved once the sum of residual values in the entire system become negligible or point to a single answer. The solution is then processed for visualization of the analysis, and the results presented as numerical values. CFD is then used to validate the performance of multiple desired outcomes.[13]

CFD, as it relates to the AEC industry, is most known for being used in analyzing air movement in buildings, fluids in mechanical equipment, life safety applications and wind forces on exterior applications. These applications can often be very critical to the design process for requirement and performance reasons, such as achieving proper ventilation within spaces and understanding the transfer of heating and cooling throughout a building. In life safety applications, CFD is used to simulated the distribution of fire and smoke under multiple scenarios, verifying that in the event of such cases, optimal safety conditions can be met. The described methods for solving CFD problems require sufficient geometrical considerations.

To properly capture spatial conditions, a modeling process where geometrical boundaries can be divided into volumes accurately is critical. Producing CFD results with a high resolution means that geometrical volumes need to be precise. Volumes should be modeled as closed geometries and removing any extraneous information from the analysis also speeds up the simulation time.[14] When designs are subject to change, finding the most efficient way of extracting geometrical volumes with minimal cleanup reduces errors in the results but also saves costly extraction exercises for each change. If these analysis techniques are to become a part of an overall iterative process, then the modeling applications behind design drivers that define geometrical boundaries can have major implications on efficiencies. Using parametric modeling platforms allows for maintaining associations between driving geometries and corresponding elements speeding up extraction exercises for running simulations. Since simulations require only boundary conditions, having the ability to reduce complex assemblies to simple face extractions makes a major difference. Rather than going through the translation of models between platforms for cleaning up geometries, certain applications can provide methods for streamlining the entire simulation workflow.

A holistic design workflow seeks to assess the design, fabrication, construction, environmental impact and value of a project. A holistic strategy can be implemented at the conceptual level, reducing the loss of information and energy caused by designing systems in isolation. The advances in technologies discussed allows for more effective collaborations between the designer, engineer and fabricator from the early stages of development where the most potential can be realized. In addition to increases in knowledge and efficiency, a holistic methodology can reduce the overall embodied energy of any design by facilitating direct design to fabrication workflows. While more energy and resources are required at the onset of design development, the assessment of the design life cycle will show a positive impact on the overall efficiency, quality and design intention.

1.01 FABRICATION & CONSTRUCTIBILITY

Digital technologies has significantly improved the capabilities of fabrication methodologies. Using digital workflows, we can design and test finished assemblies. Computer numerically controlled systems increase the accuracy and efficiency of creating parts and components while reducing the amount of time needed from design to assembly. Fabricators coordinate the information necessary for cutting, drilling and bending material in a way that can be fed directly to the fabrication machinery. For CNC milling machines, information from a digital model can be converted to a G-code that describes the tool path for cutting and machining a variety of parts such as metal panel systems, components from curtainwall assemblies, or digitally fabricated concrete formwork. Typical milling machines for curtainwall assemblies incorporate scanning technology to verify the correct profile and length of material before cutting, drilling and tapping at precise locations. For the process of bending steel tubes, there are many methods such as compression, roll, freeform, rotary draw and mandrel bending, with each method having positive and negative factors, including minimum bending radii, or the addition of a mandrel and counter dies that add cost to the fabrication. The right fabrication method should be coordinated with the design to ensure the required efficiency, cost, precision and quality control of the finished product.

These efficient manufacturing techniques involve less risk to the contractor and can lower costs and shorten the project timeline. Value engineering is often targeted toward the optimization and a reduction of unique manufacturing processes. It is especially feasible during the early design stage when a project is most flexible. The architect and fabricator can collaborate on finding a balance between the design intention and an efficient manufacturing process, allowing the desired aesthetic and materials to be fabricated for the least amount of cost possible.

Collaboration becomes especially important in understanding the unique needs of each fabricator, understanding their processes and workflows so that the design can be translated without loss of fidelity. Fabricators will often rebuild a design model to accommodate their unique workflow and machinery. While the fabricator always requires some degree of coordination, the designer can work toward producing useful and transferable information that can translate through different stages of the project. A holistic design workflow aligns the methods of the designer and fabricator, to be understood as one complete process.

1.02 CONTRACTS & DELIVERY METHODS

In a typical design-bid-build relationship, there are major divisions between the construction team and design team. The separation of the teams typically leads to a lack of channels for sharing information between members. We know that in a typical contractual setup, there is a hierarchy which acts as a barrier for resolving issues. When a design element needs clarification, an RFI is submitted. If the response generates a change in the scope of work, it may result in a change order with cost implications to the project. Architects, who want to maintain the integrity of design processes while reducing redundancies can look to other contractual relationships. A design assist relationship, for example, allows us to be a part of the building process in a much more intricate relationship with the production processes. This relationship is most known as a way of working directly with fabrication specialists to engineer and specify how building components are made and installed. This kind of integration is not an easy one, but it comes with many merits.

Working with experts in fabrication and engineering can ensure that the vision we set out to accomplish can be maintained all the way through a project. In order to achieve this there are three phases to the contracting that need to take place. The first phase is where the owner makes clear the scope of work, expectation of the specific contract, a budget and scheduling of the design assist process. The second phase is when the selected contractor of the design assist relationship works in tangent with the architect to identify and specify appropriate data about the building systems under consideration. This collaboration is meant to amplify the architects design by producing precise documentation for the contractor to use toward the fabrication and construction phases. During this phase, the architect and contractor can establish a common language for developing digital information about the building systems. This opportunity can be exploited by developing design information that can effectively directly into the fabrication process, eliminating the redundancies that often take place when information has to either be reproduced or doesn't adequately define building systems.

Companies including Zahner, Shop Construction and Gehry Partners are known for using design assist setups to build projects with high amounts of complexity. This relationship is necessary for being able to produce the kind of work these companies are known for. Each one of these companies also make use of sophisticated parametric software that establishes a common language for developing and describing building systems. The tools used to develop their projects aren't just design oriented but also engineering specific, which enables a design to production process.

1.03 DIGITAL TECHNOLOGIES

We now know that digital technologies, especially that of representation can play a fundamental role in the process of design to fabrication. In any 3D modeling environment, all geometrical definitions can be divided into these basic elements (points, lines, circles, curves, surfaces, and solids) and as any design evolves so do the relationships between all of these construction elements. Achieving constraints such as planarity of all geometries globally greatly reduces the complications that arise down the line, but it is not the case with every project. These geometries lend themselves to construction logics with a lot more ease than others. Surfaces that are perpendicular to each other can be captured through construction logics in numerous ways. Any trade in the building industry understands conventional geometrical relationships; a 90-degree angle is probably the easiest way to define a relationship between one element and another. As positions of elements in space become more complex their translation into construction logics also increases in difficulty. Materials also come with numerous unique limitations. It is often that more exuberant forms have to undergo some optimization to adapt to material and construction constraints.

If geometrical flexibility is desired from the beginning, then knowing material constraints and driving these limits into the digital modeling process can significantly improve how execution is performed. Sheet metal type materials are inherently constrained by their structural properties and developability. Sheet type materials fall into the category of developable surfaces, adhering to bending methods with minimized difficulty. Developable or ruled surfaces can be described as a set of points swept by a moving straight line. It means that the surface can be unrolled onto a flat plane without stretching or ripping the surface. Through certain kinds of production methods, sheet metals such as aluminum can be transformed into single curved panels. Due to known performances of sheet type material, certain digital techniques can be performed before further development of the associated building systems. It ensures that building systems and geometries can be achieved. Ruled geometries are easier to describe within industry standards, but when dealing with complex surfaces certain digital interrogations need to take place before further development.[15]

Curvature analysis techniques allow us to take unique design geometries and investigate the degree and acceleration of curved forms. It becomes critical to analyze surface geometry when formal qualities become a major element of any design. If complex surface control and quality can be measured, analyzed and interrogated, then the overall success of fabrication and construction can be better maintained. Additionally, visualization of curved or complex surface analysis can directly inform how certain materials might be fabricated or constructed in later phases. Surface analysis techniques can also reveal imperfections or deformations in curvature which are not easily visible in the digital model. These types of anomalies can lead to major project setbacks or decreased quality if not resolved from the early stages. It turns out that one of the best ways to anticipate difficulties in complex geometry is to establish a parametric and analytical framework for designing desired forms. It requires that methodologies for arriving at complexity be made intelligent through parametric techniques with proper analysis tools.[16]

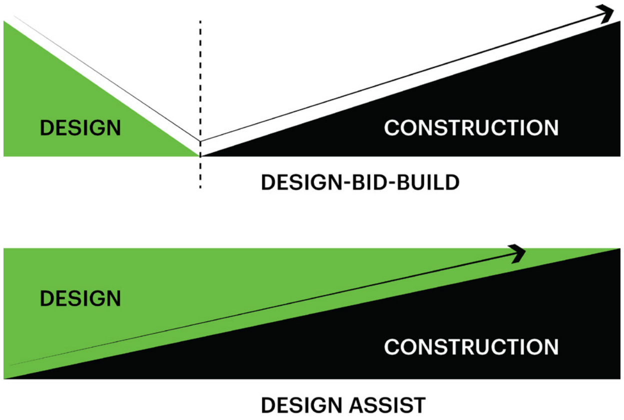


Figure 14: Contractual Relationship Diagrams

1.04 MODELING METHODS

The dominant mode of utilizing computers in architecture today is that of computerization; entities or processes that are already conceptualized in the designer's mind are entered, manipulated, or stored on a computer system... The problem with this situation is that designers do not take advantage of the computational power of the computer.[17]

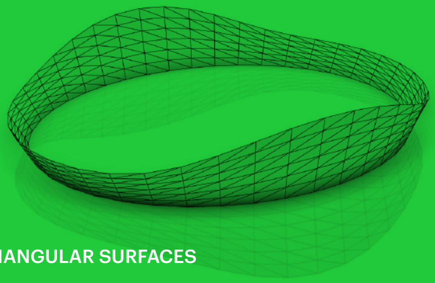
-Kostas Terzidis

With the exponential growth in computational power due in large part to the semiconductor industry, we can be sure that computing power and software technology will continue to improve. It enables designers

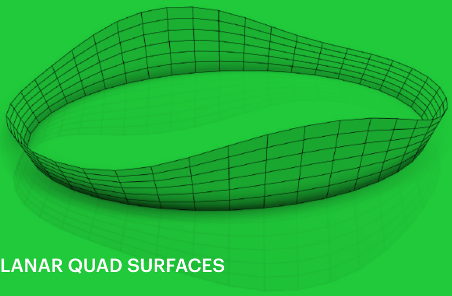
Geometric Rationalization is the product of driving manufacturing and constructibility constraints into design geometries.

Geometric rationalization methods provide key tools for generating discrete geometrical counterparts that can be made manufacturable but being able to integrate optimization constraints directly into the design process can yield more advanced design methodologies.

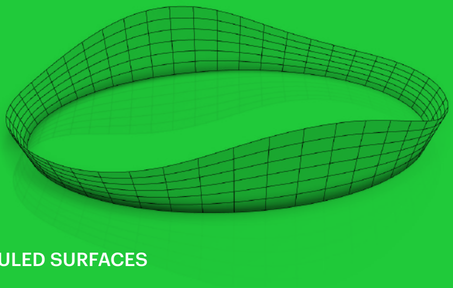
TYPES



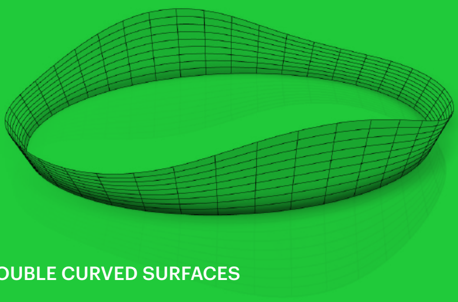
TRIANGULAR SURFACES



PLANAR QUAD SURFACES



RULED SURFACES



DOUBLE CURVED SURFACES

OPTIMIZATION SOLUTIONS

TRIANGULAR MESHES

PLANAR HIGH NODE COMPLEXITY

PLANAR QUADRILATERAL MESHES

PLANAR LOWER NODE COMPLEXITY

DEVELOPABLE SURFACES

RULED SURFACES LOWER MANUFACTURING AND DETAIL COMPLEXITY

DOUBLE CURVED SURFACES

COMPLEX SURFACES HIGH MANUFACTURING AND DETAIL COMPLEXITY to continue developing problems of geometry and building systems. The challenge is discovering ways of taking advantage of these developments throughout the design process. While these advancements in computing power have increased the computing capacity for simulating physical behaviors, they have in large part been underutilized by architectural design. We are becoming aware that investigations into computing possibilities within other fields make way for opportunities within the design and construction fields. Understanding the behaviors of internal and external interactions in other areas of science will bring ways of exploring ideas of form and material like never before.

The prevailing methods of using computing technologies have predominantly been through the computerization of ideas. Computerization takes place in the simplest form of design techniques by manually describing preconceived ideas into the computer, every press of a button or click of a mouse, explicitly defining how much information goes into the work. The limitations with this way of working are in how we take advantage of the computing power available to designers. The relationship between designer and computer here is reduced to drafting, while the computing capacity of today provides us with opportunities to process and produce information algorithmically.

While all software applications come equipped with already defined tools and commands that contain algorithms, they are limited by how the user treats them. We should point out that working within these confines reduces the speed and degree of possible solutions that can be generated. If we think differently about using our digital environments, through codes and algorithms for design opportunities, then we drastically change our relationship with computing. We can then use computational methods to establish interactions between systems, information, algorithms and other external factors.

The role computation has in design can have transformational impacts in design intelligence. The effort of setting up algorithms and tools for processing information and establishing interactions at a global level can produce solutions that we would never come across designing manually. Computational design is also not just a way of designing but also a way of thinking. Establishing relationships through computer language and sets of information makes designers better problem solvers.

Computational methods can be used to establish internal routines and rules for looking at numerous possible outcomes while maintaining global effects of the variable changes. Computational methods force us to think about solving problems by designing the system of possibilities through abstraction, constraints, parameters, algorithms and mechanisms for processing information.[18]

> Computational thinking is thinking recursively. It
>
> is parallel processing. It is interpreting code as data
>
> and data as code. It is type checking as the generalization of dimensional analysis. [19]
>
> -Jeannette M. Wing

As it relates to architectural design, the combination of these two methods of modeling can produce both a relationship to established architectural methods and computational techniques. The description that follows is just one of many examples for setting up these relationships. It is not limited to any one application, but the procedure can be used in many plat-

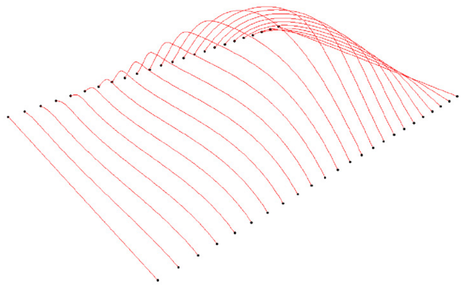


Figure 15: Ruling Curve Network

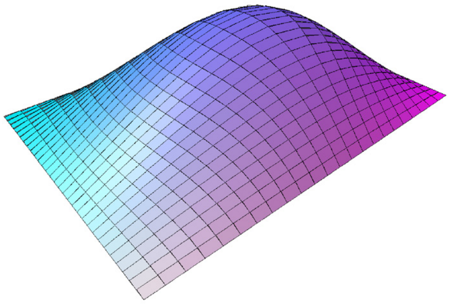


Figure 16: Planar Quad Surface Rationalization

forms available to designers.

We begin by establishing boundary constraints, or limitations that are usually dictated by building limits. The design limits or envelope boundaries can be created through construction geometry which is defined through explicit modeling using a series of construction objects (points, lines, planes, splines, and surfaces). The construction objects explicitly modeled can then begin to take on parameters which are defined through formulas as measures (length, angle, distance and area). Formulas are established by scripted language, allowing parameters to be driven using a variety of formula types. These formulas then drive constraints (Lengths, Strings, Angles, Real Quantities and Areas). Once the parameters have been defined, they can be made accessible through strings in the code or a custom interface. Using parameters during the construction geometry modeling phase can be very useful and serve as an efficient way of maintaining relationships and controlling drivers. Operations can then be made on construction geometries and, with instant parametric feedback, the interdependencies can be analyzed and investigated further.

Resulting design solutions for this phase are now parametrically tied to the generation of any updates which will propagate through continuous modeling operations, so long as they are a part of the coding or can maintain reactions to the first generation of information. This serves as a conceptual framework for combining two modeling methods, but can be approached in numerous ways and with much more sophistication. It enables the capacity to take on external information loops and algorithms that then work on generating geometrical data, providing higher design resolutions.

1.05 ARCHITECTURAL GEOMETRIES

"Only a dialectic relationship between technology and society can bring about enduring techno-social transformations - and with them, meaningful changes in architectural form" -Mario Carpo

Computational technologies have allowed us to produce an astounding variety of geometrical forms. Even more so as discoveries of the relationships between natural systems and mathematics are brought into digital applications. The application of computational methods to physical problems has led to establishing relationships between materials, behaviors, and performance. These relationships provide the possibility of informing developments in complex geometry that lend themselves to constructability, performing routines that allow designers to analyze, create and rationalize complex geometry into constructible counterparts. The relationship between discoveries in computational form, materials and manufacturing technologies will eventually merge to the effect that designers might design both form and novel material processes simultaneously.

Although there are numerous types of computational geometries and methods for generating them, we will only discuss dominant geometrical types which relate to common forms of fabrication and constructability techniques. With design applications like Rhinoceros, Maya, CATIA, Inventor and many others, freeform geometries can be modeled with minimal effort. The difficulties arise when designers produce geometries that do not respect the process of manufacturing and material performance.

Since the default setup for modeling in these platforms is material and fabrication agnostic, there is a high degree of freedom. Although this gives any designer the ability to exercise creativity beyond the confines of performance and constructability, solving issues of architectural geometry becomes a major challenge for successful execution. For this reason, more robust applications can embed meta-data about any geometry, including material performance and added constraints for taking advantage of performance and cost effectiveness, which we will look at more closely later.

The geometrical types discussed here include freeform surfaces, developable surfaces and planar surfaces. In solving issues of description and constructability for complex geometry, there are two primary solutions: discrete differential geometry and numerical optimization. Differential geometry provides us with the tools necessary for capturing the behavior of geometry. Complex geometry is understood regarding localized change, curvature, acceleration and topology. A major part of differential geometry is the topology of geometry, which is important when dealing with curvature and maintaining smoothness along freeform surfaces. The rules of topology are maintained so far as any geometry is continuous. Manipulations include bending, folding or stretching, but are broken if the geometry is split or separated. Maintaining topology makes it possible to analyze geometrical smoothness with methods like Gaussian curvature.

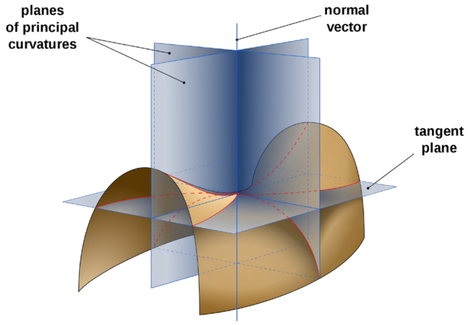


Figure 17: Gaussian Curvature (Saddle Surface Diagram)

The Gauss-Bonnet theorem in differential geometry is a major example of looking at local measurements and being able to understand global or topological characteristics. It is the product of two primary curvatures (K = K1 K2). Gaussian curvature provides a method for measuring intrinsic curvature on any given surface. If there is no bending along one direction, then there is zero Gaussian curvature. When there is zero curvature (K1 K2=0) along one primary edge and positive along the opposite, then the Gaussian curvature is zero. The resulting surface is known as a developable surface and geometrical type as Euclidean geometry. If the bending is going in the same direction along all sides, then there is positive Gaussian curvature. The resulting surface is a sphere, and the geometrical type is known as spherical geometry. However, if the curvature is bending in two opposite directions, then there is negative Gaussian curvature. This is known as a pseudo-spherical surface and its type is a hyperbolic geometry.[20]

This kind of analysis is only a small part of understanding how to approach optimization properly. The numerical optimization methods are more relevant for generating approximations of complex geometry because they lead to the discretization of geometry toward constructibility.

1.06 OPTIMIZATION TECHNIQUES

The process of manifesting geometrical complexity always begins with some base design geometry. These initial design geometries are more commonly explored using NURBS (non-uniform rational b-spline) surfaces. They are geometries that can be modeled in several platforms including Rhinoceros, Maya, and other 3d modeling environments. There is much detailed information describing how NURBS are formulated but as a general rule an NURBS geometry can be defined by its order, weighted control points, knot vectors and evaluation rules. The ability to increase the density of control points together with setting the degree of the curvature makes NURBS highly flexible, which is why they are more commonly used for designing complex surface geometry. With this flexibility in geometry comes the issue of having to look at methods for generating discrete counterparts, which can be used for manufacturing of materials.

There are several optimization methods for taking these types of geometry through optimization routines. The resulting solutions always attempt to provide solutions for building systems and structures that can be built from certain fabrication processes. The relationships between form and fabrication bring major challenges with increased formal complexity requiring more sophisticated solutions. The process of taking complex geometries and making them appropriate for fabrication is largely based on the concept of rationalization, where geometrical representations are approximated by subdivision techniques. This requires dividing a large geometrical problem into discrete parts through subdivision and optimizations. This is also known as the panelization of continuous geometry into discrete elements including types such as planar surfaces, single curved surfaces, and smooth double curved surfaces. The uniqueness of any given geometry can have significant implications on the difficulty and level of rationalization since these counterparts often lead to approximations which deviate from the input geometry. The solutions always attempt to lie as closely as possible to the original design. Resulting rationalized geometries can then pose the challenge of high amounts of variability, which has been the subject of several advanced computational workflows. Attempting to maximize the fabrication of similar geometrical definitions can reduce cost significantly. Looking for ways to create as much repetition as possible and limit uniqueness reduces the amount of labor and material required to manufacture. For this reason, several constraints and goals are applied to optimizations including simplifying geometrical complexity, variability, size and energy required to process.

Taking into consideration the design geometries but also subsequent layers of support elements and dependent systems introduces new complications. The necessary support structures and components pose another even greater challenge for meeting structural and manufacturing constraints. The generation of constructible surface geometry has to be integrated into the generation of support structures. Even rationalized geometries can produce high-cost solutions because of inefficiencies associated with the layers of material necessary to achieve a specific solution. By aligning shared geometrical continuities such as ruling wires or edges with structural elements, we can better coordinate supporting elements.

The two methodologies we will discuss later for tackling the problem of complex geometry are discrete differential geometry and numerical optimization, both of which are necessary for understanding how to solve optimization challenges. These methods establish solutions for discrete geometric surfaces which behave as analogs of continuous geometries. These methods provide us with the basis for solving geometrical complexity and iterating through possibilities which adhere to constructability constraints.

Polyhedral geometries are often used as solutions to complex geometries. Composed of planar surface geometries, polyhedral geometries provide more economical solutions to surface construction. Being planar, there are advantages from the manufacturing side that provide benefits of material usage and fabrication technique. Triangular meshes are one such solution, where the surface geometry is triangulated to approximate the underlying smoothness. Triangulated Meshes also provide the ability to move vertices or adjust their location without compromising the planarity and coincidences of adjacent surfaces. These meshes can be easily generated using curve networks that lie on the base surface. This produces a smoother result of the triangulation since edge continuity is highly visible and alignment often depends on smooth curve networks. Triangulated solutions produce closer approximations of surface geometry using planar systems but can also pose costly challenges associated with the quantity of surface geometries required to achieve higher quality results. Planar quad meshes produce effective solutions, resulting in meshes composed of planar quadrilateral surfaces.

There are advantages in using quadrilateral surface structures, including the reduction in edge conditions globally. Planar quads typically share four edges at any given vertex, reducing the amount of connection complexity involved in describing each node. Additionally, because of the reduction in edge construction, the fabrication times are also reduced along with reduction in the underlying material necessary to support these systems. Planar quad meshes also produce limited results due to the higher degree of constraints associated with approximating a lower count of edge conditions. These surface geometries can be generated by extracting a generatrix curve lying on the base surface and sweeping it along a secondary directrix curve without rotation along the path. The resulting conjugate curve network is then used to generate planar quad meshes that are planar, or as close to planar as possible. Using conjugate direction field optimization has been proven to be one of the most effective ways of generating planar quad meshes that best capture smoothness. When approaching complex geometry with a quadrilateral surface optimization routine, achieving planarity for any given surface has to be done globally. There are several numerical methods used to this end including, constrained minimization, nonlinear least squares, penalty methods, augmented Lagrange methods and more. All of these methods, to be successful, often require an understanding of both the continuous domain and discrete domains to be produced. So optimizing the continuous domain before panelization leads to better results.

Developable surfaces or single curved surfaces also provide us with an approach to optimizing complex geometry. Single curved surfaces, as was mentioned before, can be made flat without deformation. These geometries can be effective for covering large areas that are treated with sheet material such as metal or wood. Their developability also provides straight lines which are often used for the design of supporting structures which can have major impacts on constructability.

The relationship between developable surfaces and planar quad meshes also provides solutions that allow large planar quad meshes to be approximated using a series of ruled surfaces, producing a D-Strip model. One common approach to achieving developability from complex geometry is to extract optimized network curves on a design geometry and optimize the resulting surface incrementally. The D-Strip boundaries and ruling across the surfaces are the network of curves, which is also a semi-discrete network of conjugate curves. The benefits of these continuities provide a basis for defining specific structural members such as beams, extrusions, and other components.

Other special cases for D-Strip models include geodesic strip models, cylindrical strip models, and conical strip models. These types are covered in further detail by the work of H. Pottmann et al. We only mention that together these models offer a variety of solutions for optimizing and solving problems of panelization. While providing solutions for paneling freeform surfaces, these solutions also provide planar edge curves that can address applications of manufacturing and structural assemblies.[21]

1.07 INTEROPERABILITY

Exchanging data between the multiple platforms available to designers can be a challenge for maintaining the accuracy and intelligence of information. Due to the variety of design and engineering platforms, it becomes increasingly challenging to coordinate efforts and have the information transfer from one specialized application to another. There have been developments in how applications talk to each other, mostly contained within cad packages that share the same developers. This makes some interoperability problems easier, but applications that don't have those features are then forced to translate information into other applications. This often leads to errors during the translation process and leads to complications that greatly affect the entire design process. Knowing the numerous file types and pipelines for taking information from one environment to the next becomes an essential piece of knowledge for designers who want to have the flexibility of working in multiple environments, lending themselves to specific tasks. Certain file types also behave better with certain kinds of information, including mesh geometries, NURBS, 2D Data and numerical data.

Establishing the proper transfer protocols and pipelines can significantly improve the accuracy of information across platforms, but also the quality of data. Beyond the transfer of datumized information, making links between platforms through custom gateways has the potential to integrate capabilities in specific applications to the design process. Through plug-ins like the Granta Eco Advisor, both Autodesk's Inventor and Dassault Systemes CATIA can link geometrical features directly to material properties stored in their database. This link brings specificities of materials into the geometrical definitions, providing designers with instant feedback on LCA and performance. A link like this has the potential to produce design solutions which take into account the manufacturing, cost and environmental impacts of materials and form.

1.08 AUTOMATION & PARAMETRIC MODELING

Parametric modeling together with Automation techniques is a major part of design practices which can achieve geometrical and systems complexity in projects. Parametric design extends the designers ability to evolve ideas through iterative routines. By establishing relations between form and information, parametric techniques can produce all possible instances that remain within the constraints either defined or generated algorithmically. This concept of parametric design can be traced back to Goethe's ideas of morphology, which investigated the differences and connections between form and formations. Transformation for Goethe was the effect of internal mechanisms that would actualize physical attributes or metamorphosis. This idea led to the notion of geometrical relationship to processes or geometrical behavior to function. This same concept was further advanced in mathematical approaches through the work of D'Arcy Thomson. Establishing the relation of forces to organization and patterns using mathematics. Parametric design through these works emerged as computational ways of looking at associative relationships between information and form. Parametric design can then be understood, as regarding the interdependencies of certain geometrical constraints. However, it is more profound meaning is that of creating methods for interconnecting certain behaviors of systems and forces, and how they are represented as related geometric and mathematical procedures.

By combining the concepts of parametric modeling and design, we can begin with looking at the system of possibilities that we want to define. This system can be set by describing a design problem through parameters and variables. Using scripting language(s) together with algorithms, actions, and reactions, we can establish a recursive system which is generative but also produces geometric solutions adhering to certain limitations initialized by the designer. The parametric design also provides the designer with a variety of possibilities that are recursively generated from the interdependencies, often leading to unpredictable but optimized solutions.

Most CAD packages can be extended to provide these types of mechanisms through their API, controlling functionalities already embedded within each application. Adjusting variables result in alternative solutions, which can have relations to performance, constructability, cost, aesthetics or a combination of these.

1.09 MODELING METHODOLOGY

The Master Model methodology has been used widely for applications dealing with complex systems engineering projects, where there is a need to take a single source of design information all the way through production and execution efficiently. The aerospace and automotive industries use this methodology for dealing with improved data quality and reducing shop floor errors. The inefficiencies in establishing a workflow between conceptual stages through manufacturing and construction can be met with effectiveness through methodologies like the Master Model approach.

The Master Modeling method sets out a unique way of organizing data through a tree structure which visualizes the top level relationships between elements, parts and products. By using the tree structure, the designer can maintain and manage relationships between all parts of a project data structure. With the ability to isolate any single part within the tree, the tree structure provides a high degree of authoring. The individual parts can be accessed individually while maintaining their relationship with all other parts and products within the tree. This means that entire products containing multiple parts can be assigned to separate team members as each works on specific parts of a project in a tangent. The efficiency of not having to open the entire model which often contains a high amount of data makes working collaboratively much more effective. No single part can be worked on simultaneously, ensuring that there is no duplication of effort or time wasted during design development.

The Master Modeling approach is not unique to one platform but can be employed using several PLM applications. The example data trees on the top right were assembled in CATIA & Autodesk's Inventor Pro, which highlight the tree relationships to constituent parts. Every product in both examples contains parts, and every part contains geometrical information. In addition to these tree structures, there are other high-level components which can be embedded within the data tree.

Drawing components or parts can be integrated into the data structure as a part of the modeling process so that any part modeled explicitly or through automation is associated with a drawing. The drawing templates are all associative, in a way that updates their content as any model is updated. While there are certain documentation capabilities within other methods that maintain associations, we will highlight the benefits of being able to embed documentation templates within parts and system assemblies. In most conventional designs that conform with industry standard descriptive techniques, the problem of documentation can be generalized with few drawings which capture entire design intent. With designs where complexity produces a large number of variabilities and requires extensive documentation for every unique condition, embedding documents into the part modeling is critical. As system assemblies are modeled, instantiated or automated using scripting methods (which we will look at later), documentation can be automatically generated within the part or product structure. This ensures that as models continue to increase in fidelity that the associated documentation is also maintained and synchronized. The benefits of using a Master Model approach can be utilized not just in producing 3D information but also capturing 2D documentation as a part of the entire process.

Typical data structuring systems like those used in Revit often lead designers to produce a limited amount of 3D information and add detail as disconnected overlays of 2D information, allowing errors in coordination. This method of managing large quantities of building information also requires that users access

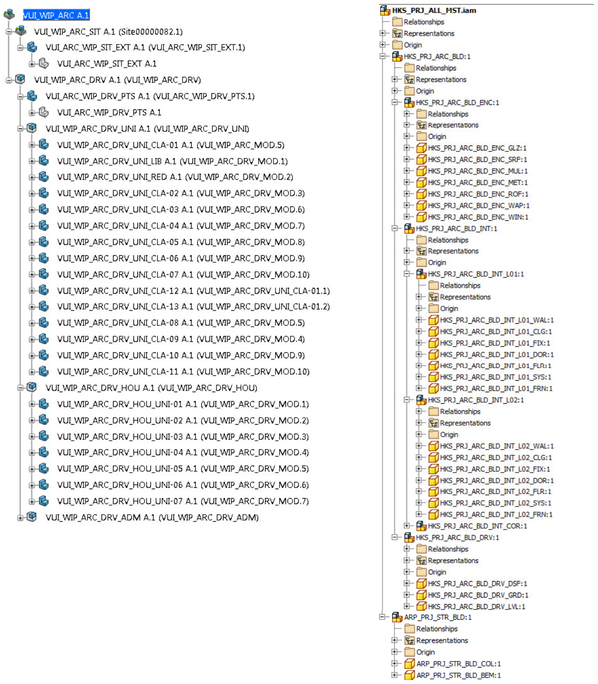


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Figure 18: Master Model Tree Model (CATIA Left) (Inventor Right)

1

MASTER MODEL

DRIVER/CONTEXTUAL MODEL
VERTICES
WIRES
GRIDS
DRIVING DESIGN GEOMETRIES (SURFACES, SOLIDS, EDGES ETC.)
PLANES (BLDG LEVELS, INTERSECTION ETC.)

REFERENCE/DESIGN MODEL
DESIGN/TRADE IMPORT MODEL
SURVEY INFORMATION (POINTCLOUD MODEL)

COMMUNICATION MODEL (SUB TRADE INTEGRATION)
DESIGN INTENT
SCOPE & DISCIPLINE

COORDINATION MODEL
STRUCTURAL GEOMETRIES
SOLID GEOMETRIES
SHIPPING
SHOP DRAWINGS
SCHEDULES

FABRICATION MODEL
MOCK-UP
BILL OF PARTS
QA/QC
SHOP DIRECTIVES

INSTALLATION MODEL
FIELD DIRECTIVE

SEQUENCING

large portions of a model even when the work only involves a limited area. Dividing up models into much smaller parts or elements in platforms like Revit is difficult for large scale projects. Team members are then required to open large amounts of building information, varying by the amount of elements on individual worksets, to perform small tasks and minor updates. Loading large models requires high processing power and longer wait times. Once a model is loaded, users may then take ownership of elements or entire worksets containing disciplines or groups, depending on how the project is structured. This makes it problematic for team members to work simultaneously within proximity in a model.

Discrepancies in information produced or shared between collaborators is a major issue in how data is coordinated and communicated. The limitations in maintaining associations and controlling those relationships in conventional BIM applications often leads to mistakes and errors between disciplines. The division of modeling efforts within these tools means having to separate models and bringing them together as referenced information only. This means that associations between disciplines like structures, enclosure systems and interiors are divided and managed independently without sufficient linkage between geometrical information. When something gets updated, shifted or displaced in one model, the modifications do not always propagate throughout the adjacent systems that have relationships to the changed elements. There are certain parametric capabilities within platforms like Revit, but these parametric relationships are easily modified which leads to incorrectly placed elements and accidentally removed information. These are just a few challenges that can be major causes of loss in productivity, time, cost and quality.

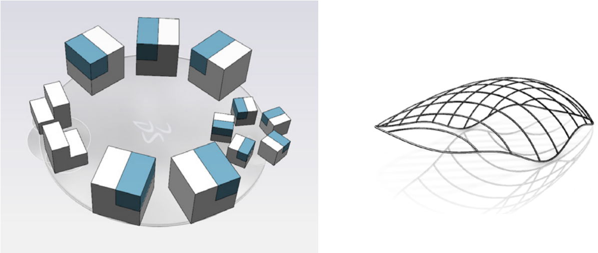


Figure 19: CATIA Component Model & Component Product Browser

In conjunction with the master modeling approach, there are two subsets which add increased efficiency to integrated modeling organizations. These types are known as assembly type design methods. They are defined as bottom-up approach and top-down approach, with each providing certain efficiencies that combined make the development of information and management increasingly effective.

The bottom-up design approach is one of the most known methods in applications like CATIA, Inventor, Solidworks, Siemens NX Pro and other engineering applications. It begins with the creation of a part type files in which drivers or components can be modeled. These parts are then placed into a level product file by inserting each part and constraining their position and relation to one another using assembly constraints. Using this method provides the ability to focus on the development of detailed components and establish a higher amount of information about any given element into the design before establishing physical constraints with other elements. It also makes the management of highly complex assemblies easier to manage since any one part can be opened individually without having to access the entire assembly. Any relationships established with other parts are maintained even during the updating of individual parts.

The second method is known as the top-down design approach, where components are created within the context of an assembly or product level file type. This approach involves parts that can be generated directly from the assembly level using the skeletal framework method. The parts created at the product level can still be accessed or modified individually after they have been created. This approach also makes it easier to produce a high amount of complex assemblies much faster while visualizing the entire design in real time.

Together with scripting and automation techniques, both of these techniques can provide the master model methodology with a high degree of complexity and definition. The opportunities in using methods like this for the design of buildings challenges the designer to look at the organization of model information in ways that lead to the delivery of that information for production processes. Each part can be detailed, delivered and manufactured without having to undergo tedious extraction exercises. This approach has been integral to engineering processes ranging from the automotive industries to aerospace industries but has also been used in the design of buildings with great success.

1

PRODUCTION

Tracing the production process to extraction and methods for transforming materials is critical to understanding and ensuring the qualities of final building systems.

2

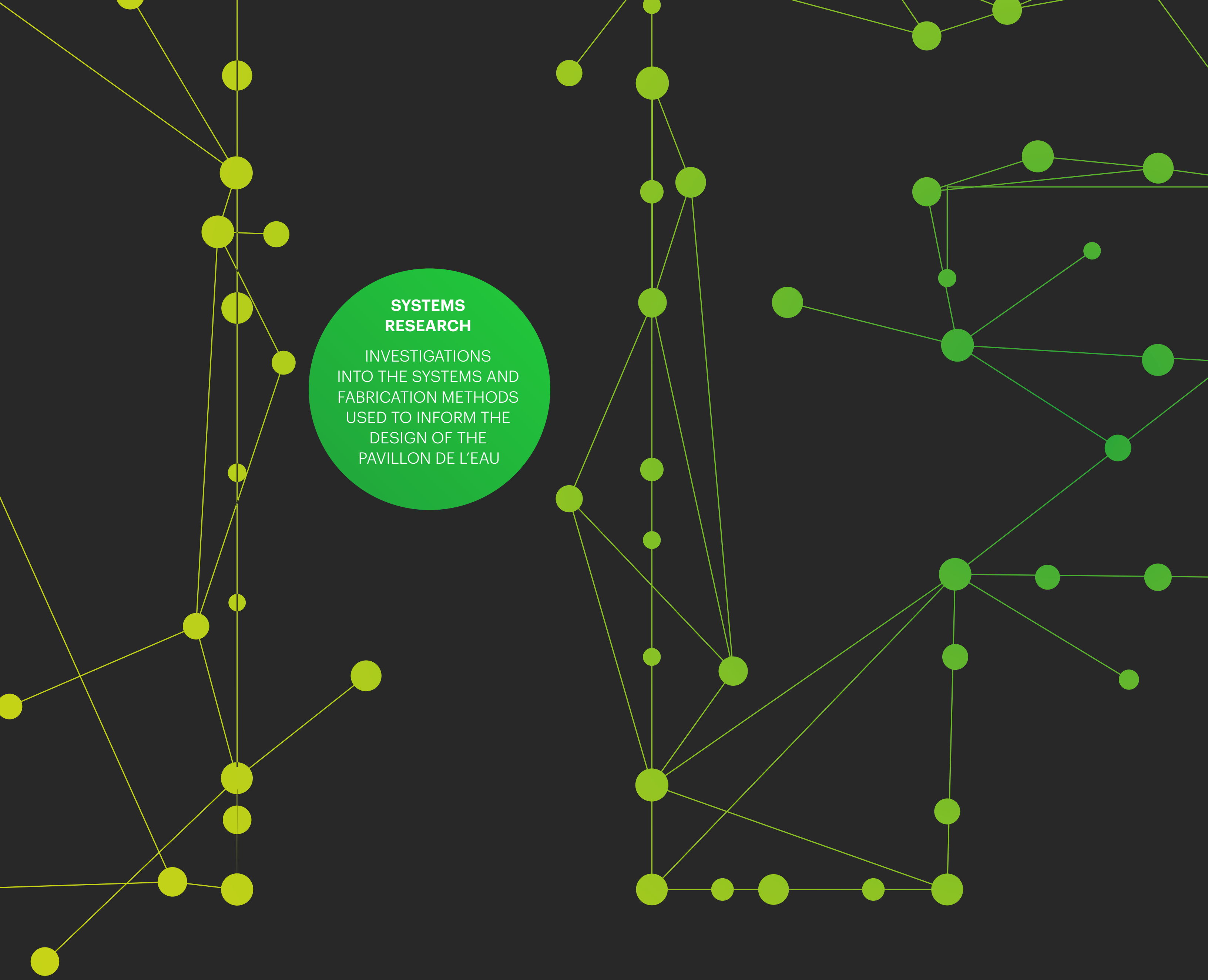
APPLICATION

The application of any material to a specific function is determined by the production process and verified by the performance criteria. Higher performing application require a higher production processing methods which continue to improve.

3

PERFORMANCE

The performance of any material system depends highly on the production process. There are numerous ways of achieving specific material properties (see figure) and qualities but performance can also guided by the engineering of a systems requirements during design.



SYSTEMS RESEARCH

INVESTIGATIONS INTO THE SYSTEMS AND FABRICATION METHODS USED TO INFORM THE DESIGN OF THE PAVILLON DE L’EAU

02

The material and technical qualities of building systems reveals the behavioral correlations that can be exploited for performance and constructability.

SECTION 02 |

MANUFACTURING & CONSTRUCTION

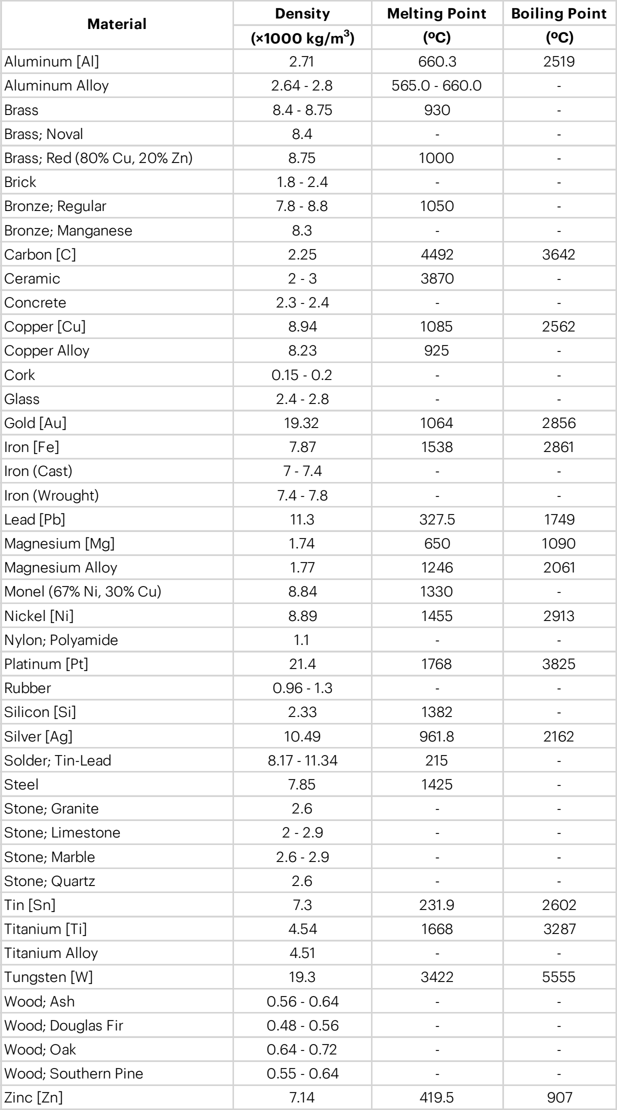
Researching and understanding building systems used in a project is of absolute importance in a holistic design workflow, where fabrication methods are considered during the entire design process. A thorough understanding of the limitations and opportunities of each system will inform much of the designer's decisions, leading to a much more beneficial collaboration with the engineers, fabricators and contractors. In a standard project delivery method of design-bid-build, a fabricator is not brought into the project team until after the designer has finished the contract documents describing the intention of their design. In a holistic design workflow, all aspects of a project are considered from design to fabrication. Through the use of advanced digital workflows, technology can be harnessed to design, test, automate, quantify and fabricate building components.

While the AEC industry involves thousands of building systems and fabrication methods, the following systems describe the research that was directly applied toward the systems in our research case study, the Pavillon de L'eau. These systems are described in their material attributes and construction methods, and highlight the unique opportunities that technological advancements can enrich and expand the possibilities of each material and system.

2.01 AESS SYSTEMS

The use of architecturally exposed structural steel (AESS) has become increasingly popular in contemporary design. Following strict standards put forth by the American Institute of Steel Construction (AISC), a benchmark can be achieved through the use of samples, specifications and a detailed matrix covering the additional cost associated with fabrication, erection and coatings. Methods and costs associated with AESS vary from fabricator to fabricator and are reflected in the matrix by outlining an expected range in additional cost to the steel. All percentages are based on the total weight of steel and include fabrication and erection. Enhancement to the visual appearance and increases in cost are directly related to the additional work required to remove typical imperfections to the surface and minimize tolerances. Typical welding aids and surface marks are removed or minimized depending on the level of finish desired. Welds are ground smooth or contoured and blended so as not to be visible when finish coats are added. Show through welds on the far side of a structural connection are minimized. Edges are ground, gaps are closed, and surface marks are removed to a level outlined by the architect.

A detailed specification is required to establish the expected conditions and finish of the steel. The first section of the specification outlines the submittals, quality assurance, delivery, storage and handling, project conditions and coordination. The second part of the specification outlines the products. This includes a detailed description of the products, primers and finishes, fabrication tolerances and methods for grinding and contouring welds, shop connections and priming and galvanizing. The third part of the specification outlines the execution of the finished



Material	Density	Melting Point	Boiling Point
	(×1000 kg/m^3)	(ºC)	(ºC)
Aluminum [Al]	2.71	660.3	2519
Aluminum Alloy	2.64 - 2.8	565.0 - 660.0	-
Brass	8.4 - 8.75	930	-
Brass; Noval	8.4	-	-
Brass; Red (80% Cu, 20% Zn)	8.75	1000	-
Brick	1.8 - 2.4	-	-
Bronze; Regular	7.8 - 8.8	1050	-
Bronze; Manganese	8.3	-	-
Carbon [C]	2.25	4492	3642
Ceramic	2 - 3	3870	-
Concrete	2.3 - 2.4	-	-
Copper [Cu]	8.94	1085	2562
Copper Alloy	8.23	925	-
Cork	0.15 - 0.2	-	-
Glass	2.4 - 2.8	-	-
Gold [Au]	19.32	1064	2856
Iron [Fe]	7.87	1538	2861
Iron (Cast)	7 - 7.4	-	-
Iron (Wrought)	7.4 - 7.8	-	-
Lead [Pb]	11.3	327.5	1749
Magnesium [Mg]	1.74	650	1090
Magnesium Alloy	1.77	1246	2061
Monel (67% Ni, 30% Cu)	8.84	1330	-
Nickel [Ni]	8.89	1455	2913
Nylon; Polyamide	1.1	-	-
Platinum [Pt]	21.4	1768	3825
Rubber	0.96 - 1.3	-	-
Silicon [Si]	2.33	1382	-
Silver [Ag]	10.49	961.8	2162
Solder; Tin-Lead	8.17 - 11.34	215	-
Steel	7.85	1425	-
Stone; Granite	2.6	-	-
Stone; Limestone	2 - 2.9	-	-
Stone; Marble	2.6 - 2.9	-	-
Stone; Quartz	2.6	-	-
Tin [Sn]	7.3	231.9	2602
Titanium [Ti]	4.54	1668	3287
Titanium Alloy	4.51	-	-
Tungsten [W]	19.3	3422	5555
Wood; Ash	0.56 - 0.64	-	-
Wood; Douglas Fir	0.48 - 0.56	-	-
Wood; Oak	0.64 - 0.72	-	-
Wood; Southern Pine	0.55 - 0.64	-	-
Zinc [Zn]	7.14	419.5	907

Figure 20: Material Properties Data

product. This includes the examination of material, preparation and erection of steel, use of field connections, and a quality control examination by an independent testing and inspection agency.

To dictate the level of finish to a fabricator, the architect will specify a category for the steel to achieve. For the AISC, the levels are broken into Standard, Category 3, Category 2, Category 1 and User.

AESS CONNECTION DETAIL: **Capturing proper connection and welding details with AESS early in the design stages ensures that fabrication and cost constraints can be met.**

Figure 21: Structural Steel Detail

AESS STANDARD

This baseline follows the AISC Code of Standard Practice Section 10 and results in a cost increase of 27%-60% above traditional structural steel. Additional labor for AESS Standard includes special care and processing, tolerances reduced to one-half standard, coping and blocking and joint gap tolerances minimized, piece marks hidden and surface defects minimized.

AESS CATEGORY 3

This level of finish is used for high-profile conditions that are out of reach and can be viewed at a distance of 20 feet or more. The additional cost ranges from 22%-45%. Additional labor for AESS Category 3 includes special care and processing, piece marks hidden, rolled members distortion minimized and the bolt head orientation dictated.

AESS CATEGORY 2

This category is specified for high-profile conditions that are out of reach and can be viewed in proximity within 20 feet. The additional cost associated ranges from 67%-125%. The additional labor includes all aspects outlined in Category 2 as well as all welds ground smooth and contoured and blended, weld show through minimized, field welding aids removed and weld access holes closed at full pen welds.

AESS CATEGORY 1

Properties	Carbon Steels	Alloy Steels	Stainless Steels
Density (1000 kg/m^3)	7.85	7.85	7.75-8.1
Elastic Modulus (GPa)	190-210	190-210	190-210
Poisson's Ratio	0.27-0.3	0.27-0.3	0.27-0.3
Thermal Expansion (10^{-6}/K)	11-16.6	9.0-15	9.0-20.7
Melting Point (°C)			1371-1454
Thermal Conductivity (W/m-K)	24.3-65.2	26-48.6	11.2-36.7
Specific Heat (J/kg-K)	450-2081	452-1499	420-500
Electrical Resistivity (10^{-9}W-m)	130-1250	210-1251	75.7-1020
Tensile Strength (MPa)	276-1882	758-1882	515-827
Yield Strength (MPa)	186-758	366-1793	207-552
Percent Elongation (%)	Oct-32	Apr-31	Dec-40
Hardness (Brinell 3000kg)	86-388	149-627	137-595

Figure 22: Structural Steel Properties Data

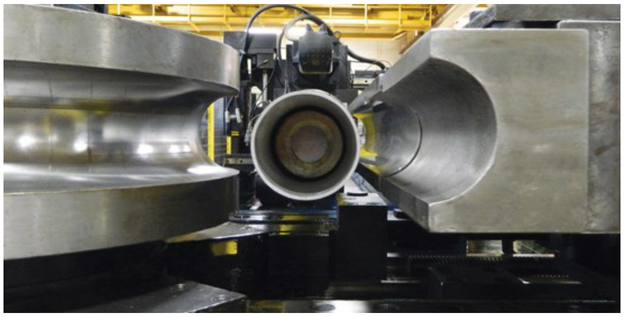


Figure 23: Metal Bending Machine

This benchmark is the highest pre-set category of AESS steel, used for high profile conditions that are within reach and can be viewed in close proximity. The cost increase associated ranges from 96%-195%. Additional labor includes all items outlined in Categories 3 and 2 as well as tolerances reduced to one-half standard, continuous welds, coping and blocking and joint gap tolerances minimized, surface defects minimized, mill marks removed, grinding of shear edges and the sealing of welds to close open gaps.

AESS USER

This category is an interactive input of custom selections by the architect. The fabrication and erection classifications are selected by the architect for individually specified components.

AESS IN CONTRACT DOCUMENTS

AESS members are often poorly described or identified in contract documents, leading to discrepancies between the design intention and what is bid. Through the use of a digital fabrication model, structural members can be easily identified and categorized to the level desired. Additionally, fabrication methods can be identified during the design process and help to eliminate disputes between the designer and contractor over the finished product. A detailed digital exploration between the architect and fabricator can set up a clearly defined scope of materials and quality.

2.02 ETFE ENCLOSURE SYSTEMS

Ethylene Tetrafluoroethylene (ETFE) is a polymer used as a contemporary alternative to glass building enclosures. ETFE is extruded into ultra-thin sheets called foils and utilized in a system of single, double and triple layers. Single layer systems are reinforced with wires and cable stays. Double and triple layers are used as part of a pneumatic system capable of spanning large distances. The common terminology for this application is film or foil membrane structures. The production process for ETFE sheets can range in thickness from 50um to 500um, depending on the loading and resistance requirements. The multiple layers of ETFE are typically sealed together with space in-between for inflation. The inflated ETFE cushions are used in skylights, large span canopy applications and enclosure systems for their capacity to maintain transparency without the structural and cost implications of glass.

As a result of the lightness of the ETFE assembly and its spanning capabilities, the structural support can be greatly reduced, creating a much lighter and open aesthetic than traditional glazed systems. Although ETFE foil systems are relatively new, research from existing projects show no sign of embrittlement or deg-

ETFE:
The provides a lightweight solution to enclosures with geometrical flexibility while allowing natural light to filter through.

Figure 24: Allianz Arena, Munich, Germany ETFE Facade by Herzog & de Meuron

radation and are expected to have a life expectancy between 50 and 100 years.

TRANSPARENCY

ETFE has a transparency in the range of 90%-95% light transmission per foil. It also allows ultraviolet light through the system making it exceptionally suitable for plant life, while showing no signs of yellowing or degradation of the material. At the same time, a large proportion of infrared light is absorbed by the foils, improving the energy efficiency of the building.

WEIGHT AND SPANNING CAPABILITIES

ETFE foil cushions weigh approximately 1.3-2.4 pounds per square foot, making it significantly lighter than a comparable curtain wall system. The lightness of the system also allows the supporting structure to be spaced further apart and reduce the overall size of the members. The size of ETFE foil cushions is limited by wind and snow loads acting on the system. Rectangular cushions can span to approximately 10-15 feet in cross-section and several hundred feet in length. Triangular cushions can be larger, as allowed by loads. Cable stays are added to specific locations with increased snow loads or wind uplift

STRENGTH AND FLEXIBILITY

ETFE systems are certified as a class C non-fragile roof system and can withstand impact loads, but must be monitored or replaced once an impact occurs. Replacement of ETFE cushions can be localized to only the affected area and can be done with a relatively low amount of labor or disruption to the rest of the system. In addition to the high strength of the material, ETFE foil has a high elasticity of up to 600%, making it resistant to damage. At its breaking point, ETFE has a tensile strength of 52 N /mm2.

FIRE RATING

ETFE foil has a low flammability and melts at around 500 degrees Fahrenheit without forming droplets. The material is considered to be self-extinguishing and will shrink away from the heat source, creating natural ventilation to discharge smoke.

CUSHIONS

Cushions are created with inflated sections of extruded ETFE foil that are welded together and clamped in an aluminum track. An air inflation hose is integrated into the bottom foil of the cushion at a specific location to maintain a steady pressure, and a pressure control valve allows excess pressure to be released from the system.

CLAMPS

The cushions are clamped into extruded aluminum tracks with gaskets, creating a water and air-tight barrier. The profile of the extrusions varies depending on manufacturer and are customized depending on whether the clamp holds one or two pillows and whether or not additional features such as integrated gutters and bird protection are desired. The clamps are attached to the structural support in a way that the fasteners do not penetrate through the aluminum extrusion. The underside of the extrusions is bolted to a standoff that is attached to the steel structure. These standoffs vary in size and profile and can be customized on a project basis.

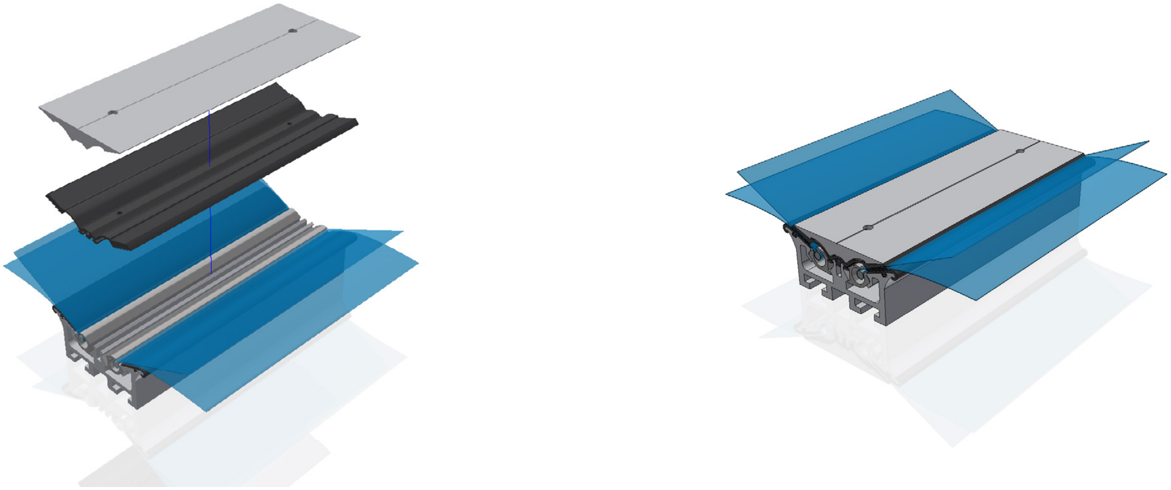


Figure 25: ETFE Connection Detail Model

ENVIRONMENTAL CONTROL

Additional solar control can be added to the foils through the use of frits and reflective coatings. Where cushions are clamped and at welded seams, an uncoated margin must be left for proper adhering of the membranes. These margins are subtle yet visible in the finished surface of the fritted cushion.

A variable ETFE envelope is achievable through the use of a triple membrane system where the pressure of the top and bottom chambers are controlled separately. A frit or printed pattern is applied to the underside of the outermost layer and a negative of the pattern is applied to the underside of the middle layer. By controlling the pressure of the chambers, the middle layer moves from the center of the cushion to being pressed against the outer layer. This results in a variation of light transmission from 5% to 50%. Additionally, sensors can be added to the system to automate the variable skin to respond to environmental conditions.

AIR INFLATION SYSTEM

The air pressure within the cushions are fed by a series of air tubes that are continually inflated by air handling units. An average size roof or enclosure can be inflated by a single unit of around the size of 4′ x 4′ x 3′. The units only maintain a constant pressure, rather than continually generate air flow and have a low energy consumption. A typical unit consists of two fans powered by electric motors, with only one fan running at a given time. A dehumidification system removes excess moisture from the air fed to the cushions. While the air supply tubes are visible on the surface of the system where they connect to the cushions, the air inflation unit itself can operate remotely not to impact the aesthetic of the design.

2.03 CONCRETE SYSTEMS

Reinforced concrete structures are well known for their capacity to capture complex geometries as well as conventional forms. Concrete forms can be achieved in several ways, and it is their fluid characteristic that makes concrete one of the most explored materials in design and architecture. Unlike metals, glass, plastics, timber and other materials, concrete is most often formed on site by cast-in-place techniques or precast in factory settings. With concrete, time is a major factor during the curing process. Large projects requiring high quantities of concrete to be delivered on site can push the limits of how concrete is formed since only a limited quantity can be cast within a given amount of time.

Cast-in-place concrete is highly dependent on the formwork that is built prior to pouring. The accuracy and reinforcement of formwork has a significant impact on the quality, performance and aesthetics of the final concrete form. Details such as joints, gaps,

Figure 26: Mausoleum in Michniow, Injection Forming Concrete Construction

Figure 27: Philip Frost Museum of Science, Florida, Digitally Fabricated Formwork & Cast-In Place Concrete Construction

holes, reveals, form lines and others are affected by how formwork is designed and executed.

The properties of concrete including its fluid adaptability, strength and durability are highly dependent on the constituents and ratio of the mixture composition. The design of specific concrete mixtures includes a ratio of water to cement and combination of aggregate content (sand, gravel and crushed stone). Concrete mixes with less water are higher in strength. Concrete with a higher water ratio is weaker due to the air pores left behind by water content. However, higher amounts of water also make the concrete more fluid and easier to cast, especially when a smooth finish is desired. The most common water-cement ratio used in construction is between 0.4 to 0.5. There are also certain admixtures which can be used to improve the overall strength and formability.

Admixtures can have multiple effects on concrete including the ability to produce billions of microscopic air cells which relieve internal pressures. Air entraining admixtures improve the workability of concrete during the forming process but also reinforces the cured concrete under specific environmental conditions. For freeze-thaw cycles the increased air content improves performance by allowing water to expand into these small chambers when it freezes and out when it thaws. This avoids cracking or accelerated deterioration over the life of the concrete. Additional admixtures include water reducers which improves consistency.

DIGITALLY FABRICATED FORMS AND FORMWORK

Several methods exist for creating digitally fabricated formwork. They involve using computer-aided design (CAD) in connection with computer-aided manufacturing (CAM). This method revolves around the strategy of using the design software to communicate directly to the manufacturing machinery. Through the use of computer numerically controlled (CNC) fabrication methods, formwork can be simplified and with great precision. The concrete form fabricator and the steel fabricator reference the same digital model, allowing both teams to create coordinated construction elements while working separately. To illustrate two approaches to digital fabrication in formed concrete, the following two projects are described in detail.

BOSTON HARBOR PARK PAVILION

The Boston Harbor Park Pavilion is a beautiful example of blending digital technology in the fabrication of concrete formwork with traditional slab forming techniques. The project team consisted of Utile Architecture & Planning, engineering by Simpson Gumpertz and Heger, concrete formwork by CW Keller, concrete by S&F concrete, and construction by Turner Construction. The design consists of two concrete slabs elevated by steel columns and exposed steel ribs embedded into the concrete slabs with Nelson studs. The concrete slabs undulate to

Figure 28: Boston Harbor Park Pavilion. Digitally Fabricated Formwork & Cast-In Place Concrete Construction

Figure 29 Olympic Diving Platforms, London 2012, Form created by 5-axis CNC and Glass-fiber Reinforced Polymer Formwork for Precast Concrete Construction

channel water into a central trough, resulting in a dramatic water feature at the point where rainwater is shed from the surface. Although the geometry of the pavilion is complex, the method for pouring and reinforcing the slab was similar to standard flat slab construction. The complexity of the construction was in the creating of the wood formwork, modeled in Rhinoceros and cut by CNC machine to coordinate with the design surface used by the steel fabricator. The contoured plywood sheets from the formwork were precut and shipped to the site, already coordinated for the contractor to assemble. In order to adjust to small variations between the design model and the steel erected on site, the contoured wooden formwork was modified on site to match the as-built construction conditions precisely.

OLYMPIC DIVING PLATFORMS, LONDON 2012

Zaha Hadid's design for the diving platforms in the 2012 London Olympic Games used a combination of digital tools to go from design to fabrication. The project team consisted of Zaha Hadid Architects, Arup Engineers, Cordek Concrete and Balfour Beatty Civil Engineering / A J Morrisroe Conctractor. The six diving platforms rise gracefully out from the edge of the pool and cantilever over the edge of the water. To create the platforms, a 5-axis CNC machine was used to carve the form into blocks of expanded polystyrene (EPS) to within 10 mm of the finished surface. They were then sprayed with a high-density polyurethane foam and machined again to within .5 mm of the finish surface and coated with resin and primers, which were finished to the final polished surface. Once the platforms were created in foam, they were coated in a concrete resistant gel-coat and layered with woven and non-woven glass fiber. 18mm ply ribs were added for stiffening and coated with further layers of glass-fiber. Due to the double curvature of the platforms geometry, traditional formwork fabricated from wood or steel would not have been feasible. For efficiency and optimization, the platforms were designed with several repeating modules so that formwork could be reused for multiple platforms. The platforms were precast off-site and brought into place under tight construction space with the walls and roof of the facility already in place. The steel reinforcement bars were also coordinated in a 3D environment to allow Cordek to position the reinforcement at precise locations and ensure that the final heights of the platforms, considering long-term deflection of the concrete, would adhere to the stringent criteria of the Federation Internacionale de Natation (FINA).

2.04 EXTRUDED ALUMINUM AND SHEET METAL SYSTEMS

Aluminum is one of the most widely used materials in the manufacturing industry, from automotive design to buildings. Aluminum can be produced into many

ALUMINUM EXTRUSION:
Detailed aluminum extrusions can be achieved using higher strength aluminum alloys.

Figure 30: Aluminum Extrusion Curtain Wall Glazing Components

CNC MILLING:
CNC milling quality depends highly on the material selection and milling settings (speed, bit, material thickness and rotation speeds)

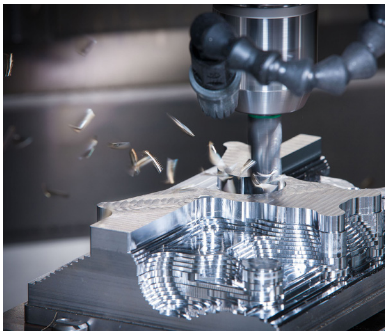


Figure 31: Aluminum Slab Milling

forms including rods, T-Ingots, extrusions, sheets, slabs and more. As one of the most abundant sources of alumina, Bauxite is a solid red clay that contains about 30-50% of alumina. Bauxite is chemically treated to remove impurities for the production of alumina, which is then transformed to aluminum by electrolysis. The aluminum is then dissolved in molten cryolite before the high electric current is run through the alumina-cryolite at 1000C to separate the pure aluminum.

Aluminum is a soft material and structurally weak, which is why it is often combined with other metals to produce alloys of varying strengths and hardness. Some of the most common mixes include magnesium, silicon and manganese for achieving lightweight products that can be formed into various forms. These are cast, extruded, rolled and formed using various machine techniques to produce structural and finished qualities. Structural aluminum alloys can be made stronger through heat treatment but can also be more expensive to produce.

Aluminum can be cut, formed, drilled, welded and more, with casting often producing the most structurally effective products. The extrusion process is typically done with aluminum billets that can come in various sizes. These billets are then preheated to 400-500C and extruded through a profile shape with a force between 1600 to 6500 tons depending on the alloy and detail formed by the die. The desired extrusion profiles can be highly complex with significant degrees of detail and finish qualities. The extrusion process can range from 5 meters to 80 meters per minute, which is also driven by the level of detail and alloy selection. Extrusion techniques are one of the most widely used for this reason and are highly effective in building and facade systems.

Sheets or solid slabs of aluminum alloys are also suitable for machining. Using CNC milling, laser cutting, water jet cutting and sawing methods makes aluminum extremely versatile for designed applications. The right selection of materials for the tooling is critical when working with tougher aluminum alloys. The method of tooling also depends on technique and form. CNC milling requires specific drill bits to be utilized depending on the desired outcome and drill speeds also affect the quality and accuracy of the final product. In certain cases, where the alloy is harder to work with, fluids can be required to keep the machining from overheating the aluminum causing it to melt and produce imperfections.

Laser cutting of aluminum sheets is also a widely used technique but poses challenges due to the material's reflectivity and its low melting point. The mirrored surface of aluminum can cause the beam to be reflected, damaging the lens and sensitive instruments. For this reason, pure aluminum is seldom cut with laser beams. The laser cutting process uses a focused beam together with gas to achieve accuracy. The laser beam itself is generated through a resonator which is delivered through the nozzle after going

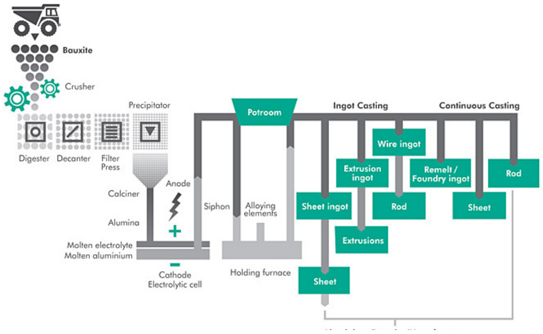


Figure 32: Aluminum Production Process Diagram

Figure 33: Aluminum Laser Cutting

through a series of mirrors. The focusing device usually consists of a zinc-selenide lens or a parabolic mirror which focuses the beam at a converging point. A power density of more than 107 W/cm2 can be achieved at the convergence point by defining the focal length or distance from the optics delivering the beam. The parameters affecting the accuracy and quality of the cutting can be attributed to the following; pulse frequency, type and pressure of cutting gas, diameter and type of nozzle, distance of nozzle and cutting material, focal length, focal position, cutting speed, acceleration, material thickness and laser power.

2.05 STONE SYSTEMS

Buildings have made use of stone throughout history. As a natural material, stone can be sourced throughout the world and exists in a variety of types. It is known for being highly durable and is mostly used in applications that require long lifespans and little maintenance. The structural properties of various stones also make stone high in compressive strength but weak under shear forces. The table in Figure 36 shows the different weight and structural properties of stones commonly used in building applications.

The extraction process for stone begins at large quarries where abundant sources can be found. By drilling and cutting using diamond tools and iron wedges. The stone is then extracted into large blocks and transported for manufacturing of smaller units or slabs. CNC waterjet cutting technologies make it possible to carve stone wth a high level of detail. Waterjet cutting uses an ultra-high pressure jet of water with abrasive material to cut through hard materials. The pressure delivered by the nozzle can range between 40,000 psi to 100,000 psi capable of cutting stone and metals. With the advent of multi axis CNC machines, water jet cutting technologies have advanced significantly with the ability to sculpt entire 3D forms using robotic systems.

Stone has two major applications in construction; as a continuous sheathing where it is supported by a substrate or as a backing wall where it is point supported. Although stone has a high compressive strength, using it for its structural properties can be increasingly expensive. As a result, stone is most used in finishes and external applications. Stone can also be finished and polished to achieve unique aesthetic qualities using machining and chemicals.

Recycling for stone usually takes place through either reuse of existing elements with minor treatment or as reconstituted stone. Reconstituted stone is crushed stone that is then cast into a mold from which it can be reused as a finishing material. The structural application of reconstituted stone typically uses steel reinforcement for adding higher strength. This recycling method gives stone a high LCA rating because of the

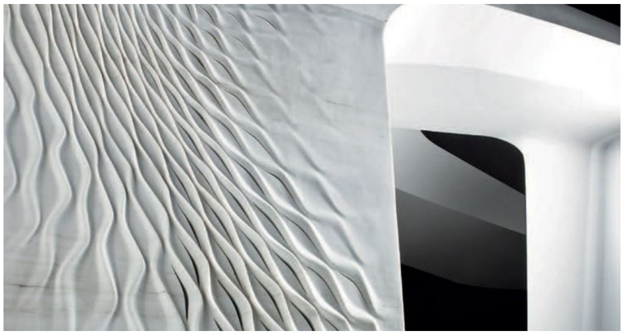


Figure 34: Waterjet CNC Fabricated Stone Wall Design by ZHA

Figure 35: Granite Quarry

longevity and EOL potential in future uses. Reclaimed stone is often used in paving and other construction applications that require durability.

The most commonly used stones are granite, limestone, sandstone, marble, slate and basalt. These natural stones have high compressive strength but are weak in tension. Each can be found in varying colors and textures.

Stone in cladding systems requires the consideration of several factors including, gravity, seismic and wind loads. Facade applications rely on metal structural supports for fixing the material in place. Using brackets and dowels with specified joint widths, the cladding can be made to appear as a continuous surface or have the divisions emphasized. The brackets and dowels are supported by a continuous frame or substrate supported by a concrete or metal structure.

While stone can be manufactured in large sized, its facade applications are typically constrained to 1 m x 11 m, dependent on the type of stone and the processing techniques.

In cladding applications, blocks are most commonly sliced to a thickness of 3/4 in (2cm) or 1-1/4 in (3cm). This is accomplished using circular blade saws, diamond wire saws, gang saw with steel shot or a splitter. Naturally exposed products can have a rough face for a desired natural look with only the backside sliced flat or finished through secondary cutting and polishing.

Figure 36: Stone Water Jet CNC Fabrication

STONE	WEIGHT lb/cu. ft	STRENGTH lbs/sq. in
Granite	165	13000
Basalt or Trap	185	12000
Limestone	160	7500
Sandstone (stray)	140	5000
Slate	175	10000
Marble	170	7500

Figure 37: Granite Properties Data Sheet

Figure 38: Landesgartenschau Exhibition Hall, Stuttgart University, Professor Achim Menges, Image by Roland Halbe

Figure 39: Kuka robot cutting a plywood panel for the Landesgartenschau Exhibition Hall

03

Looking to proven approaches that exemplify innovation in the practice of architecture

HOLISTIC WORKFLOWS

BUILT PROJECTS USING ADVANCED DIGITAL TECHNIQUES TO COORDINATE FROM DESIGN TO FABRICATION

SECTION 03 |

EXEMPLARIES

3.01 FONDATION LOUIS VUITTON

PARIS, FRANCE

Gehry's firm is one of the most prominent design practices in the field of Architecture when it comes to designing and building complex structures. The relationship between the material and the digital is intricately interwoven as a part of the process but also as a part of the culture of design. Maintaining a degree of flexibility through materials and craft is paramount in discovering new forms and ways of expressing material qualities. The fabrication process and digital environment are a part of the same space both physically and methodologically, with an equal amount of effort dedicated to these domains. There are physical models dispersed throughout the office, models ranging in materials from aluminum to different types of wood. The process of making and designing is an iterative dialog between the computer and the physical models, operating on the material and digital simultaneously. The firm without a doubt maintains this duality because of the need to manifest complexity while keeping the expression of the physical qualities of their models as they transition to the digital and eventually construction. This relationship with the material enables the office to evolve the language of form and technical solutions continuously. Discovering new ways of bringing materiality into the digital and the other way around is embedded in Gehry's' practice.

Figure 40: Fondation Louis Vuitton, Paris, France by Gehry Partners

1

PROJECT DATA

Project:	**Fondation Louis Vuitton**
Location:	**Bois de Boulogne, Paris, France**
Architect:	**Gehry Partners**
Site Area:	**1 ha**
Project Area:	**11700 sq m**
Project Year:	**2014**
Engineers:	**Setec Batiment**
Facade:	**RFR/TESS**
Consultant:	**Gehry Technologies**
Sustainability:	**S'Pace; Terao**
Manufacturing:	**UHPFRC**
Contractor:	**Vinci**

As advances in the building industry have taken place so too has Gehry's' ability to evolve the complexity of his designs. Through interdisciplinary partnerships with various experts, the ideas have been able to continue evolving. Developing solutions in tangent with advances in other industries has been a key factor toward accomplishing increased complexity. Bringing in new ideas, whether they be from the academic, research or professional domains, injects new virtuosities into the practice. The need to invest in new ideas is true for many notable firms that compete in a world where art, technology and the sciences continue to

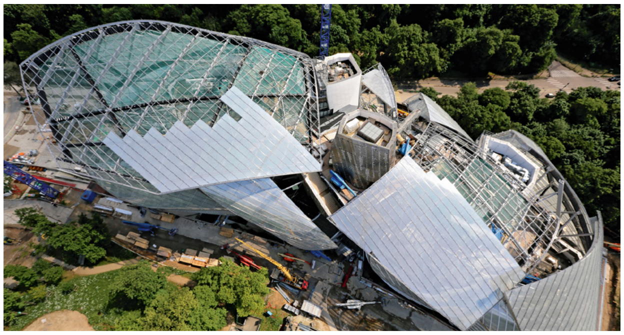


Figure 41: Fondation Louis Vuitton Glass Panel Installation

Figure 42: Fondation Louis Vuitton Glass Sail Frame Construction

find new points of convergence.

In 2006 it was officially announced that Frank Gehry would design what would be one of the most artistically expressive buildings of our time. The Fondation Louis Vuitton took nearly 14 years to complete with eight years of research and development, and six years of construction. The result was a testament to design and engineering accomplishments made possible through technology and materials research. Situated in the Bois de Boulogne park on Avenue du Mahatma Gandhi in the Jardin d'Acclimatation, the museum would be comprised of 11 galleries, a 350-seat auditorium, a restaurant named after the Architect and multiple public spaces, with a total of about 3,850 m2 of exhibition space. This undertaking began with inspiration from 19th-century glass Architecture such as the Crystal Palace and Grand Palais in Paris but also building on ideas that Gehry has been working on throughout his life. This vision that would attempt to achieve a synthesis of light, motion, space, and materiality into a singular experience produced an engineering challenge that would bring together a fleet of skills and knowledge.

The Fondation Louis Vuitton covers an entire area of 13,500 m2 with about 7,000 m2 of usable space divided into two levels and reaching a height of about 46m. Located at the center is the "Iceberg", containing the major part of the galleries and spaces, but is also the main body of the building which is made of reinforced concrete, clad with approximately 16,000 ceramic tiles. Each element having a unique geometry to capture the complexity of the form and facets accurately. The building is surrounded by a superstructure which anchors into the "Iceberg" for support, made of steel, timber, and curved glass. This structural framework supported 12 sails with a span of about 30m each and comprised of 3,600 glass panels in total.

Despite the size of the project, the magnitude of its complexity employed more than 800 people at its peak working simultaneously during the research and study phases. The need to continuously come up with new solutions to the challenges of Gehry's' design meant that all teams had to come together and even relocated so that they could work in the same space to collaborate in real time on the complex issues of the numerous building systems.

Using a single platform for a design meant each team could integrate knowledge and information from every discipline and trade involved. By bringing all of the information provided by every trade into CATIA the development and refinement of each component could be coordinated within a single master model but also organized by discipline and trade. A master model which would start with design drivers and gradually transition into a high fidelity model and a

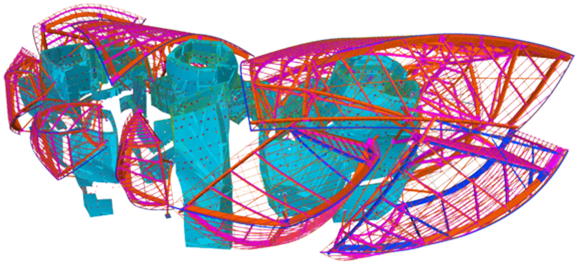


Figure 43: Tekla Structural Model of FLV Sails

Figure 44: FLV Glass Sail Mock-Up

single source of construction information for the entire building.

To understand the profound impact digital technologies, have in the process of making, we must abstract the concept of differentiation. Since the materialization of certain components can be specified and generalized at the same time. Each technical solution has degrees of variability so that its purpose can be maintained within a given context. This is most true when it comes to working with structural elements that are initially specified to solve a number of problems but must adapt to their given context. Adaptation then results in variability, provided that the solution be general in nature, for example, a mechanical connection which brings steel and timber elements together to form structural stability. If its goal is maintained then, each element can be made unique, able to maintain a number of performative constraints and still be traced back to an initial state of purpose. In this frame of thought, systems, assemblies, and whole structures can be made up of a finite number of differences but grouped into coherent frequencies.

The complexity realized in the Fondation Louis Vuitton takes these notions of geometric complexity and reduces the language of the digital to constructible projections which rely on other disciplines to inform and detail. With the Architect working to drive disciplinary and construction knowledge into the design, a process is developed where a higher understanding of fabrication and construction constraints live in the same digital environment. Digital technology in this approach becomes the mediator between an idea and its informed realization. Allowing the Architect to push design limits in a way that is constantly informed by the processes of craftsmen, fabricators, and digital designers but also allowing the same digital technology to analyze and simulate physical behaviors. This represents a methodology which can be traced back to the beginning of this building from the conceptual stages, when the first sketches were made and digitized into geometrical drivers, all the way through construction.

The Fondation Louis Vuitton's design presented the project teams with the complex challenge of solving structural, fabrication and material limitations. Along with these difficulties, there was also the preparing of construction documentation, producing a logistical strategy from transportation to lifting members on the site and at the same time scheduling and tracking the hundreds of thousands of elements. The only way Gehry Partners and the other teams would be able to meet these challenges was through the use of CATIA, the same technology used on many of his projects including the Guggenheim in Abu Dhabi, the Battersea Development in London and the Walt Disney Concert Hall in Los Angeles. By having every partner in the project adopt this technology, the design team could work in close collaboration with the many teams

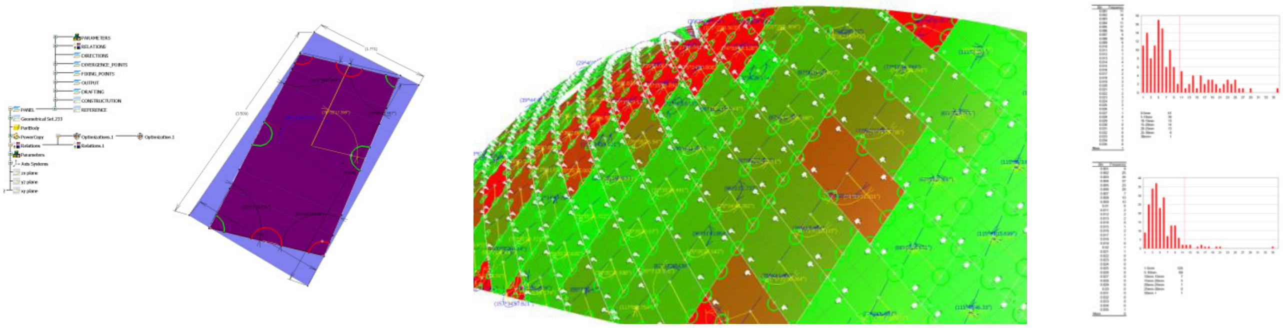


Figure 45: FLV Curved Glazing Automation, Parametric Instantiation and Frequency Analysis

working through the life of the project, including, the research and development team, the fabrication, construction team and the many consultants.

Moving from the top down, the "sails" were made up of steel columns and timber beam "tripods" which held up the long-span larch glulam beams and carbon steel truss assembly. Structural members varied in every way conceivable, spanning between 3m to 35m long and shaped uniquely to capture the form of the sails. The structural timber beams were attached with duplex stainless steel inserts

The 3,600 glass panels, which form the roof "sails" contain a total of 13,300 m2 of glass area, each with its bending radii between near flat to 3m and orientation. A lot of research and development went into the fabrication of these glass panels, most of which was focused on running penalization routines and developing formulas for discretizing each "sail" through material and performance constraints. The analytical process for these elements took place within CATIA, using scripting and automation tools that were developed specifically for this project. The digital process made it possible to run through various iterations and continuously feed constructability feedback back into the process of tool adaptation. The glazing sheets were all made up of 6mm (0.24in) tempered glass, a 1.52 mm (0.06in) interlayer and 8mm (0.31in) tempered glass, with the 6mm panel covered by a reflective coating and a 50% opacity white frit on the internal side.

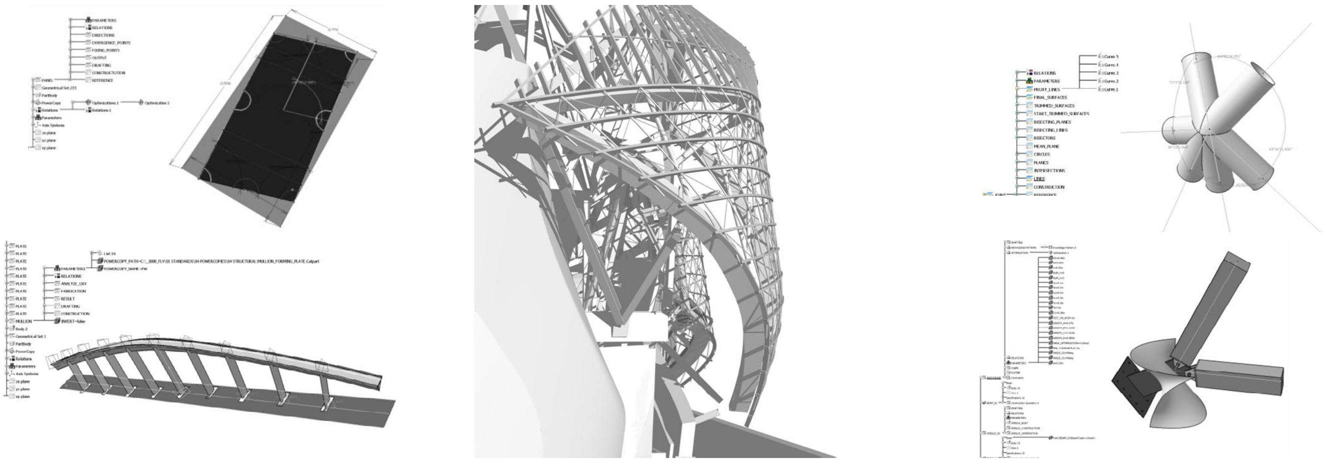


Figure 46: FLV Parametric CATIA Components for Glass Sails (Left) & Structural Model Templates (Right)

Taking all of these variables into account, the digital model was utilized to generate data that would then be used to achieve specific radii through a CNC cylindrical glass bending machine. The limitation was that the machine could only perform cylindrical molds which then led to the optimization of each panel through a cylindrical glass optimization routine. Together these cylindrically molded panels would achieve the illusion of a freeform surface made of glass. By using CATIA to perform optimization's, a parametric component was defined with multiple parameters including geometrical, material and installation constraints along with local surface deformation outputs. Once the local surface deviation was analyzed, there could be a global surface optimization highlighting global deviation but also producing frequency results that would be used to instantiate from a group of families with varying curvature. Together these techniques produced a high amount of complexity in a coordinated model, resulting in the finalized Fondation Louis Vuitton Museum.

Figure 47: DDP Exterior Photograph

2

PROJECT DATA

Project:	**Dongdaemun Design Plaza**
Location:	**Seoul, South Korea**
Architect:	**Zaha Hadid Architects**
Site Area:	**65000 sq m**
Project Area:	**89574 sq m**
Project Year:	**2014**
Engineers:	**Arup**
Facade:	**Group 5F**
Consultant:	**Evolute**
Energy:	**Daeil ENC**
Sustainability:	**Soosung Engineering**

3.02 DONGDAEMUN DESIGN PLAZA

SEOUL, S. KOREA

The Dongdaemun Design Park & Plaza (DDP) is located in Seoul, South Korea and designed by Zaha Hadid Architects ZHA. It was commissioned as an urban redevelopment project to reinvigorate the surrounding downtown area. The site was previously home to Seoul's Dongdaemun Stadium, which had become obsolete in a part of the city which needed urban re-

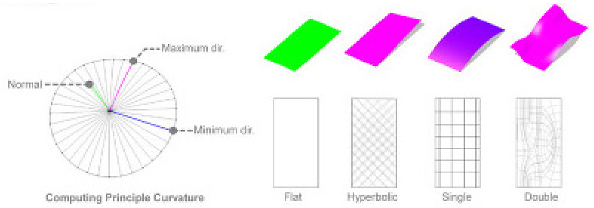


Figure 48: DDP Panel Type Optimization CATIA Model

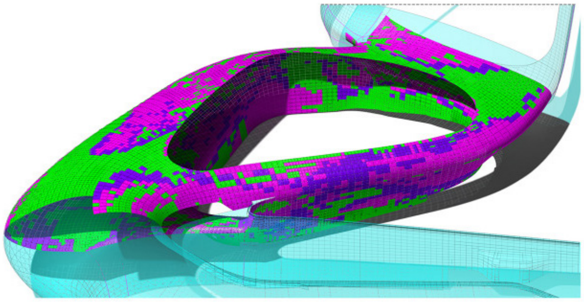


Figure 49: DDP Panelized Facade Type Color Coded CATIA Model

newal. The Seoul Metropolitan Government decided to demolish the Stadium and undergo the development of DDP.

The Dongdaemun Design Park & Plaza was comprised of 86,574 square meters of building area, a plaza and a landscape park which included art exhibition spaces, conference areas, design laboratories and a media center for the public. The entire facade of DDP was clad in more than 45,000 uniquely formed aluminum panels. The annex buildings that were part of the park were also designed using freeform geometries but constructed out of reinforced concrete, with a precision requiring cross sections at every 15 cm (Ghang Lee, Ph.D. and Seonwoo Kim (2012). The complexity of this project required the unique use of workflows not standard in conventional practice. A combination of computational tools, together with scripting techniques, analysis and fabrication logics embedded within the digital modeling environment. The techniques used, although utilized in other Zaha projects had to be tailored to DDP and were critical to the entire process.

Characterized by complex geometrical curvature, the facade of DDP had to go through advanced technical and computational methodologies in order to bring the project to life. The underlying form of the facade, is driven by topological continuity which captures multiple degrees of acceleration. With some areas curving in higher degrees than other, the design geometry was divided into a combination of freeform surfaces, ruled surfaces and flat surface geometries. The driving geometry was the basis for being able to classify each surface type. The challenge was to translate the underlying formal intent into a constructible language which could take material, manufacturing and cost constraints and drive them into the digital modeling process.

The facade of DDP had to go through multiple optimization and subdivision routines in order to come up with viable fabrication technique. Specialized panelization tools had to be developed in order to divide the complex geometry into manageable sizes that were informed by manufacturing limits. Using panelizing techniques within CATIA allowed the design team to take the entire facade surface domain, discretize the surface into construction geometries which would inform the creation of panelization routines. The construction data was further used for the creation of parametric components, which could then be instantiated based on curvature analysis data. The curvature analysis investigations provided information that could be used to classify a series of panel types which included faceted, double-curved, single curved and flat panels. Once a classification of panel types based on the curvature were defined, the creation of intelligent panels could be automated using specialized scripting within the digital model in order to automate the placement of each panel. This resulted in a total of 45,133 unique panels, comprising of 21,738 double curved panels, 9,554 single curved panels and 13,841 planar panels.

The optimization of DDP's facade was a problem of computational rationalization, heavily informed by constructability constraints. The goals to be met were a combination of overcoming manufacturing, economic and time constraints. The rationalization process attempted to take this highly variable surface domain and minimize the variation of unique elements required to achieve the design intent. Numerous supporting elements were also a part of this rationalization process, affected by rationalization strategies that could meet the goals.

While forming technologies are well known and established for sheet metal in aerospace and automotive industries, the economies of scale make certain solutions such as solid die forming technologies very expensive for building facade applications. The technology developed for the manufacturing of aircraft panels, known as Digitally Adjustable Tooling that uses multi-point FORMing or DATAFORM, was the solution adopted with minor adjustments for the facade of DDP. DATAFORM was funded by the European Commission as a research project that focused on competitiveness for manufacturing methodologies. The group responsible for the technology included several European partners, academic and engineering specialist working through R&D for 3 years to develop the instrument STREP.

This method uses flexible dieless forming and rapid positioning of multiple points controlled digitally to achieve any configuration. The design specifications of a design form are loaded into the operating system which controls the punch array, able to translate the CAD data into positioning points for each punch element or pin. The system can take in design specifications including material information which can be calculated for any deformation during the forming process. Together with FEA analysis, the surface behavior can be predicted prior to forming, to take into account possible defects in the resulting formed panels. The punch array additionally leaves small dimple-like dents where the punches push on the surface, but using an elastic membrane between the machine pins and the metal panel helped reduce the appearance of these dimples.

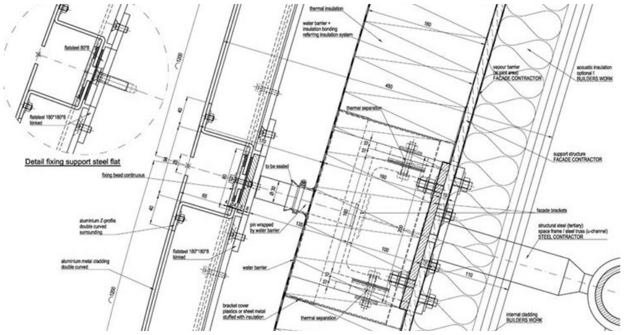


Figure 50: DDP Facade Detail ZHA

The final solution capable of achieving the desired result included a multi-point forming machine, press machines to clamp down the sheet metal as the forming took place and finally a multi-point press which would press down on the sheet metal once it had been formed to refine any imperfections. This multipoint stretch forming process had certain size limitations for the maximum sizing of each panel with double curved panels reaching 1200 mm x 1600 mm in size and maximum tolerances for edges between 0.8 to 1.6 mm. The spacing between each double-curved panel being 25 mm meant that the maximum deviation could be no more than 2 mm. With the total of 45,133 unique panels, precision and coordination had to be facilitated using some of the most advanced computational and manufacturing technologies.

Mock-Up tests provided the necessary validation of these methods in coordination with the underlying structure. The first mock-up took a section of the facade with the highest complexity, with panels exhibiting the highest amount of curvature. This mock-up was approximated and not computerized which resulted in fabricated panels failing to match the smoothness desired. In addition to this, the edges of each joint were not aligned or equally spaced, producing a large degree of imperfections. The second testing mock-up for this section of the facade was done through optimizing the surfaces into single curved panels. The multi-point forming method was used to produce these single curved panels resulting in smooth surfaces and the required joint conditions.

The final mock-up after a series of test utilized a computerized multi-point stretch forming machine. With the capacity to bend the sheet metal in both directions by adding the upper multi-point press machine. So that as panels were bent from the pressure underneath the additional curvature required on double curved panels would be achieved using the upper press. These formed panels were then laser cut using a 5-axis robot arm. The ultimate cost of producing double curved panels using this approach was $260 per panel compared to a cost estimate of $7,000 per sq. m using conventional methods, with an average processing time of 15 for each curved panel.

The digital methodology played a major role in making the design, engineering and fabrication of the DDP facade. Analysis and parametric tools were essential to ensuring the constructability of each panel. Without the use of parametric digital technologies, it would have been impossible to produce this level of variability. Computational technologies provided an integrated approach, where material constraints and advances in manufacturing knowledge could be brought into the digital environment for achieving constructability.

Figure 51: Barclays Center Exterior Photograph

3

PROJECT DATA

Project:	**Barclays Center**
Location:	**Brooklyn, New York**
Architect:	**Shop Architects**
Project Area:	**675000 sq ft**
Project Year:	**2012**
Engineers:	**Thornton Tomasetti**
Facade:	**ASILimited**
Consultant:	**SHoP Construction**
Facade Steel:	**Admetco / Dissimilar Metal Design**
Manufacturing:	**UHPFRC**
Contractor:	**Hunt Construction Group**

3.03 BARCLAYS CENTER

BROOKLYN, NEW YORK

The Barclays Center Arena is located in Brooklyn, New York, designed by SHoP Architects and commissioned by the developer Forest City Ratner Companies as a major phase in the redevelopment of the Atlantic Yards. The Barclays Center is a multi-story 670,000 sq. ft. multi-purpose arena with 18,000 seats, 105 suites, public concourses, courtside areas and an adjacent basketball facility. The site occupies a wedge-shaped portion of the 22 acres redevelopment zone and is defined by two major intersecting streets, Atlantic and Flatbush Avenues.

The arena layout was inspired by Ellerbe Becket's Conseco Fieldhouse as a departure point for the interior functions. SHoP's design re-imagined the internal elements together with a facade that wrapped the entire complex as a series of continuous bands. The facades continuous geometrical drivers were clad with an array of unique panels, which would surround the entry canopy lifted 30 feet above the ground plaza.

The facade is made up of 12,000 uniquely sized pre-weathered steel panels covering 85 percent of the entire exterior. The material selected for the panels was A588 steel because of its ability to produce a corrosion-retarding layer on its own, eliminating the need to paint or finish them. These panels were supported by 950 large assemblies (5 feet wide and between 10 to 40 feet tall). These assemblies also included the supporting steel sub-structure, which varied between 18 inches to 5 feet in depth, the curtain wall panels, and glazing units. These assemblies were all prefabricated, transported and installed on-site as a unitized system. This entire design to construction process was made possible through specific digital methodologies which incorporated a high level of detail and manufacturing intelligence within the 3d model.

Designing the complex geometry and turning that surface model into an array of complex assemblies meant that SHoP had to utilize advanced digital tools like CATIA. The design geometry was initially created in Rhinoceros to achieve the formal intention but was eventually migrated to CATIA where the design geometries would undergo optimization routines and refined for more detailed model development. SHoP worked closely with their affiliate, SHoP Construction to take on the fabrication modeling side of the project. Their close relationship with the designers and fabrication team enabled a higher degree of flexibility but also reduced the redundancies that normally take place during design development, construction documentation and fabrication phases.

Figure 52: Barclays Center Canopy Structural Framing Photograph

The use of CATIA allowed SHoP Construction to develop parametric models of the assemblies and the 12,000 unique panels with unfolding tools for describing each panel and laying them out on the suppliers 3/16 inch meal sheets which measured about 60 inches in width. These layouts were then used to maximize the material efficiency and output. The digital model was not only used for the fabrication process but also served as an erection tools for sequencing the assembly process and coordinating the many components associated with the entire facade.

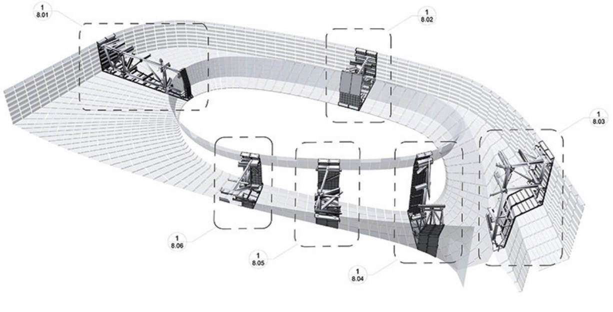


Figure 53: Barclays Center Canopy Assembly Diagram

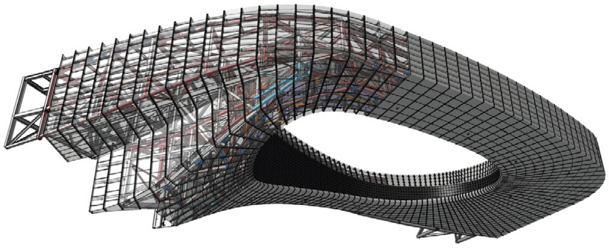


Figure 54: Barclays Center Canopy CATIA Structural/Assembly Model

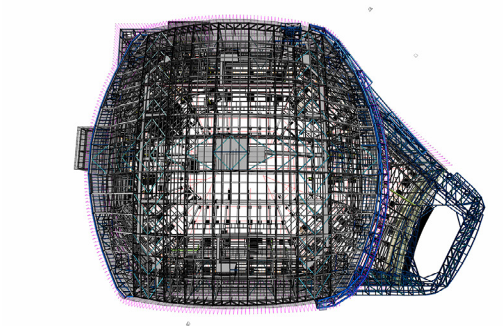


Figure 55: Barclays Center Enclosure CATIA Model

The model also incorporated additional information about the panels and system such as panel weight, fabrication constraints for curvature and tolerances needed to achieve the desired effect. The panels were then fabricated using CNC cutting and bending machines which relied on the data directly exported from the digital model. In order to achieve the corrosion effect, the panels were then run through an accelerated weathering process, which put them through 12 - 16 soaking and drying cycles a day for more than three months.

DIGITAL WORK-FLOWS AND INTEROPERABILITY

SHoP Architects together with SHoP Construction worked with Dassault Systemes CATIA (3D Experience) for its ability to bring together an integrated fabrication and coordination model. Although the design team began with a simplified version of the design geometries in Rhinoceros, the decision to utilize CATIA came early in the design phase. By using the parametric capabilities of the application, SHOP developed intelligent components for each element in the facade system. The use of engineering templates was an effective way of capturing element types within a single setup that could adjust and adopt local constraints when instantiated globally. The detail development could take place in phases, with higher fidelity engineering templates being developed at later stages in the process and additional constraints embedded into the model.

Automation played a key role in the modeling of the thousands of parts that had to be modeled. Using automation tools within CATIA such as Knowledgeware, the designers were provided with the tools necessary to write knowledge patterns and actions for generating construction geometries which would be the support elements for the assemblies and their components. This kind of automated work flow is also known as skeletal modeling, where the elements required for detailed components are generated through scripts

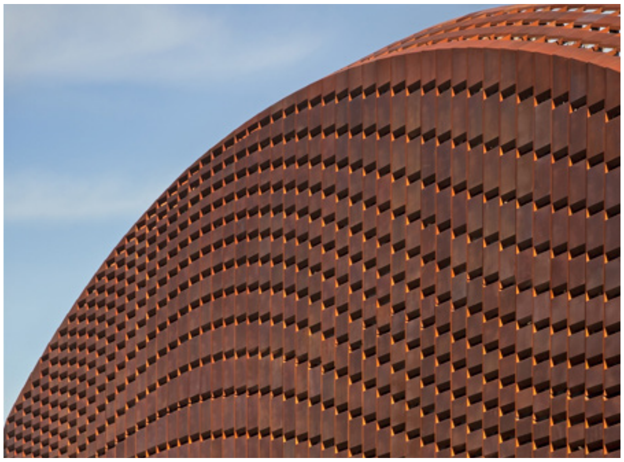


Figure 56: Barclays Center Facade Closeup Photograph

and algorithms, but can be adjusted using control variables quickly and effectively. As these scripts are run, the contained supported elements then propagate through the model updating every part in order to iterate through the multiple design options. This kind of flexibility allowed SHoP to look at the impacts of numerous design options and their associated costs.

STRUCTURAL ENGINEERING & DETAILING

The design of the facade resulted in an estimated 230,000 sq. ft. of the weathered steel panels with a total cost of about $30 million. By digitally laying out the fabrication models and simulating the CNC process, the area of material used was optimized to 15,00 sq. ft. CATIA offered the capability of exporting CNC code directly from the laid out models eliminating the need to translate information through other platforms.

The structural engineering for Barclays was provided by Thornton Tomasetti which included steel connection details and the erection engineering logistics. The detailed models they provided were delivered in Tekla, which contained a complete detailed design for adaptable conditions. These models helped inform the parametric modeling process and minimized the required material for structural performance optimization.

Thornton Tomasetti also provided support for the arched roof made up of a two 350 foot tied arch trusses spanning across the longest direction of the arena. The lateral system and diaphragms were specified to resist both thrust forces from the roof arches and minimize the tension on the arches by ties. The entire superstructure which supports the facade system was also designed and specified by the engineer to reduce noise from the surrounding traffic.

The outcome of this project delivery method resulted in streamlining the fabrication and installation phase. Rather than delivering detailed construction documents to the contractor, SHoP was able to bypass this by engaging the entire team with advanced modeling techniques and ensuring the constructability of the entire facade in the manufacturer’s shop, producing assembly diagrams for execution. The laser scored elements added additional control by clearly labeling how and when components would come together. This process is just one example of SHoP’s attempts to transform the way practice and technology are integrated into the design to construction process.

Figure 57: ARTIC Construction Photograph

Figure 58: ARTIC ETFE Enclosure Close Up Photograph

2

PROJECT DATA

Project:	**Anaheim Regional Transportation Intermodal**
Location:	**Anaheim, California, USA**
Architect:	**HOK**
Site Area:	**16 acres**
Project Area:	**67880 sq m**
Project Year:	**2014**
Engineers:	**Thornton Tomasetti**
Facade:	**Thornton Tomasetti**
Consultant:	**Buro Happold**
Contractor:	**Clark Construction**

3.04 ARTIC

ANAHEIM, CALIFORNIA

“What matters is not the enclosure of the work within a harmonious figure, but the centrifugal force produced by it.” -Italo Calvino

The Anaheim Regional Transportation Intermodal Center (ARTIC) serves as the nerve center of Orange County, California’s public transportation network. The three-floor terminal houses two platforms for train and commuter rail, 13 bus stands, taxi stations, bicycle racks, pedestrian walkways, nearby parking for 1,082 automobiles, and restaurants and transit-oriented retail. The 67,880 square foot terminal is iconic for its soaring catenary-shaped tubular steel diagrid structure with a 200,000 square foot ethylene Tetrafluoroethylene (ETFE) roof system. The complex structure was designed, fabricated and constructed in a coordinated effort of interoperable tools and digitally driven construction methods. The completed terminal represents a paradigm in contemporary building technology through the successful collaboration of designers, engineers, enclosure and geometry consultants, fabricators and contractors, and an educated owner. The project was completed in 2014 at a total cost of $188 Million, with $68 Million for the terminal. It is the winner of multiple awards. It won an AIA TAP/BIM Citation for Stellar Architecture Using BIM, an award from the American Institute of Steel Construction for Innovative Design in Engineering and Architecture with Structural Steel, Project of the Year Over $75M from the American Public Works Association Public Works, and is certified LEED Platinum by the U.S. Green Building Council. The project team consisted of HOK as the design architect, Parsons Brinkerhoff as the contract architect, structural engineering by Thornton Tomasetti, MEP engineering by BuroHappold North America, ETFE enclosure fabrication by Vector Foiltec, steel fabrication by Beck Steel, and construction by Clark Construction Group.

DIGITAL WORK-FLOWS AND INTEROPERABILITY

Paramount to the success of the project is its use of building information modeling (BIM) in the in the workflow for project delivery. Interoperability between the tools of the various team members was of the utmost importance in coordinating between the design, engineering and construction teams. The design team worked in a combination of Rhinoceros, Grasshopper, Custom Scripting VBA and ultimately CATIA to provide information and construction geometry for the building enclosure. Revit was used as an intermediary tool for combining information from the designers and engineers. A workflow from Rhino to Revit was used for architecture, AutoCAD and SAP2000 to Revit for structural engineering, and CATIA to Revit for the enclosure designer. Multiple energy, simulation, and fluid dynamics tools were brought into Revit for the MEP engineer. The construction geometry and the establishment of the Geogrid, a three-axis datum defining coordinates in space known as Geopoints, was hosted in CATIA where it could be scheduled as an excel file and given to the contractor. The contractor was then able to run clash detection between the various parties through the use of Navisworks. The most prominent design elements of the transit center, the complex steel form and ETFE enclosure, were designed and fabricated from the highly detailed BIM model created in CATIA.

STRUCTURAL ENGINEERING

The diagrid of doubly curved tubular steel arches was optimized for its structural efficiency and aesthetics. The geometry of the arched enclosure was defined by an algorithm describing a catenary curve then swept along an axis to produce a torus. The torus was then used as the base design surface for the diagrid structure, but also discretized into a series of sub-surfaces for describing the ETFE pillows. The geometrical drivers for the steel diagrid are established at intersections along the arched surface and two arrays of mirrored planes. The framework of points and arcs was brought into the structural model in SAP2000 for sizing structural members and analyzing internal forces, stresses, deformations and non-linear buckling. Thornton Tomasetti had to generate the structure in multiple formats for different needs, making interoperability between platforms especially important. Custom proprietary tools were used to exchange information, such as importing structural members from Rhino into Revit, or from Revit into Tekla for detailing the steel connections. In order to increase the efficiency of updating changes to the structural design, custom scripting was developed in CATIA to automate model changes to the thousands of components. This allowed for flexibility in the project, where elements could be controlled parametrically and globally updated.

ETFE ENCLOSURE MODELING & DETAILING

The entire enclosure for ARTIC was modeled parametrically in CATIA, with a system for taking the design geometry and extracting driving wires that could undergo iterative changes. Object oriented scripting and automation techniques in this setup were used to populate the 3,000 components that made up the ETFE enclosure. The metal extrusion retaining profiles were arranged at set distances normal to the design

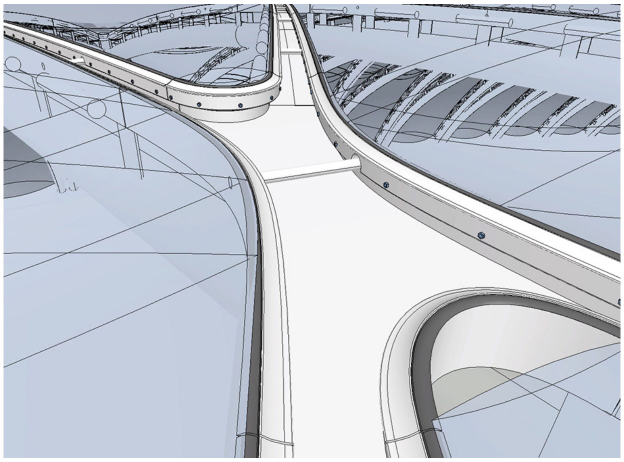


Figure 60: ARTIC intersection detail of aluminum tracks at ETFE system

surface, centered on each driving wire. The intersections then had to be treated uniquely, with intersection clamping components that would require custom fabrication specifications. Each of these nodal detail clamps were modeled in CATIA and delivered to the shop for fabrication with minimal modifications. CATIA provided the robust parametric modeling capabilities necessary for this project but also gave the designers assurance that model interdependencies were maintained throughout the enclosure and project. The complex structure was modeled in detail, giving a precise description of the interface and connections between the structural components, the building systems and the enclosure. Detail components from the many portions of the building, such as at the supports of the north curtain wall, were taken from the fabrication model and sent directly to a CNC milling machine to quickly and accurately manufacture the pieces. The tracks for the ETFE cushions and the intersection points were designed and fabricated to coordinate with unique conditions along the varying curvature of the doubly curved surface. Material quantities and profiles were also generated from the digital model to calculate the exact amount of steel, aluminum supports and the profile outlines of each of the ETFE cushions.

ERECTION SEQUENCING AND CONSTRUCTION

Having a comprehensive BIM model also allowed the contractor to plan and test for the sequencing of erecting the complex steel structure. This also allowed the steel fabricator to plan how to divide up the structure and plan how the members would be assembled and welded in the field. One critical factor in maintaining the precision necessary to fabricate the complex surface was the use of a Geogrid generated in Catia. Unlike the industry standard of locating geometry off of dimensions from column grids and the elevation from a floor level, the Geogrid was able to locate precise coordinates in space at points along the design surface, known as Geopoints. This allowed the fabricator to verify the exact requirements of the components and gave the contractor a necessary tool for assuring the accuracy of the construction.

Figure 59: ARTIC Steel Erection Photograph

PROJECT COORDINATION

Coordination for the project was achieved by importing the various design models into Navisworks to run clash detection between the enclosure and interior, between the mechanical, electrical and plumbing design models, and the structural systems. This allowed the contractor and architect to coordinate between the project team members efficiently.

RELYING ON THE MODEL FOR CONSTRUCTION

The BIM model was used extensively to verify the precision of construction. In a statement made by Clark Construction Group the contractor noted, "Due to the complexities of the project utilizing GeoGrid dimensions, it would be impossible to coordinate locations without a model. The fabrication of the structural steel was designed with complex compound curves and the only means to fabricate this material is by the use of a model. Once fabricated, the only means of erect with the tolerances was by using the Geopoints. The as-built model is the only way to accomplish this task."

APPLIED RESEARCH

THE APPLICATION OF SYSTEMS RESEARCH AND ADVANCED DIGITAL WORKFLOWS ON A DESIGN PROPOSAL

04

Applied research into pilot projects will provide insights toward future developments

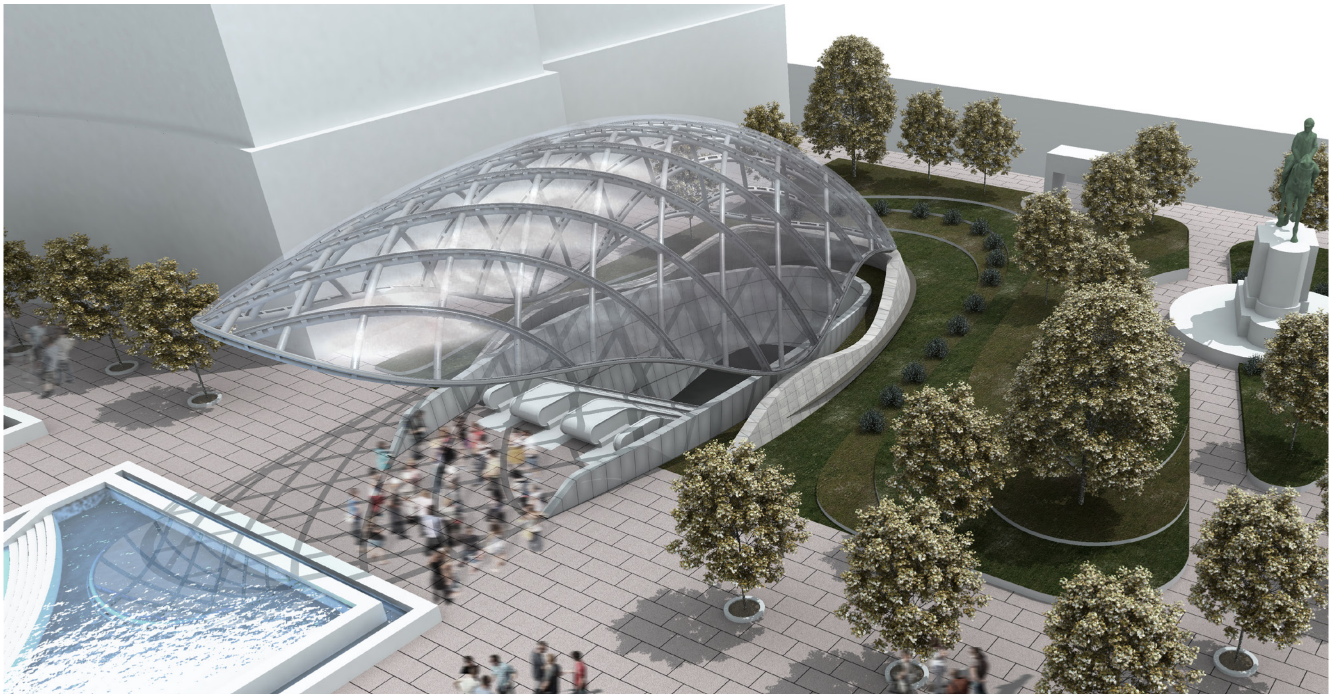


Figure 61: Pavillon de L’eau Model

SECTION 04 |

PAVILLON DE L’EAU

NAVY MEMORIAL/NATIONAL ARCHIVES

WASHINGTON, DC

The culmination of our research has been executed on a design proposal for a metro rail entrance canopy at the site of the United States Navy Memorial, adjacent to the National Archives in Washington, DC. The memorial, first proposed during the planning of the District by the French-born American architect Pierre L’Enfant, honors all past and present personnel of the U.S. Navy service. At its center, the memorial plaza is flanked by a series of cascading pools and fountains. Its northern edge is defined by two large neoclassical style mixed-use buildings, a market square, and its southern boundary is split diagonally from the National Archives by Pennsylvania Avenue. Just outside the southeast plaza fountain is the Archives/Navy Memorial station entrance taking thousands of commuters underground on a daily basis.

1

PROJECT DATA

Project:	**Pavillon De L’eau**
Location:	**Washington, DC, USA**
Architect:	**HKS**
Site Area:	**TBD**
Project Area:	**TBD**
Project Year:	**2016**
Engineers:	**SGH**
Enclosure:	**Vector Foiltec**
Consultant:	**Dassault Systemes**
Contractor:	**TBD**

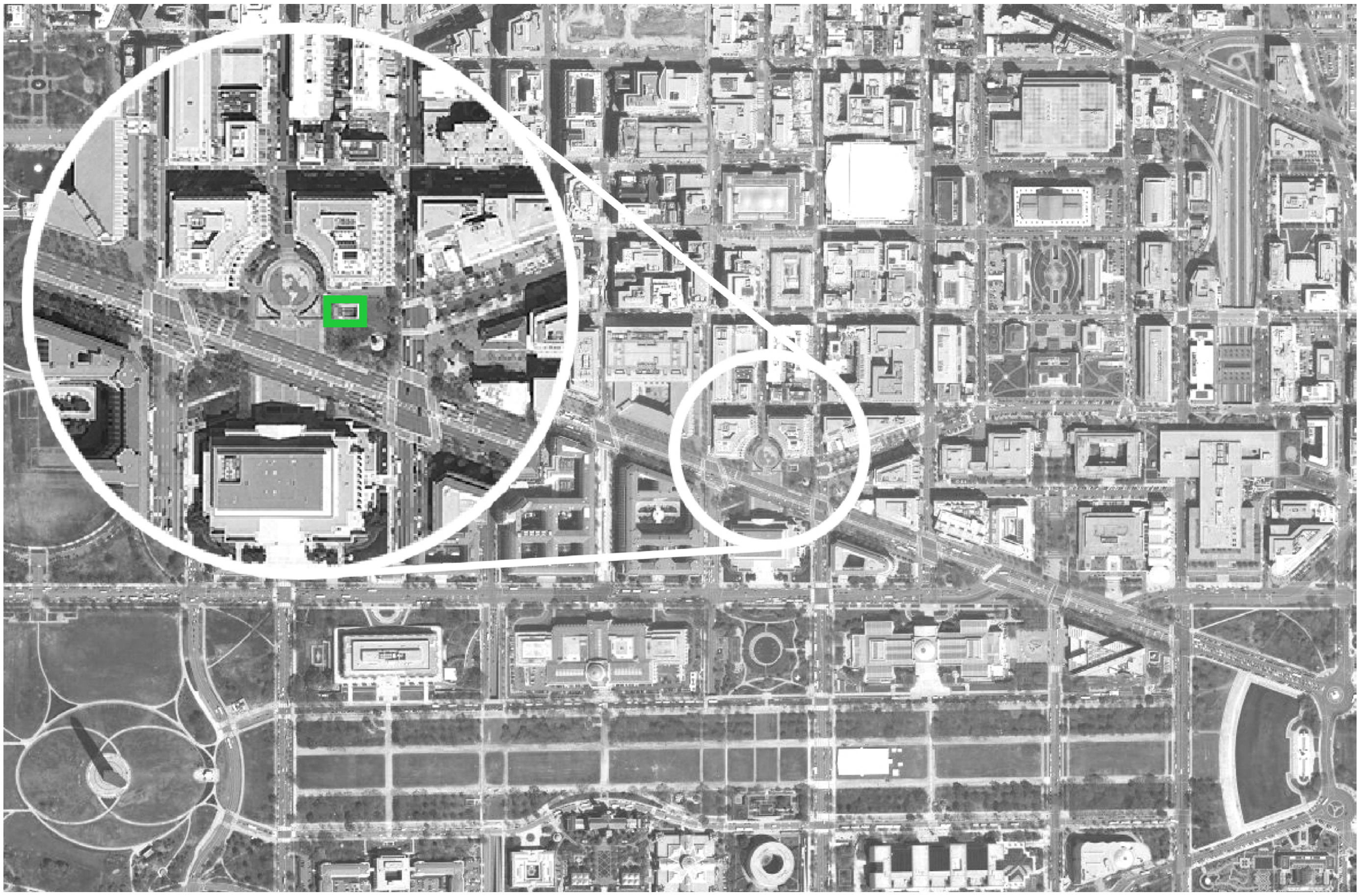


Figure 62: Site Plan of Navy Memorial / National Archives Metro Station Entrance, Washington , D.C.

Figure 63: United States Navy Memorial, Washington, D.C.

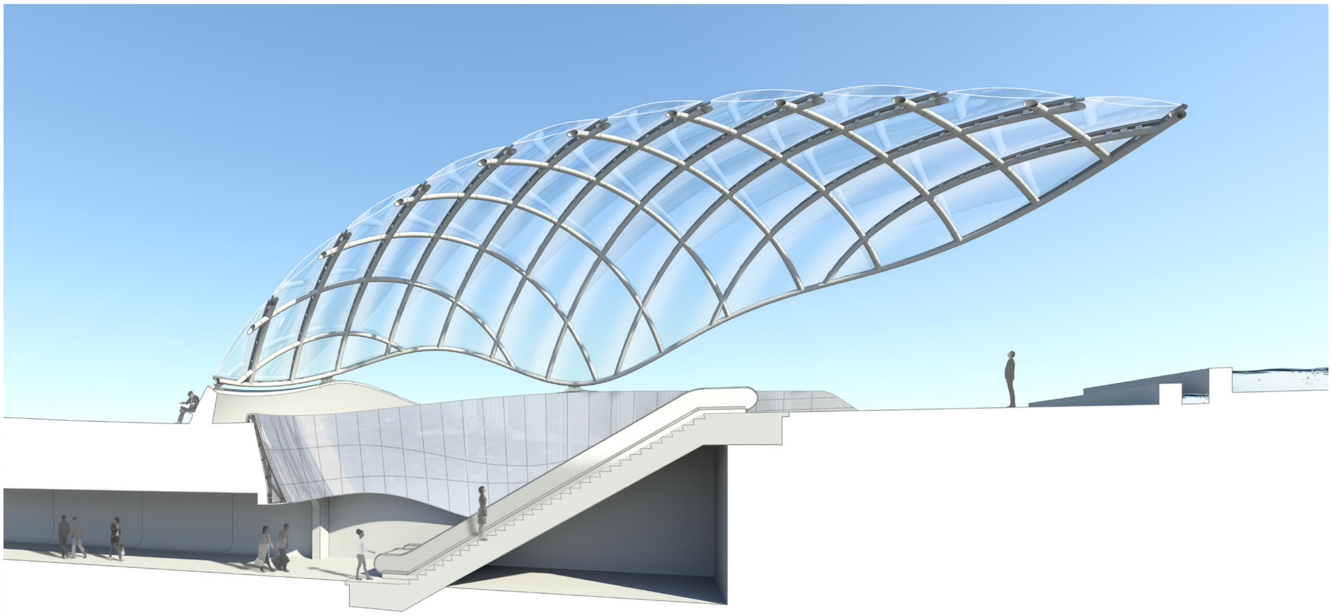


Figure 64: Pavillon de L'eau, Section Perspective

The Pavillon de L'eau, or Water Pavilion, seeks to encapsulate the spirit of the memorial while providing shelter and a prominent gateway to and from the site. Drawing inspiration from marine technology and the legacy of Navy engineering, our design attempts to establish an interplay between deep water biological form, structure and materiality. These inspirations gave nascence to the idea behind this project, but our vision was guided by the informed decisions provided through advanced digital methodologies. We began informing our ideas by material and engineering processes utilizing similar technologies used in naval design and engineering.

Engaging our partners at the early stages, we began by working directly with SGH Structural and Building Enclosure Engineers during the schematic stages. We used design technologies and methods which included parametric modeling, geometrical rationalization, LCA, and FEA to assess wind and snow load effects on our design. Our collaboration with SGH En-

1

INITIATION

Designing with parametric and computational modeling tools enables the fluid development of high degrees of variability and an iterative process as analytical methods validate the design.

2

MANAGEMENT

The tree structure is a way of managing and maintaining data across all parts and disciplines for controlled coordination and manufacturing processes. The model can be translated and packaged as a deliverable for processing without isolating the development of any part during design.

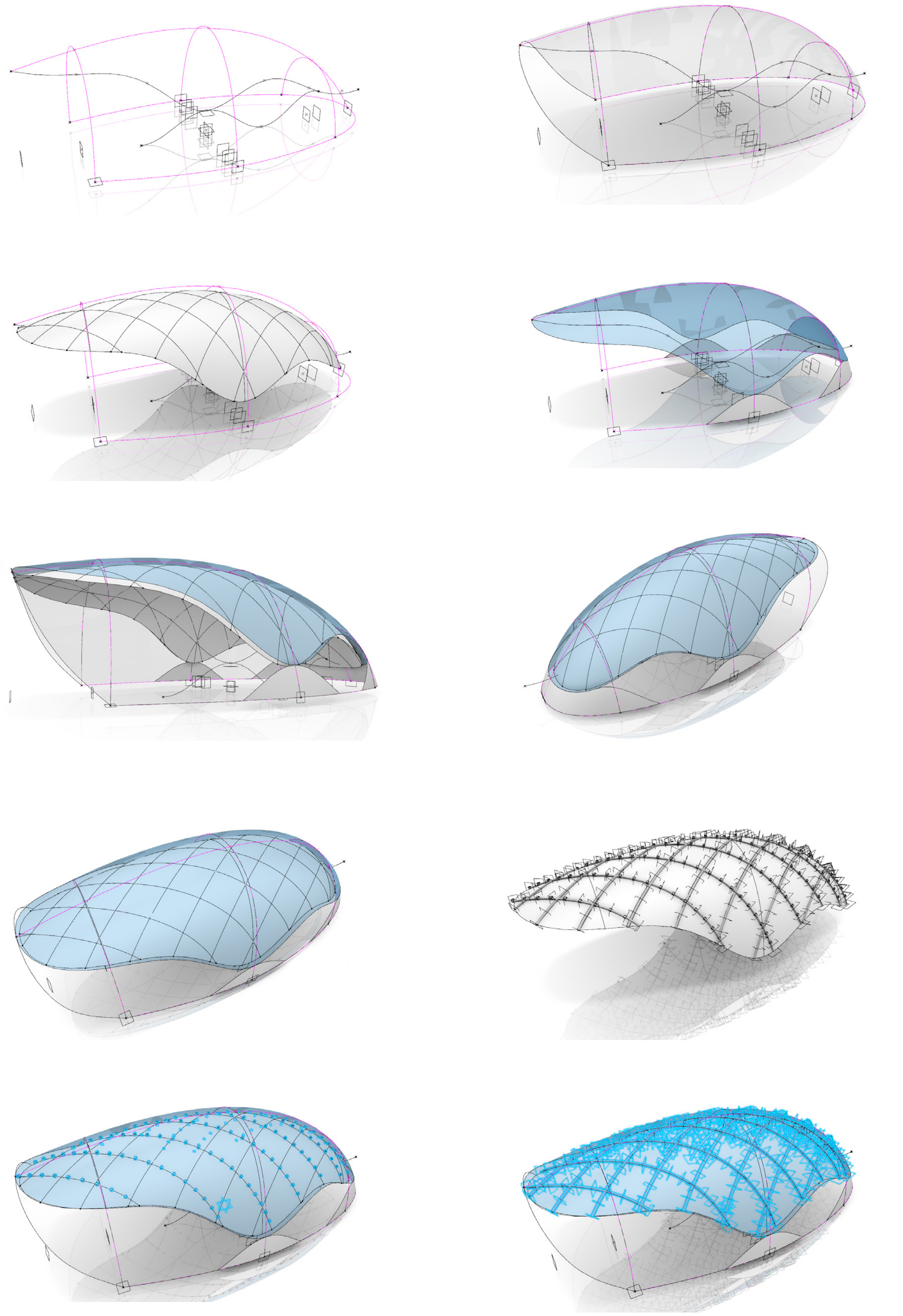


Figure 65: Pavillon de L'eau Model Process

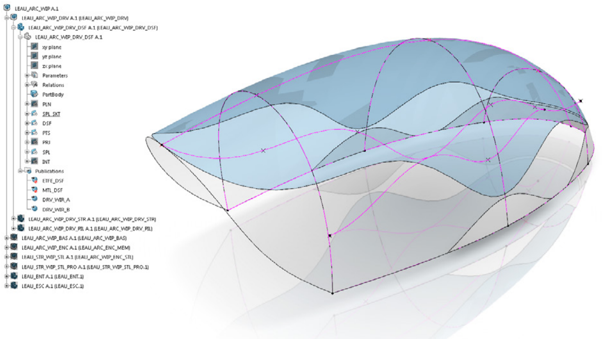


Figure 66: Pavillon de L'eau Construction Geometry Model

gineers and Dassault Systemes enabled us to digitally mock-up our design with a high degree of construction intelligence while maintaining the conceptual framework which began as a vision for re-imagining this icon for the United States Navy Memorial.

The form of the canopy is driven by five curves, starting at its base, the perimeter curve is shaped by an equation for a water drop and then manipulated to increase the span of the canopy. Their driving curves are then used to create a network surface which is parametrically controlled. The resulting surface provides the first surface geometry which then undergoes subsequent operations, dividing up the geometry into a series of zones for material expression and continuous differentiation.

The granite and stainless steel base rise out of the plaza, supporting the ETFE membrane arranged in waves of transparency, echoed by the fluid form of the lightweight steel structure, aluminum supports. The canopy rests at points along three main curves that embrace the metro entrance, while the western edge cantilevers high above and gently slope to its tip in alignment with the edge of the fountain below. The steel diagrid structure adds strength and beauty that complements the shape and movement of the form. Continuous ETFE pillows along the primary structural tubes of the diagrid give the asymmetrical canopy movement, bringing the eyes from the base to the outermost point and towards the memorial.

The interior surface wrapping around the opening of the escalators is formed in reaction to the canopy shape and panelized with stainless steel skin that responds to the form of the canopy and allows more light into the tunnel below. Wings from the stainless steel entrance wall rise out and extend out to channel visitors into the entry of the gateway. Alongside the stainless steel wall, a small walking path is left between the canopy base and the opening, guiding people around the entry opening with views of the freeform wall and canopy. The undulating granite base conceals the steel support within, revealing only the pin connections are touching at one point on both the north and south edges and three points along the eastern base. The surface of the base blends with the form of the canopy while allowing the ETFE cushions of the enclosure to be elevated for protection.

The structure of the canopy is composed of an architecturally exposed steel diagrid, consisting of a 14" round tube at the perimeter and 12" primary and secondary tubes forming the interior grid. Aluminum up-stands for ETFE pillow attachment are regularly mounted on the steel tubes. The grid spacing has been optimized to balance the weight of the steel structure with the ideal span of the ETFE cushions enclosing the structure.

4.01 COLLABORATION

When following a holistic approach from design to fabrication, the unique requirements and processes of the fabricator must be considered. Methods of digital translation, optimization, and engineering vary from fabricator to fabricator, even within the same type of building assembly. A clear understanding of what the fabricator expects to receive from the designer, whether it be a highly detailed construction model, points, and lines describing a geometry, or simply a spreadsheet of data points, the designer should create a thorough work plan with clear deliverables. If a single fabricator has not been determined at the onset of design, the designer should create a workflow that can accommodate each acceptable manufacturer without the need to rebuild the design model once a fabricator has been determined.

Equally important to determine are the design criteria associated with a system or fabrication method. Required spacing, dimensions, and profiles, tolerances, bending capacity, material limitations, and system interfaces should be understood to inform design decisions for performance and aesthetics.

PAVILLON DE L'EAU COLLABORATORS

Collaborators in our case study for the Pavillon de L'eau include Simpson Gumpertz & Heger for structural engineering and building technology, Bird Air and VectorFoiltec for ETFE enclosure systems, A. Zahner Company for metal panel systems, and Dassault Systemes for digital technology.

Our relationship with Simpson, Gumpertz & Heger was the combination of two firm-wide research fellowships targeted to exploring cross-disciplinary collaboration. This allowed us to test workflows and data translation between design and analytical platforms. Our schematic design surface was analyzed and optimized for sizing and spacing of structural members, and the developed design model was done in collaboration for structural and performance detailing. This exchange and the methods used for analysis are described in detail in Section 4.09.

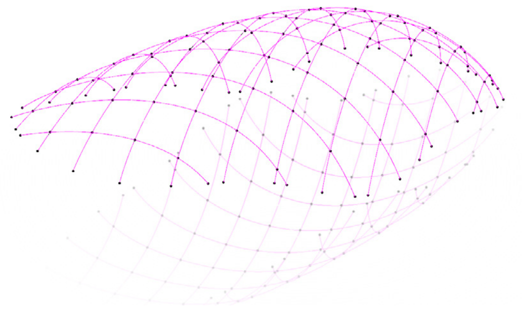


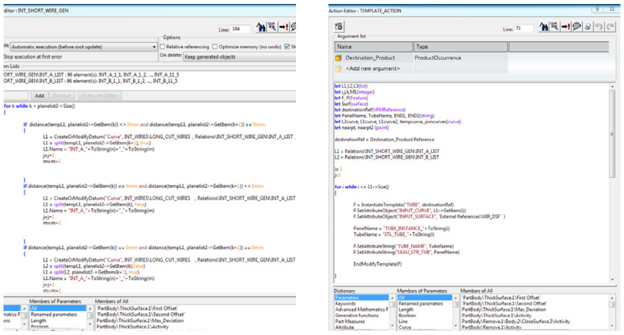
Figure 67: Skeletal Modeling Wire Frame

The schematic design for the project was reviewed by two ETFE fabricators, Bird Air and Vector Foiltec. This allowed for typical profiles, spacing, and orientation of cushions, detailing and of structural connections, and criteria for the inflation system to be incorporated into the design development. Through discussions with VectorFoiltec, spacing for the ETFE cushions was determined that coordinated with the optimized structural design of the steel diagrid.

The pavilion was designed using Dassault Systemes 3D Experience, provided through the A. Zahner Company. Zahner uses the 3D Experience as part of their fabrication workflow, allowing the model information to be transferred directly into their fabrication technologies. The following digital workflow methods and automation techniques were used with the intention that their output would contain information directly usable by the manufacturer, create efficiency throughout the iterative design process, and build a workflow of cross-disciplinary collaboration.

4.02 DESIGN GEOMETRY

The design geometries began with setting a network of driving curves, with each curve containing parameter controlling the height, curvature and tangency rules. The driving network of curves was the outcome



```
ORT_WIRE_GEN\INT_A_LIST : 96 element(s): INT_A_1_1, INT_A_1_2, ..., INT_A_11_5
ORT_WIRE_GEN\INT_B_LIST : 96 element(s): INT_B_1_1, INT_B_1_2, ..., INT_B_11_5
```

```
for k while k < planelist2->Size()
{

	if  distance(templL1, planelist2->GetItem(k)) <> 0mm and distance(templL1, planelist2->GetItem(k+1)) == 0mm
	{
		L1 = CreateOrModifyDatum("Curve", INT_WIRES\LONG_CUT_WIRES , Relations\INT_SHORT_WIRE_GEN\INT_A_LIST ,
		L1 = split(templL1, planelist2->GetItem(k+1), true)
		L1.Name = "INT_A_"+ToString(n)+"_"+ToString(m)
		j=j+1
		m=m+1


	}
	if distance(templL1, planelist2->GetItem(k)) == 0mm and distance(templL1, planelist2->GetItem(k+1)) <> 0mm
	{
		L1 = CreateOrModifyDatum("Curve", INT_WIRES\LONG_CUT_WIRES   , Relations\INT_SHORT_WIRE_GEN\INT_A_LIST
		L1 = split(templL1, planelist2->GetItem(k), false)
		L1.Name = "INT_A_"+ToString(n)+"_"+ToString(m)
		j=j+1
		m=m+1


	}
	if distance(templL1, planelist2->GetItem(k)) == 0mm and distance(templL1, planelist2->GetItem(k+1)) == 0mm
	{
		L1 = CreateOrModifyDatum("Curve", INT_WIRES\LONG_CUT_WIRES   , Relations\INT_SHORT_WIRE_GEN\INT_A_LIST
		L2 = split(templL1, planelist2->GetItem(k),false)
		L1 = split(L2, planelist2->GetItem(k+1), true)
		L1.Name = "INT_A_"+ToString(n)+"_"+ToString(m)
		j=j+1
		m=m+1
```

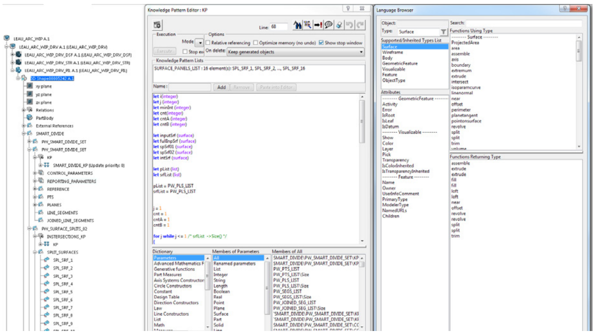
```
'PartBody\ThickSurface.1\First Offset`
'PartBody\ThickSurface.1\Second Offset'
PartBody\ThickSurface.1\Max_Deviation
PartBody\ThickSurface.1\Activity
```

Name	Type
Destination_Product	ProductOccurrence
<Add new argument>	

```
let L1,L2,L3(list)
let i,j,k,M1(integer)
let F, P(Feature)
let Surf(surface)
let destinationRef(VPMReference)
let PanelName, TubeName, END1, END2(string)
let L2curve, L1curve, L1curve2, tempcurve, joincurves(curve)
let nearpt, nearpt2 (point)

destinationRef = Destination_Product.Reference

L1 = Relations\INT_SHORT_WIRE_GEN\INT_A_LIST
L2 = Relations\INT_SHORT_WIRE_GEN\INT_B_LIST

i= 1
j=1

for i while i <= L1->Size()
{

	F = InstantiateTemplate("TUBE", destinationRef)
	F.SetAttributeObject("INPUT_CURVE", L1->GetItem(i))
	F.SetAttributeObject("INPUT_SURFACE", `External References\WIR_DSF` )

	PanelName = "TUBE_INSTANCE_"+ToString(i)
	TubeName = "STL_TUBE_"+ToString(i)

	F.SetAttributeString("TUBE_NAME", TubeName)
	F.SetAttributeString("LEAU_STR_TUB", PanelName)

	EndModifyTemplate(F)

}
```

```
`PartBody\ThickSurface.1\First Offset`
`PartBody\ThickSurface.1\Second Offset`
PartBody\ThickSurface.1\Max_Deviation
PartBody\ThickSurface.1\Activity
PartBody\Remove.1\Body.2\CloseSurface.3\Activity
PartBody\Remove.1\Activity
```

Figure 68: Knowledge Pattern (Left) & Action Script (Right)



```
LEAU_ARC_WIP A.1
  LEAU_ARC_WIP_DRV A.1 (LEAU_ARC_WIP_DRV)
    LEAU_ARC_WIP_DRV_DSF A.1 (LEAU_ARC_WIP_DRV_DSF)
    LEAU_ARC_WIP_DRV_STR A.1 (LEAU_ARC_WIP_DRV_STR)
    LEAU_ARC_WIP_DRV_PIL A.1 (LEAU_ARC_WIP_DRV_PIL)
      3D Shape00005242 A.1
        xy plane
        yz plane
        zx plane
        Relations
        PartBody
        External References
        SMART_DIVIDE
          PW_SMART_DIVIDE_SET
          PW_SMART_DIVIDE_SET
            KP
              SMART_DIVIDE_KP (Update priority: 0)
            CONTROL_PARAMETERS
            REPORTING_PARAMETERS
            REFERENCE
            PTS
            PLANES
            LINE_SEGMENTS
            JOINED_LINE_SEGMENTS
          PW_SURFACE_SPLITS_02
            INTERSECTIONS_KP
              KP
            SPLIT_SURFACES
              SPL_SRF_1
              SPL_SRF_2
              SPL_SRF_3
              SPL_SRF_4
              SPL_SRF_5
              SPL_SRF_6
              SPL_SRF_7
              SPL_SRF_8
              SPL_SRF_9
```

```
SURFACE_PANELS_LIST : 16 element(s): SPL_SRF_1, SPL_SRF_2, ..., SPL_SRF_16
```

```
let i(integer)
let j (integer)
let minInt (integer)
let cnt(integer)
let cntA (integer)
let cntB (integer)

let inputSrf (surface)
let fullInpSrf (surface)
let spSrf01 (surface)
let spSrf02 (surface)
let intSrf (surface)

let pList (list)
let srfList (list)

pList = PW_PLS_LIST
srfList = PW_PLS_LIST


j = 1
cnt = 1
cntA = 1
cntB = 1

for j while j <= 1 /* srfList ->Size() */
{
```

```
SMART_DIVIDE\PW_SMART_DIVIDE_SET\KP
SMART_DIVIDE\PW_SMART_DIVIDE_SET\KP
PW_PTS_LIST
PW_PTS_LIST\Size
PW_PLS_LIST
PW_PLS_LIST\Size
PW_SEGS_LIST
PW_SEGS_LIST\Size
PW_JOINED_SEG_LIST
PW_JOINED_SEG_LIST\Size
`SMART_DIVIDE\PW_SMART_DIVIDE_SET\KI
`SMART_DIVIDE\PW_SMART_DIVIDE_SET\KI
SMART_DIVIDE\PW_SMART_DIVIDE_SET\CC
```

Figure 69: Model Tree (Left) & Engineering Knowledge Language Browser (Right)

of several investigations studying the relationship between freeform geometry and structural performance. The swept curves produced a surface geometry that would touch the ground on one side and gradually lift upward in the opposite direction with the highest point lying near the center of the sweep. The desired effect and performance was a surface geometry that would transfer surface loads efficiently while maintaining the design intent.

The desired effect and performance resulted in a surface geometry that would transfer loads as efficiently as possible without compromising the overall geometry definition. This design surface would be the basis for all of the material systems that would go into the project. Visible in the continuity between elements and their transitions. By using this design geometry as the basis for all systems, a higher level of parametric control is enabled. The driving geometry represents the primary domain and the division of this domain into other systems define the sub-domains. Any operations made on the design geometry (primary domain) automatically affect the generated surface sub-domains. In this case, we have surface geometry defining the ETFE membrane, clamping, and extrusion supports, primary and secondary structure, concrete form, masonry panels, curved metal panel system and concrete edge conditions.

4.03 SKELETAL DESIGN METHODOLOGY

The skeletal design methodology within parametric design applications has the potential to drastically reduce the time it takes to go through design iterations. When designing a project with large amounts of detailing and assemblies, using skeletal modeling as a framework for developing detailed elements allows the designer to go into any generated components or part without affecting the entire system. The flexibility of using skeletal modeling can be seen in how the structural steel members for Pavillon de L'eau were created. The skeleton for all of the elements was scripted using a knowledge pattern with variables and constraints that were adjusted over a hundred times before arriving at the final solution. The wireframe functioned as a skeletal framework for modeling subsequent elements, generated using additional knowledge patterns, engineering templates and action scripts which together provided the flexibility of iterating through numerous solutions.

This method reduces the time it takes to arrive at optimized solutions and also reduces the amount of errors that can occur with large assemblies. Since skeletal modeling can produce high quantities of specific components, the ability to both synchronize them with the skeletal framework but also work on each element independently can bring high levels of resolution to components early in the design process. This has major impacts on the manufacturing and fabrication phase downstream resulting in higher design resolutions and minimized errors on the field.

LIFE CYCLE ANALYSIS - ALUMINUM PRIMARY PRODUCTION

PRIMARY MATERIAL PRODUCTION:
ENERGY, CO2 AND WATER
EMBODIED ENERGY, PRIMARY PRODUCTION 200 TO 220 MJ/KG
CO2 FOOTPRINT, PRIMARY PRODUCTION 12 TO 13 KG/KG
WATER USAGE 1100 TO 1200 L/KG

MATERIAL PROCESSING:
ENERGY
FORGING, ROLLING ENERGY 6.0 TO 6.7 MJ/KG
METAL POWDER FORMING ENERGY 23 TO 26 MJ/KG
VAPORIZATION ENERGY 16000 TO 17000 MJ/KG

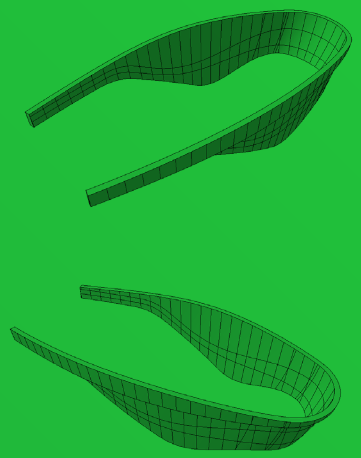
MATERIAL PROCESSING:
CO2 FOOTPRINT
FORGING, ROLLING CO2 0.45 TO 0.50 KG/KG
METAL POWDER FORMING CO2 1.9 TO 2.1 KG/KG
VAPORIZATION CO2 1200 TO 1300 KG/KG

MATERIAL RECYCLING:
ENERGY, CO2 AND RECYCLE FRACTION
EMBODIED ENERGY, RECYCLING 33 TO 37 MJ/KG
CO2 FOOTPRINT, RECYCLING 2.6 TO 2.9 KG/KG

MODEL

TOTAL SURFACE AREA: 243.39 M2

PANEL COUNT: 220



MATERIAL PROPERTIES - ALUMINUM

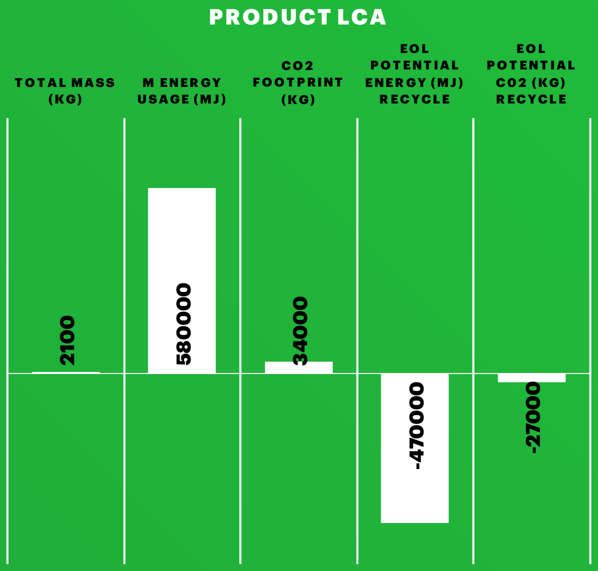
MECHANICAL PROPERTIES

YOUNG'S MODULUS 68 TO 71 GPA
POISSON'S RATIO 0.33 TO 0.34
YIELD STRENGTH (ELASTIC LIMIT) 240 TO 270 MPA
TENSILE STRENGTH 260 TO 300 MPA
COMPRESSIVE STRENGTH 230 TO 260 MPA
ELONGATION 6.0 TO 11"% STRAIN

THERMAL PROPERTIES

MAXIMUM SERVICE TEMPERATURE 110 TO 170 °C
MINIMUM SERVICE TEMPERATURE -270 °C
THERMAL CONDUCTIVITY 160 TO 170 W/M.°C
SPECIFIC HEAT CAPACITY 930 TO 970 J/KG.°C
THERMAL EXPANSION COEFFICIENT 23 TO 25 STRAIN/°C

LCA IMPACT REPORT



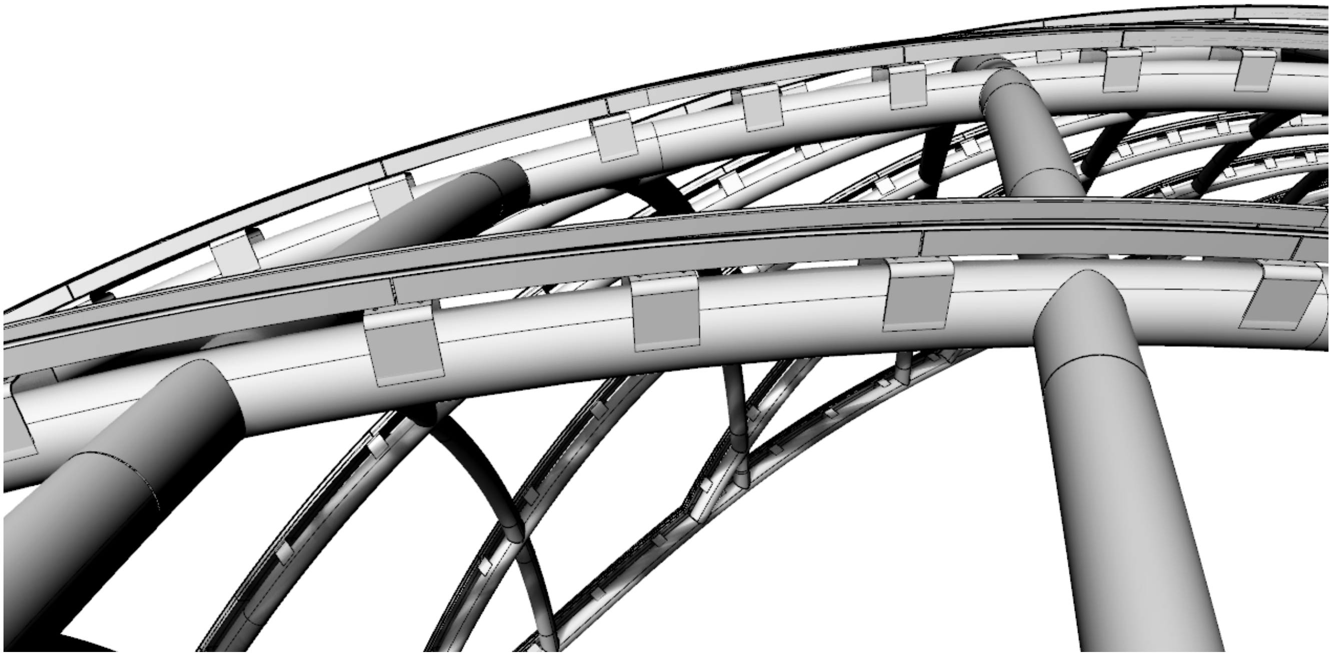


Figure 70: Pavillon de L'eau Close-up of Steel Frame, Upstands and Aluminum Track

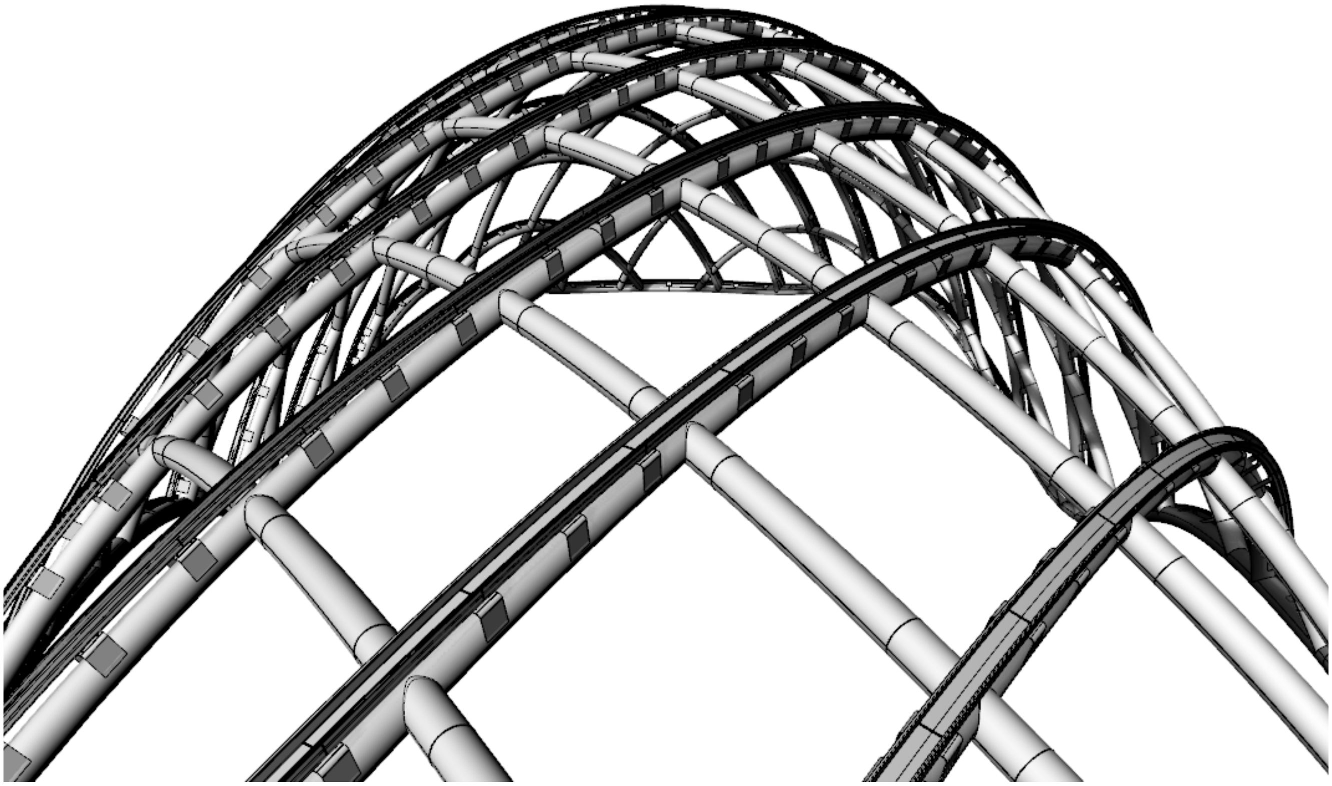


Figure 71: Pavillon de L'eau Close-up Aerial View

LIFE CYCLE ANALYSIS - STEEL PRIMARY PRODUCTION

PRIMARY MATERIAL PRODUCTION:
ENERGY, CO2 AND WATER
EMBODIED ENERGY, PRIMARY PRODUCTION 25 TO 28 MJ/KG
CO2 FOOTPRINT, PRIMARY PRODUCTION 1.7 TO 1.9 KG/KG
WATER USAGE 43 TO 48 L/KG

MATERIAL PROCESSING:
ENERGY
CASTING ENERGY 11 TO 12 MJ/KG
FORGING, ROLLING ENERGY 2.6 TO 2.8 MJ/KG
METAL POWDER FORMING ENERGY 39 TO 43 MJ/KG
VAPORIZATION ENERGY 11000 TO 12000 MJ/KG

MATERIAL PROCESSING:
CO2 FOOTPRINT
CASTING CO2 0.83 TO 0.92 KG/KG
FORGING, ROLLING CO2 0.19 TO 0.21 KG/KG
METAL POWDER FORMING CO2 3.1 TO 3.4 KG/KG
VAPORIZATION CO2 820 TO 900 KG/KG

MATERIAL RECYCLING:
ENERGY, CO2 AND RECYCLE FRACTION
EMBODIED ENERGY, RECYCLING 7.0 TO 7.7 MJ/KG
CO2 FOOTPRINT, RECYCLING 0.55 TO 0.60 KG/KG
RECYCLE FRACTION IN CURRENT SUPPLY 40 TO 44"%

MATERIAL PROPERTIES - CARBON STEEL

MECHANICAL PROPERTIES

YOUNG'S MODULUS 210 TO 220 GPA
POISSON'S RATIO 0.28 TO 0.29
YIELD STRENGTH (ELASTIC LIMIT) 170 TO 320 MPA
TENSILE STRENGTH 310 TO 430 MPA
COMPRESSIVE STRENGTH 260 TO 320 MPA
ELONGATION 29 TO 45"% STRAIN

THERMAL PROPERTIES

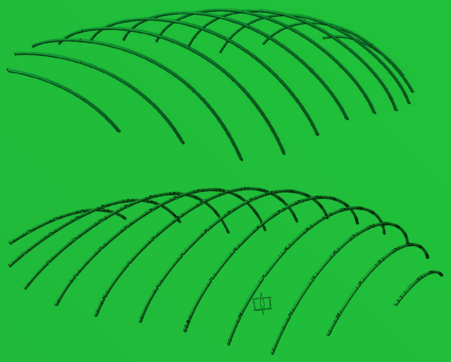
MAXIMUM SERVICE TEMPERATURE 340 TO 360 °C
MINIMUM SERVICE TEMPERATURE -68 TO -43 °C
THERMAL CONDUCTIVITY 50 TO 54 W/M.°C
SPECIFIC HEAT CAPACITY 470 TO 510 J/KG.°C
THERMAL EXPANSION COEFFICIENT 12 TO 13 MSTRAIN/°C

MODEL

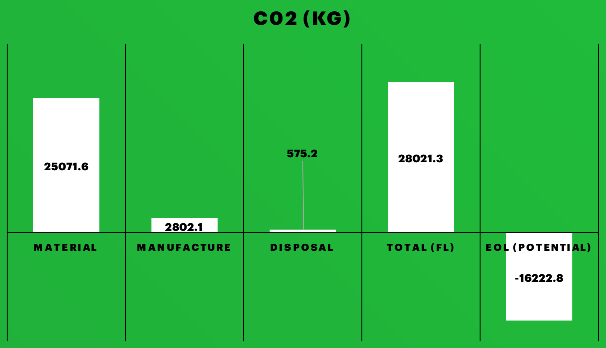
PRIMARY MEMBERS: 11 (L. LENGTH 216.8 M)

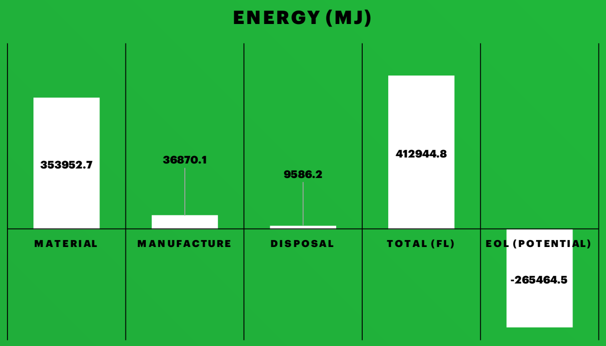
SECONDARY MEMBERS: 96 (L. LENGTH 225.4 M)

MASS: 13078 KG



LCA IMPACT REPORT





4.04 EKL ENGINEERING KNOWLEDGE LANGUAGE

Scripting languages can be found in most design applications but in the design of Pavillon de L'eau, EKL was used for developing the computational workflow necessary to automate hundreds of components. Engineering Knowledge Language (EKL) is a programming language found in CATIA made up of several basic constructs like most other scripting languages. These constructs include syntax and keyword and come with programming rules that reference items in a dictionary of members and types. The programming is built up in layers and made up using basic variables types such as string, integer, length etc. Each variable contains a value which is stored in the memory. There are also simple programming logics which are called "if" statements, which are known as methods, sub-routines or functions. As these programs are created, it is possible to process multiple variables as an input or output. When both methods and variables are grouped inside a class object, these groups can be instantiated by other classes.

CATIA EKL contains multiple class objects which are made up of simple components such as point, line, surface etc. Each one of these class objects can contain methods and properties. For example, when calling a method that produces a variable or class, the type must be equal to the pre-defined type in memory such as <List>=<List>. The programming language also includes object types which are written into memory, that include Boolean, string, real, length, integer, point, curve etc. Each member definition describes the inputs and outputs and is defined within parentheses. Object types are then used to define numerical functions, formulas, basic attributes and methods. The level of detail for using EKL can be extensive and the methods for creating programs through this language can also vary. EKL can exists within multiple workbenches in CATIA and is used within the Knowledge Advisor, Knowledge Expert, Product Engineering Optimizer and Product Knowledge Templates.

4.05 ENGINEERING TEMPLATES & AUTOMATION

During the production stage, changes in design and performance details can have major impacts on production. With tools like engineering templates, embedded within CATIA, the Pavillon de L'eau was able to capture design changes quickly and efficiently without having to redefine connection details manually. Updates and detail drawings from the engineer were modeled in detail into engineering templates which could capture all of the engineering constraints and adapt locally to unique conditions.

The supporting wireframe for Pavillon de L'eau produced over 300 unique structural members making up the primary and secondary structure. With the right parameters and constraints built into the engineering template for automating these components, the design changes in member size, position, and connection details were simply updated into the templates and propagated. The engineering templates provided an efficient way of adding detailed changes into the design with reuse of model templates created from the beginning.

4.06 DOCUMENTATION TEMPLATES

Documentation of large assemblies can be time-consuming when dealing with various unique conditions. The documentation process for fabrication is known for causing delays and incurring costs. By providing the fabrication team with sophisticated modeling techniques for capturing complexity, our designers can help streamline the entire documentation process directly from the design models. Using

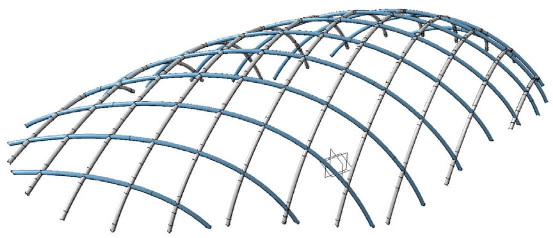


Figure 72: Pavillon de L’eau Primary & Secondary Structure

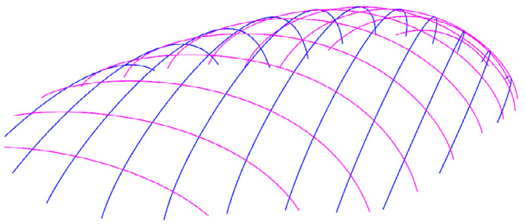


Figure 73: Pavillon de L’eau Structural Wireframe

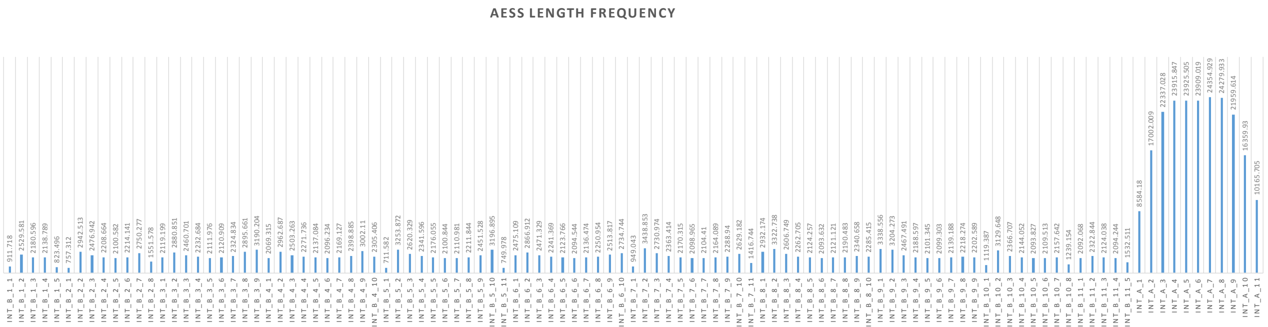


Figure 74: Pavillon de L’eau Structural Lengths

documentation templates allows documents to be parametrically associated with the generation of assemblies or components.

In the modeling of the structural members and interdependent components, using embedding documentation templates into the engineering templates produced detailed drawings that could be used to coordinate member types and assembly logistics. These drawings also provided quantities for specific welding and connection conditions for more capturing the scope of fabrication accurately.

4.07 CONSTRUCTION & ASSEMBLY LOGISTICS

The entry walls wrapping around the escalator are designed to be stainless steel panels, with curved zinc coping, providing the advantage of being easier to form using CNC manufacturing methods. Individual brackets will support these uniquely curved panels at corner points that are anchored to a concrete backup wall. Individually mounted brackets, rather than continuous sub-girts, will allow for more tolerance and adjustability during the installation of each unique panel. The joints between panels will allow for thermal expansion and contraction. The concrete backup wall will include a continuous fluid-applied waterproofing membrane applied directly to the concrete, extending the service life and durability of the concrete. The concrete backup wall waterproofing

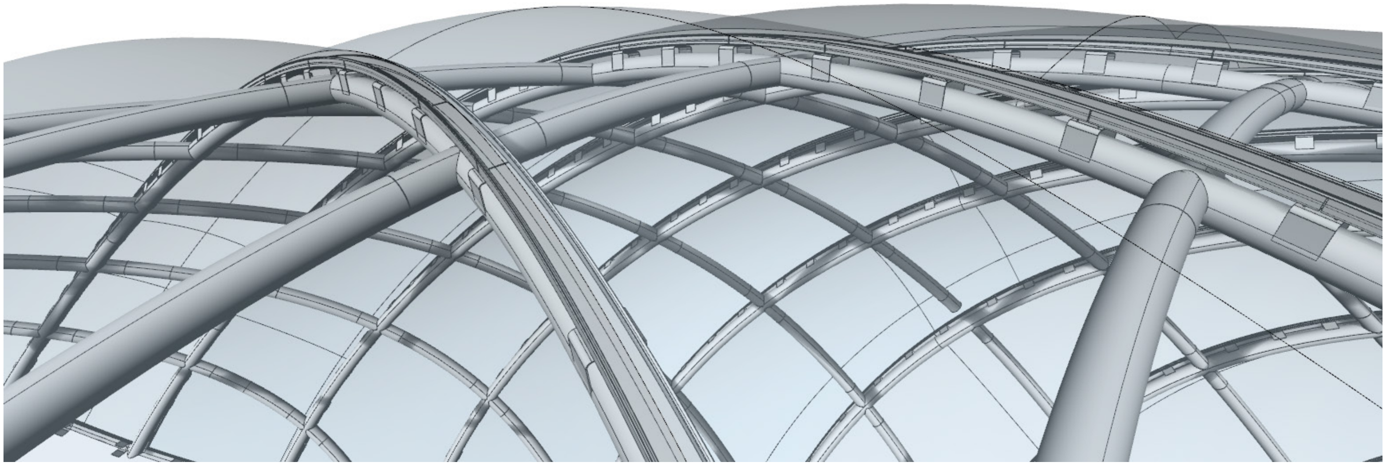


Figure 75: Pavillon de L'eau Close-up of Detailed Canopy Skin

will tie-in to the existing plaza waterproofing system, providing a continuous roof over the metro station below. The metal panel brackets are mounted directly to the concrete and extend 150 mm from the face of concrete, capturing the corner of each panel.

The panelization of the entryway accentuates the curvature of the design geometry by delineating the edge condition along the bottom of the surface. The subdivision of the surfaces takes place by first separating the primary design surface into sub-domains and then extracting the edges along each major subset. These sub-surfaces are parametrically defined using explicitly modeled curves with applied constraints, including tangential, coincidence and distance parameters. This model setup allows design changes to any of the 3D design sketches and operations on the resulting surface to maintain an associative relationship with dependent elements. Then splitting each surface to meet entryway requirements for clearances are defined using parameter controls. Establishing specific requirement constraints a part of the associative model development embeds limitations to design iterations which inform all subsequent manipulations. The difference between parametric modeling here and associative modeling is that objects are not only modeled independently through algorithmic variables but contain relationships with multiple objects, causing actions to influence reactions which propagate throughout an assembly or various assemblies. A variable change in one object can ultimate affect the entire model, providing instant feedback on certain interdependencies. This complex reactionary system is what we consider to be a truly parametric model, where interdependencies are globally informing each other.

Using control parameters for each surface, we give divisions a set spacing in the horizontal direction. The division is produced through instantiating a series of plane repetitions at set intervals, with a normal direction relationship to the edge curve at the given position.

4.08 LIFE CYCLE ANALYSIS

The material selection for the design of Pavillon de L'eau was informed by running Life Cycle Analysis on the main elements of the canopy. The structural steel and stainless steel panels posed major concerns in terms of performance, aesthetics and cost. One of the primary concerns was that the structural steel had to be protected from external conditions against corrosion and long term damage. All together the steel selection was driven by manufacturing, longevity, durability, performance and cost.

The entry wall was composed of 220 panels, with planar, ruled and double-curved surfaces. These panels were to be made of aluminum alloy, for its formability and corrosion resistance qualities. The aluminum panels would each have to undergo custom CNC manufacturing including forming and CNC cutting. These processes were put into the analysis for quantifying the energy, environmental effects, waste and end of life potentials. The benefits of using aluminum alloy vs. other materials including zinc and stainless steel were clarified from running the LCA which we did using the Granta materials database.

The LCA analysis provided detailed data on three production processes and end of life strategies. The data provided included energy use, CO2 emissions, water consumption and end of life potential. The primary material production for the aluminum panels indicated an embodied energy of 200-220 MJ/KG, a CO2 footprint of 12-13 KG/KG, and water usage of 1100 to 1200 L/KG. The material processing stage with forging, rolling, forming and CNC processing indicated an energy consumption of 6.0-6.7 MJ/KG, the metal powder forming process indicated an energy use of 23-26 MJ/KG and the vaporization process an energy use of 16000 to 17000 MJ/KG. These numbers provided us with a quantitative basis for the energy required at each step during the processing for the aluminum panels. The environmental impacts resulted in a CO2 footprint of 0.45 to 0.50 KG/KG for forging, rolling, forming and CNC methods, 1.9 to 2.1 KG/KG for metal powder forming and 1200 to 1300 KG/KG for vaporization.

The possible end of life strategies includes reuse, recycling, downcycling, combustion, and landfill. Due to the recyclability of aluminum alloys, we looked at the end of life potential by running a recycling analysis on the total mass of the material that would be used. This approach also called an open-loop strategy, reprocesses the material at the end of life by putting it back into the supply chain for reuse after conversion. This study conducted later would provide our design with an EOL or End Of Life potential for energy and CO2 savings or credits. These returns are realized through reuse by avoiding the need to undergo extraction, processing, and manufacturing of fresh materials. To study this approach deeper, we took a look at the calculations required for recycling which include the disposal processes involved in recycling, collection and secondary sorting. The energy requirement value (MJ) is calculated as:

$\text{Energy}_{\text{disposal}} = \text{Energy}_{\text{collection}} + \text{Energy}_{\text{secondary sorting}}$

If 100% of the material is recovered during this stage for recycling, then:

$\text{Energy}_{\text{collection}} = \text{Collection energy} \times \text{Mass}$

$\text{Energy}_{\text{secondary sorting}} = \text{Secondary sorting energy} \times \text{Mass}$

where:

Collection energy (MJ/KG) = 0.2

Secondary sorting energy (MJ/KG) = 0.5

Mass = Mass of part

The calculation for CO2 footprint savings is solved

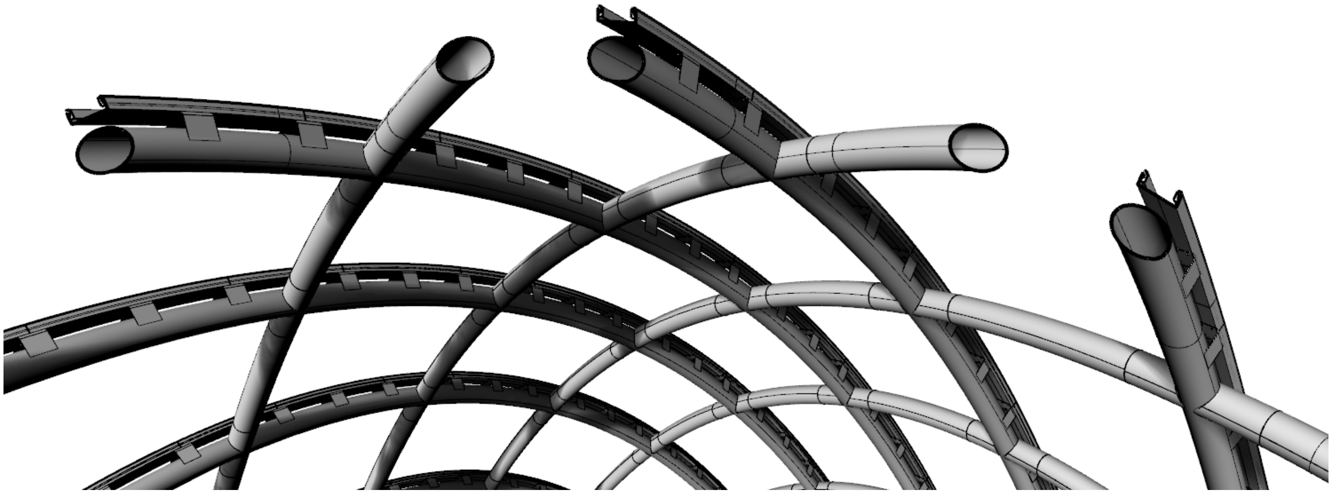


Figure 76: Pavillon de L'eau Section of Steel Frame, Upstands and Aluminum Track

from the energy usage, with a standard rate of CO2 (KG) produced per (MJ) of energy used:

CO2-disposal = . Energy disposal

where:

= CO2 footprint, source (kg/MJ) = 0.07

After sorting comes the calculations for energy costs and CO2 footprint associated with recycling processes which are offset by the saving of energy and CO2 avoided by using new materials. If 100% is recovered during the sorting process, then recycling calculations can be solved as:

$\text{Energy}_{\text{end-of-life potential}} = (\text{Energy}_{\text{recycling}} - \text{Energy}_{\text{production}}) \text{ x Mass}$

and

$\text{CO2-}_{\text{end-of-life}}$ potential = $(\text{CO2-}_{\text{recycling}} - \text{CO2-}_{\text{production}})$ x Mass)

where:

$\text{Energy}_{\text{recycling}}$ = Embodied energy, recycling (MJ/kg) for the material

$\text{Energy}_{\text{production}}$ = Embodied energy, primary production (MJ/kg) for the material

$\text{CO2-}_{\text{recycling}}$ = CO2 footprint, recycling (kg/kg) for the material

$\text{CO2-}_{\text{production}}$ = CO2 footprint, primary production (kg/kg) for the material

Mass = Mass of part

The final calculation for the aluminum alloy panels using a recycling EOL strategy indicated -27000 KG of CO2 and -470000 MJ of energy. For materials that are frequently recycled, including metals and glasses, the energy and CO2 cost required for recycling is usually a lot lower than the cost of manufacturing new materials. The negative values are credits to these costs, providing a positive indication that using materials like aluminum alloys are beneficial in the long run and much more appropriate for future use strategies.

A similar LCA analysis was conducted on the primary and secondary steel. We began by first looking at the production processes of steel, including the mining of fresh materials and the reuse of recycled materi-

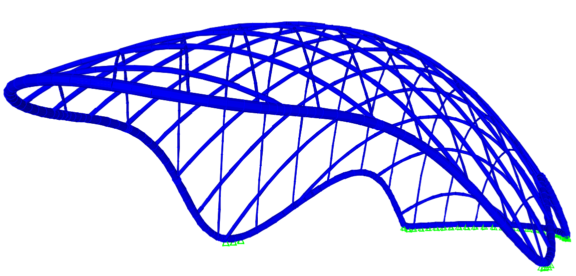


Figure 77: Structural Analysis SAP Model (SGH Engineers)

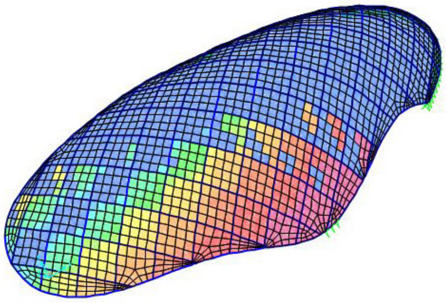


Figure 78: Structural Analysis FEA Model (SGH Engineers) Wind Load Simulation

als since the majority of steel is made from recycled materials. About 70% of all steel production in the world is made from recycled material. The energy requirement and CO2 emissions generated from melting, casting and fabrication methods were a part of this calculation. The total steel for the primary and secondary structure was 13078 KG with 6280 KG for the secondary members and 6798 for the primary members. With a primary material production energy demand of between 25-28 MJ/KG, a CO2 footprint of between 1.7-1.9 KG/KG and water consumption demand of from 43-48 L/KG. The material processing stage and recycling strategies also looked at this criterion (Energy, CO2, and Water).

Additional factors about their manufacturing process had to be studied before coming to a conclusion. The manufacture of stainless steel entails a mixture of 10% chromium minimum and regular carbon steel during the molten state. Once it has cooled, the stainless steel is treated with acid for the removal of impurities. Stainless steel is also naturally corrosion resistant. Despite its resistance, rusting can still occur if imperfections or impurities allow water molecules to oxidize. The added protection for these cases comes from a process called passivation, which provides increased protection against corrosion by applying an outer layer. The other option, galvanized steel is manufactured by coating regular carbon steel with molten zinc using a hot-dipping technique. The molten zinc provides a protective layer around the steel which is about a millimeter thick. This thin layer is effective as a protective coating, but its thickness means that any scratched or damaged areas are immediately exposed to potential corrosion. Comparing these factors against additional solutions gave us the best possible solution for achieving a durable and performative solution.

It became apparent that stainless steel provided the best combination of solutions vs. other steel types including galvanized steel and painted steel. These other solutions also required additional steps for both galvanization and painting, since these coating systems required more processing they also added more cost. Galvanization added $1.10 per SQ. Ft, while IOZ/Epoxy/Polyurethane coating systems added $3.36 per SQ. ft. The galvanization of steel adds 30.5 MJ/KG while a coating system adds 83.2MJ/KG. To ensure these applications perform against corrosion and failure, maintenance for the coating system needs to take place every 15 years, while the galvanized method is compromised when damage to the thin outer layer occurs. It becomes clear that during the life of these applications, maintenance alone will add significant energy and emission impacts.

The structural performance, durability, and corrosion resistance together with a deeper understanding of the life cycle implications made clear the subsequent steps necessary to coordinate other factors that would affect the entire canopy system. This includes the number of welds required to maintain the per-

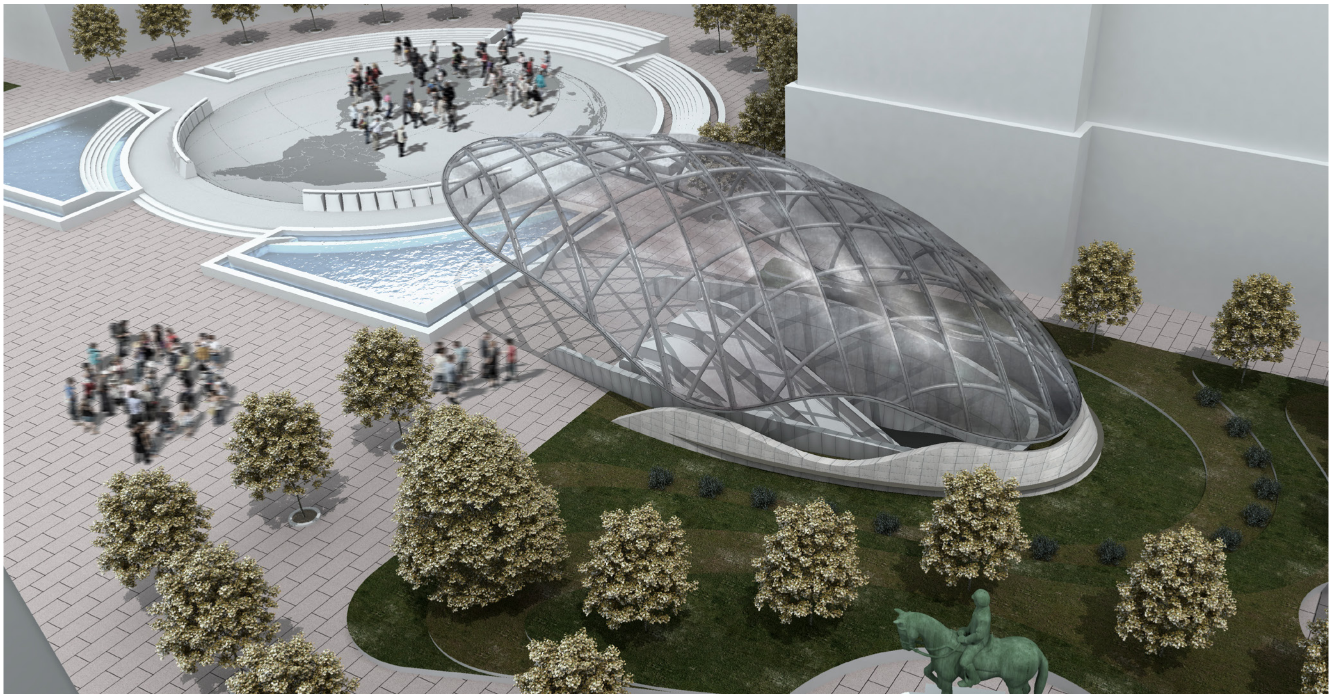


Figure 79: Pavillon de L'eau Exterior Rendering

formative qualities of this material and the finishing qualities that should be specified during manufacturing and fabrication.

Life cycle analysis technology alone won't make things clear, but using the data generated helped us establish certain relationships between material processes and their impacts on the overall design. These impacts were also critical to ensuring we engaged the right partners for manufacturing and fabrication.

4.09 STRUCTURAL ANALYSIS

In order to attain the structural requirements of the canopy, we had to find unconventional methods for establishing a workflow that would allow us to look at multiple performance criteria and explore various structural configurations. The freeform geometry and variated system relationships of the canopy drove our efforts toward establishing data transfer workflow with Simpson Gumpertz & Heger Engineers. Known for their expertise in structures, building enclosures and materials, SGH played a vital role in the design explorations and structural validation of the canopy.

The structural investigations with SGH began by taking the design drivers directly from CATIA and running them through multiple simulation techniques. The driving model in CATIA, which parametrically linked the entire design, assemblies, and components to construction geometry was delivered to SGH for analysis, design, and optimization of the structural system. The design drivers included the design surface, the control wires, and the vertices, which provided sufficient information for the engineers to begin work on setting up a parametric analysis model.

SGH had recently started testing an in-house Rhino-based beta program that is capable of full interoperability and exchange of information between geometric models in Rhino and analytical models

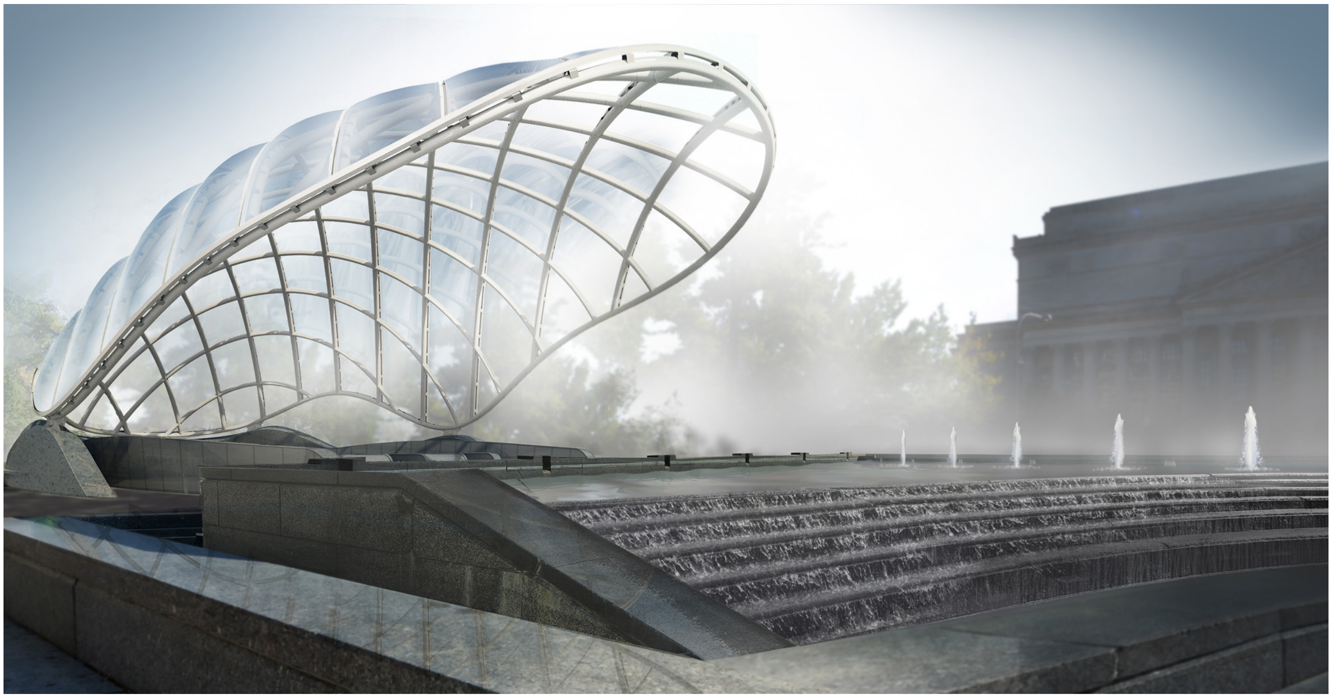


Figure 80: Pavillon de L'eau Exterior Rendering

in SAP2000, a commercially available structural finite element analysis developed by Computers and Structures, Inc. The integration of Rhino, a parametric modeling program, with SAP2000, a high fidelity finite element analysis engine, significantly improved SGH's internal workflow as it enabled them to parameterize the structural model. It allowed them to rapidly and efficiently iterate on multiple geometric configurations, material solutions, and other design considerations without having to manipulate input variables manually. This capability is especially critical in rapidly and successfully analyzing and designing an optimal structure with complex geometric constraints and multiple design drivers. The pavilion proved invaluable in validating structural optimization techniques.

By parameterizing the structure in Rhino and using the in-house interoperability program to analyze design options in SAP2000 instantly, SGH was able to employ various optimization techniques in Rhino to modify and then evaluate, with a high fidelity analysis engine, the various geometric options based on the primary design drivers. For instance, the parametric distribution of control wires for the primary and secondary tube framing enabled SGH to rapidly vary and evaluate multiple spacing configurations and ultimately develop a framing arrangement that balanced the architectural and structural constraints of the Pavilion. This level of control allowed us to look at several iterations rapidly without compromising the design intent or having to translate information between architectural and structural models constantly.

4.10 STRUCTURAL PERFORMANCE

The ability to parameterize a structural model and rapidly iterate on multiple geometric configurations based on a myriad of design drivers is only as valuable as the accuracy of the finite element model and its embedded assumptions. In addition to meeting aesthetic goals, the structure must be safe, perform appropriately under service levels loads, and be made

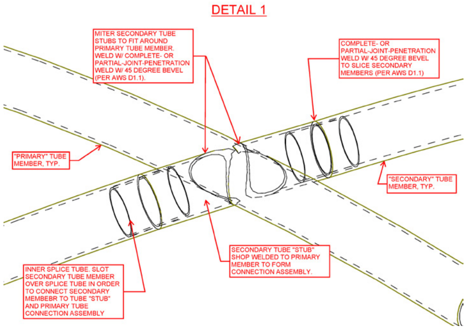


Figure 81: Structural Detail of Steel Diagrid Connection

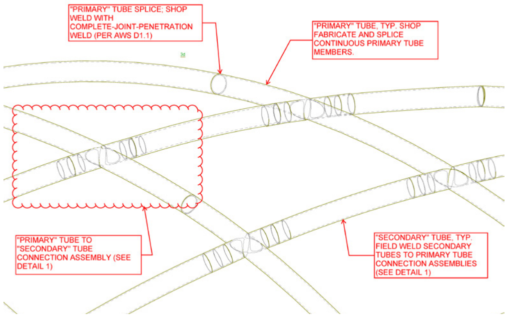


Figure 82: Structural Detail of Primary and Secondary Steel Tubes

constructible. The structural model was developed as a center-stick finite element analysis (FEA) model using SAP2000. This application is a robust FEA platform used for a range of structural engineering analysis and design applications including but not limited to high-rise buildings, long-span trusses, space trusses and tension-integrity structures, nuclear structures, concrete-shelled structures, nonlinear performance-based seismic analyses, and much more.

The curved structural steel tubes were modeled in SAP2000 as discrete 1-d frame elements. One of the many strengths of SGH's in-house program is its ability to rapidly discretize complex geometric information and make it compatible with a finite element program. For instance, the curved steel tubes were discretized into multiple straight elements to form the curves of the intersecting tubes. Because of the thin profile of the pavilion, it was necessary to take advantage of all sources of potential rigidity in the members and connections to limit deflections and improve the overall performance of the structure. With this in mind, the connections at the intersections of the "primary" and "secondary" frame elements were modeled (and detailed, as will be discussed later) without flexural releases, which resulted in framing members that behave as continuous elements through the intersecting nodes. The expectation that the frame elements are fully continuous from one side of the pavilion structure to the other side, enabled SGH to take advantage of the additional flexural stiffness that was critical in helping to improve the deflection limits of

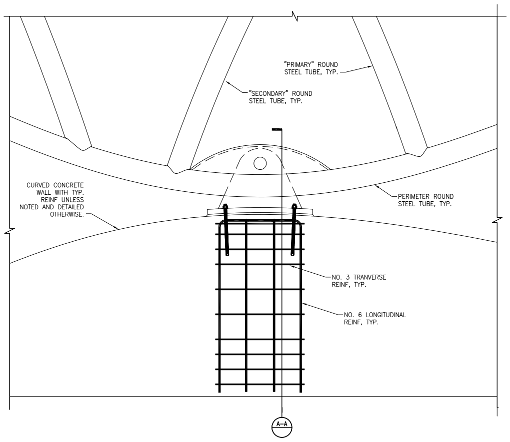


Figure 83: Structural detail of section through canopy base connection

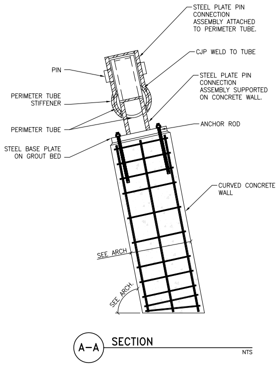


Figure 84: Structural detail of cross-section through canopy base connection

Figure 85: Existing Escalators at Navy Memorial / National Archives Metro Station

the structure.

The choice of round tubes as the primary structural members for the pavilion framing was in part driven by the suitability and advantages such members offer in the analysis of a structure like the one in this pavilion, which is continuously curving in multiple directions at the same time (e.g. Double-curved). Because the structural analysis and design properties of round tubes are equal in all directions—effectively, the mechanical properties are "isotropic"—the orientation of the member local axis does not have to be continuously rotated along the curving surface, and the model can be more rapidly constructed and analyzed. Furthermore, typical steel design considerations like flexural instabilities (i.e. Lateral torsional buckling), which are primarily controlled by the unbraced lengths of the members, do not control the design of round tubes. It made analyzing and designing the members far more expedient, and more importantly, allowed for greater flexibility in determining the spacing of the frame lines.

The etfe membrane was modeled as shell elements with zero In-plane and out-of-plane stiffness. The etfe shell elements were "continuously" meshed at discrete, relatively small intervals along and to the steel base frame. The etfe membrane system and clamping rails were treated the same way a standard backup wall or unitized glass curtain wall would be treated in relation to a post-tensioned concrete or steel-framed structure. The etfe system is not behaving as a composite system with the steel tube structure and does not contribute to its structural properties. As far as the structural analysis is concerned, the etfe shell elements were only used to distribute uniform gravity and lateral winds loads to the steel tube structure. By modeling the etfe as flexible shell elements, we enforced the expectation that the etfe does not act compositely with the steel structure and does not affect the structural properties. The etfe shell structure in conjunction with the closely spaced mesh points along the steel frame elements meant that distributed loads, such as snow and wind loads, were distributed to the steel frame elements uniformly and based on tributary areas.

4.11 APPLICATION OF LOADS

In a curved, framed canopy structure like the pavilion, which is highly indeterminate with multiple load paths, there is no distinction between a gravity load system and a lateral load resisting system. Because of the lack of distinct load paths and atypical geometry, the performance of the structure, which includes strength and serviceability (deflection) requirements, needed to be evaluated holistically for multiple load combinations and patterns. For instance, the complexity of the curved surface necessitated the application and analysis of multiple wind load patterns with different orientations projected orthogonally to the curved etfe shell elements. In a standard finite element analysis program, it is quite difficult to project wind loads onto curved surfaces, especially along axes that are skewed from the global principal axes of the structure. SGH used their in-house rhino based program to parameterize the lateral wind and gravity loads so that the structural performance of the pavilion could be evaluated for multiple wind load directions in combination with the vertical projections of gravity loads, such as snow and miscellaneous hung loads. Furthermore, the wind and gravity loads could be rapidly updated while iterating the geometry according to the various design drivers.

4.12 STRUCTURAL DETAILING

To maintain the clean, uninterrupted curves and smooth lines of the structure, as well as to not create obstructions for the etfe clamping track attachments along the steel tubes, we sought to minimize the number of connection types throughout the steel structure and simplify those that were typical. In addition to the aesthetic appeal of the round tube structure, round tubes can be connected to one another using mitered, welded connection details. Per the design and detailing processes given in the American Institute for Steel Construction Manual and specifications (aisc-360), such as table k3.1: “available strength of round HSS to HSS moment connections”, and the welding specifications are given in AWS d1.1. SGH was able to design tube-to-tube moment connections where the “secondary” member ends are mitered, fitted to the faces of the continuous primary members, and welded using complete- or partial- joint penetration welds. Per the AISC specifications, these types of connections are capable of transferring shear and moments; thus the secondary members that connect to either side of a primary member will act as continuous members, which is consistent with how the structure was modeled and analyzed (as discussed above). These detailed moments were incorporated into the parametric model as 3D engineering templates, capable of adapting to each condition provided by the input geometries generated through some computational scripting.

To facilitate ease of erection of the steel superstructure, we designed the connections such that the continuous primary members could be shop fitted (using the standard AISC table k3.1 tube-to-tube moment connection detail) with tube” stubs.” These details were used on either side of the primary member at the intersection points of the primary and secondary members. During field erection, secondary member segments would be spliced to the "stubs" of adjacent primary members (an inner splice tube is used to facilitate the field connection of the secondary member to the connection assembly) at all intersection points using complete- or partial- joint penetration welds. The attachment and build-up of the secondary member segments to the continuous primary members would eventually form a network of intersecting tube members that ultimately results in the curved structure of the pavilion.

The decision to use "true" pin connections to support the structure at discrete points along the base of the pavilion was both aesthetically and practically driven. Practically speaking, a true pin support is highly desirable for a truss-like tube structure where the structural integrity is derived primarily from axially loaded members as it limits induced moments in the structure, especially at the base where they are not needed nor desired. Furthermore, SGH sought to limit the moments induced in the supporting curved concrete wall, which meant that the wall could be thinner and not require as much reinforcement. Aesthetically, a pinned connection that limits the build-up of flexural stresses in the concrete wall and steel superstructure means that fewer stiffeners and strengthening elements are required along the steel tubes or concrete walls, which might otherwise detract from the clean curves of the superstructure and its base.

CONCLUSION

The paradigm shift taking place through digital design technologies have demonstrated that material behaviors and performance strategies are becoming increasingly accessible to designers through digital environments. These digital integrations are the result of increasing economic, environmental and technological pressures placed on how we design and build. The need to make progress in these areas throughout the AEC industry has brought computing capacities which can only be exploited if we rethink how design and technology inform each other. It challenges us to think of issues of design as systems of relations beyond digital descriptions or standardized construction techniques. We have the ability to inform design across all scales through scales of processes and mechanisms that once separated industries. The way we integrate the knowledge acquired across fields into the digital domain will enhance the design process but also establish the meaningful and impactful relationships necessary for bridging gaps between knowledge.

This work served to demonstrate that it is not about the digital taking over material processes but that the subjection of design methods to the knowledge of materials and physical behaviors can improve our understanding of the consequences our decisions have toward achieving future goals. Effectively achieving these goals means that design thinking has to continuously expand into domains outside of traditional methods and common use of technological systems. We demonstrated examples in the application of using a combination of methods for arriving at solutions otherwise made impossible through conventional practice. A combination of computational, analytical and material interrogations takes place in each example studied, leading up to a proposal for the Pavillon de L'eau which served as a testing subject for putting certain methodologies to the test. The resulting project gave us a way of validating advanced methods and making them visible throughout the development of the project. With these techniques guiding design decisions we were able to realize the potential of advanced computational workflows through the lens of holistic thinking.

Future design methodologies will depend highly on new developments across disciplines and industries.

It is our role as designers to make sure that the demands we place on technological advances are directed toward improved problem-solving capacities enabled by digital technologies. We can see the effects of current approaches to design in the built environment. This awareness challenges us to look toward digital and processing technologies to affect that change. Isolating the design process from production will result in inefficiencies which we can recapture through the right integrations. The way we design today will have major consequences on how cross-disciplinary experiences and efforts take place in the future. These issues in design extend into fields we are still only beginning to exploit and make use of through our digital environments.

Figure 85: Existing Escalators at Navy Memorial / National Archives Metro Station

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