EMERGING PARADIGMS:
FROM DIGITAL REPRESENTATION TO DIGITAL FABRICATION

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Abstract

Emerging advanced technologies in digital fabrication serve as critical tools in the evolving paradigm of the contemporary classroom. The ubiquity and rapid integration of computing in post-secondary curricula over the past three decades has dramatically altered the workflows, outcomes, and pedagogy within classrooms, most notably in the realm of design professions. Where drafting tables and technical pens once served as the communication tools of choice, both academia and professional practice have quickly adopted advanced computer modeling, rendering, and animation as a standard for design representation and delivery. Recently another pedagogical evolution has emerged. Current trends have begun to shift from digital representation to digital fabrication. This paper will elaborate upon the integration of emerging digital fabrication technologies, including the laser cutter and three-dimensional printer, in an architecture curriculum and discuss the increased design sensitivities that emerged in the classroom. Though often used as tools for representation of final design concepts, fabrication technologies have the power to revolutionize design processes, learning models, and modes of communication. Through a series of projects leveraging these technologies, this paper will outline dramatic improvements in students' detail understanding, integration of iterative design process, stakeholder accessibility, mass production, and tangible design that rarely are significantly engaged in design curricula.

Keywords: digital fabrication, design pedagogy, problem-based learning, laser cutting, three-dimensional printing

COMPUTING IN THE DESIGN STUDIO AND IN THE INDUSTRY

The rapid adoption of digital tools over the past three decades has dramatically altered the landscape of every facet of contemporary life and culture from the modes in which we communicate to the methods we produce and process our work. Technology and culture have become intertwined to an indistinguishable point. As a corollary to this, architectural historians and social theorists have articulated that a civilization's culture is epitomized in its architecture. From the great pyramids of ancient Egypt to the elegance of Gothic cathedrals in France, to the contemporary there is little doubt that many of the world's greatest works of architecture would be possible without the use of architectural computing technologies. From mundane tasks such as coordinating information through email or documenting designs with Computer Aided Design (CAD) programs to complex initiatives such as photorealistic imaging and complex building performance simulations, architecture and the digital design process have developed an extremely potent symbiosis.[1]

In professional practice the adoption of computing has been instrumental in instigating rapid and dramatic changes in communication and workflow as reflected in coordinated CAD drawings, comprehensive Building Information (BIM) Models, and advanced visualization in the Architecture, Engineering, and Construction industry.[2] This onset of robust architectural computing has subsequently dramatically altered workflow, outcomes, and pedagogy of architecture and design from concept to proposal in the past three decades.[3] What was once understood as merely an efficient method of documentation has swiftly become a toolset for advanced visualization, simulation, design development, comprehensive management, and more recently prototyping and fabrication. Design work now longer ceases at the virtual. Contemporary fabrication technologies empower designers to seamlessly operate between conceptual imagery and working prototype. As a result of this paradigm shift, the academic environment has had to not only maintain currency and adopt these standards but also respond by appropriately mobilizing future generations of designers to strategically and critically utilize these technologies. This paper will elaborate upon the integration of emerging digital fabrication technologies, including the laser cutter, three-dimensional printer, and vacuum forming machine in an architecture curriculum and discuss the increased design sensitivities that emerged in the classroom

PARADIGM SHIFT FROM VISUALIZATION TO FABRICATION

The incredible comprehensiveness and precision available to designers with contemporary modeling and rendering software has resulted in a varied spectrum of visual representation in accordance to both convention and spectacle. From tantalizing, photorealistic renderings articulating design depth on qualities of space to meticulously accurate construction documents denoting methods of production, the computer has become an indispensible in tool in the visualization of architecture. Had the computer's role in the design process been limited to visualization, the sensitivities raised by noted architects and academics including Juhani Pallasmaa Steven Holl on the role of phenomenology in architecture would have been lost to a generation of architects forfeiting a richer exploration of design development for an opportunity to learn the fundamental technical skills of CAD. That architecture affects the five senses rather than solely the visual modality so prevalent in contemporary culture, is imperative for architects of all levels of experience must continuously cultivate. Not simply limited to what Pallasmaa decries as "*ocularcentrism*"[4], the appropriation of digital technologies has also established the framework for an evolution towards fabrication.

The evolution of computer aided design software has led to complex simulation potential (structural, lighting, etc) and a deep oversight on a multitude of factors that play a pivotal role in an architecture project (BIM). There is a great deal of power behind the software designers wield. Though leading-edge software is capable of not only simulating photorealistic imagery with great fidelity and accuracy, digital models have a significant robust depth in coordinating design facets including costing, scheduling, energy performance, building detailing, and structural loading. From a design perspective, parametric modeling, algorithmic architecture, and macro scripting have allowed designers to conceive of a base concept and develop generations of iterations from which to select an "appropriate" design. For some critics this has led to a potentially dangerous trend of an "auto-generative design process" where designers relinquish their artistic authority and creativity by allowing algorithms drive design decisions.[5]

Digital models eventually paved the way for technological developments that led to various methods of making manifest these digital designs. The technologies that potentially drove perfunctory "auto-generative design" has since evolved into a catalyst for a multidimensional, sensitive design process. From virtual reality to immersive-virtual environments, to augmented reality, architecture has been quick to explore technological innovations as methods of communicating and developing design work.[6] Devices such as motion-sensing controllers (Xbox's Project Natal and Nintendo's Wii-mote) and stereoscopic head-mounted displays all allow for a heightened, richer experience of what ultimately amounts to a virtual concept. Initially pioneered by engineering and medical sciences, the rapid dissemination of these advanced visualization technologies have become ubiquitous in daily life.[7,8] These evolutionary steps in software have run the spectrum from highly photorealistic digital animation and visualization in cinema (such as James Cameron's 3D Avatar) to videogames (the incredibly realistic and detailed world of Liberty City from the Grand Theft Auto Series) and have produced hardware providing users exposure to additional facets of digital realms beyond a two dimensional canvas. That users have the ability to immerse themselves in virtualized environments with panoramic stereoscopic visualization, witness photo-accurate real-time rendering, and explore infinite levels of detail in a simulated world is no longer confined to the realm of science fiction or advanced research facilities; it is today's reality. Though this saturation of incredible visualization and representation has expanded the spectrum of imaginable possibilities in both academia and mainstream media, the fact remains that such a focus on only one of the five senses has begun to lead to diminishing returns

At the onset of the 21st century digital fabrication and rapid prototyping became widely adopted in many academic institutions and initially was utilized as primarily a method of augmenting visual representation, but has since become a critical tool for design exploration.[9] The appreciation of a tangible, built form does not reside with the pristine completed representational artifact; rather, it is the evolutionary process of exploring a physical representation that strengthens a designer's design awareness and sensitivity. The ability to produce physical components of design projects has reconnected the designer with the product they imagine.

Beyond simply serving as an additional representational medium, digital fabrication is a potent tool for students to develop design sensitivities, otherwise underdeveloped or non-existent, that many academics and professionals have claimed are eroding with increasingly computer-reliant workflows.[10] Fortunately the onset of digital fabrication has opened opportunities for students and practitioners alike to investigate and respond to various design aspects presented upstream in the process as opposed to a finished product. In their seminal work, "*Refrabricating Architecture: How Manufacturing Methodologies Are Poised to Transform Building Construction*", authors Stephen Kieran and James Timberlake maintain that a seamlessness between design and construction is critical for "the complete integration of design… using tools of present information science as the enabler".[11] Digital fabrication technologies have afforded this seamlessness to contemporary designers. Greater sensitivities to multiple facets of design are surfaced as students shift from a preoccupation of architectural computing as a visualization tool to that of fabrication and prototyping. A clear trend in an appreciation of design depth may be traced through a series of projects leveraging digital fabrication throughout the entire architectural design curriculum at Ryerson University's Department of Architectural Science.

AN INSIGHT INTO THE DIGITAL TOOLS

Though there are many tools available for bringing virtualized design concepts into physical reality, the primary tools focused upon in this context are the three dimensional printer; the laser cutter, and the vacuum former. Each technology mandated appropriate training within a classroom setting and afforded users a specific functional appropriateness for production.

A three dimensional printer is capable of producing a solid artifact by translating a solid CAD model into a series of extremely thin slices which are then incrementally printed using a fused deposition material stock (depending on the machine, the print medium can range from plaster and starch to ABS plastic). This additive process is theoretically efficient as it has the potential to produce prototypes without excess material waste, however in the process of articulating overhangs and complex geometries, it is not uncommon for a support material to be deposited in tandem with the print stock. The support material may subsequently be removed either with physical force or immersion in a caustic solution that dissolves the support material without impacting the print stock. Despite the technical complexities the computer and machinery must engage with, the skill level and dexterity required for operation is relatively low so long as the CAD model is properly constructed (that is to say, produced as a truly three dimensional solid).

A laser cutter is able to translate vector line or pixel-based raster image data into a series of pulses and streams of focused light energy into a beam capable of varying degrees of controlled burning and cutting. As the pieces are effectively projections cut out from a base stock such as a sheet of plastic, this subtractive modeling method often is appropriate for articulation of elements projected onto a two dimensional plane. Unlike a three dimensional printer, the laser cutter often requires a degree of CAD competency in order to appropriately deconstruct three dimensional elements and projections onto a two dimensional plane. Once objects have been cut from a base stock, it also falls upon the user to coordinate the reassembly of the array of two dimensional components into a three dimensional composition.

Unlike the other two fabrication technologies, the vacuum former does not necessarily require a digital or computer component as the machine simply takes an extremely pliant heated plastic sheet and draws it tightly around a reusable positive mold with a vacuum. Once the heated plastic form has been cooled, it is separated from the mold and may be processed further on other machinery. Though not directly connected to digital technologies, the vacuum form machine operates on a method reliant on a casting system whereupon the repetition of precise and consistent elements is incumbent upon a mold of even greater accuracy which is achievable through digital fabrication. It is important to understand that to produce entire projects (especially at full scale) using solely a laser cutter or three dimensional printer could potentially be quite cost prohibitive or time consuming. As such, the vacuum form allows users to benefit from the precision of using a digital fabricated base unit while enjoying the benefits of rapid and economical production. The direct, hands-on approach to using this device is intuitive for students, though a degree of practice and experience may be required to best understand the constraints and outputs of the technology (such as potential webbing, popping, and draft angles).

INVESTIGATION DRIVEN AWARENESS

Where virtualized workflows on the computer have rendered a mentality shared by many design students that the pristine, time-consuming physical model serves as a final product (reproduced at a level of caricature, whether it is a simplification of operations, scale, or built conditions), educators have since appropriated these same digital technologies to elicit a greater appreciation of nuances in design development through an iterative process. The following projects issued throughout the Architectural Science curriculum at Ryerson University showcase key facets of design considerations and the depth of design sensitivity that may be elicited through digital fabrication rather than conventional digital visualization.

Tangible Design

Despite an increasing reliance on computing in architectural education and industry, many academics have struggled to negotiate the appropriate balance between the adoption of these technologies and the propensity for intuitive modes of communication.[12] Traditional modes of representation have included sketching, drafting, and physical model-making, however it is important to highlight that these are not phases in a linear design process, rather they work in tandem in order to best articulate and develop a design. Even within professional practice it is increasingly difficult to conceive of an idea solely executed on a virtual platform. Within notable architect, Frank Gehry's office, "drawings are only made after a physical model of the design is quite far along into being crystallized, and when the model is digitalized into three-dimensional software from which conventional, two-dimensional drawings can be produced."[13]

Unfortunately for many students and even those in the industry, this is not the case. The tangible aspects of design communication, whether in scale models or prototypes, need not be isolated to a final representational step in the design process. Highly detailed technical drawings, orthographic projections of plans and sections, and even photorealistic renderings, though relevant throughout the design process, do not share the same degree of accessibility to a general audience. A physical model, regardless of detail articulation or fidelity, is useful in communicating multiple facets and dimensions of design intent to a universal audience.

Strong designers can focus their ideas, appreciate the methods of communication, and know their audiences. What is lost upon many is architectural computing has a role in *developing* a design rather than *dictating* it. The limitations of user aptitude, software capabilities, and audience accessibility impact the translation between intent and communicated design. The designer, the audience, and the medium are the three critical elements of design communication. Should any component in the relationship be compromised, the appropriate presentation of a design will fail. Architectural computing has empowered designers with an array of methods of communicating their design work from highly detailed BIM models to dramatic renderings. Digital fabrication has allowed designers to reacquaint themselves with the tangible in the design process as the rapid production and developmental process has reached a reasonable turnover time that will inevitably only decrease with time.

Physical models, unlike their digital counterparts, allow for multiple views at audience's control in real-time at a very intuitive level. Performance criteria can also be evaluated and potentially reconfigured in an ad hoc manner. A good example of the value of a tangible, fabricated design interface is a third year lighting design project. Students not only had to develop a concept for a pendant light and simulate lighting performance in a digital model, but also had to physically produce multiple copies that also had to be collapsible and flat-packed within a single, standard interoffice mail envelope. In developing this project, students not only were able to bring their designs into physical reality at a fully operational scale, but also had to consider critical performance criteria such as structural stability, assembly, packaging constraints, and of course qualities of light and shade. Through the use of laser cutting and 3D printing technologies students were able to both articulate their design intentions as well as their comprehensive awareness of multiple dimensions of consideration in the design process (Figure 1). Though lights are often perceived as static elements, the fact that a tangible component was available to students in the design phase empowered them to adjust apertures configurations, connections, and locations of pieces in order to control the quality of light in a very dynamic manner.

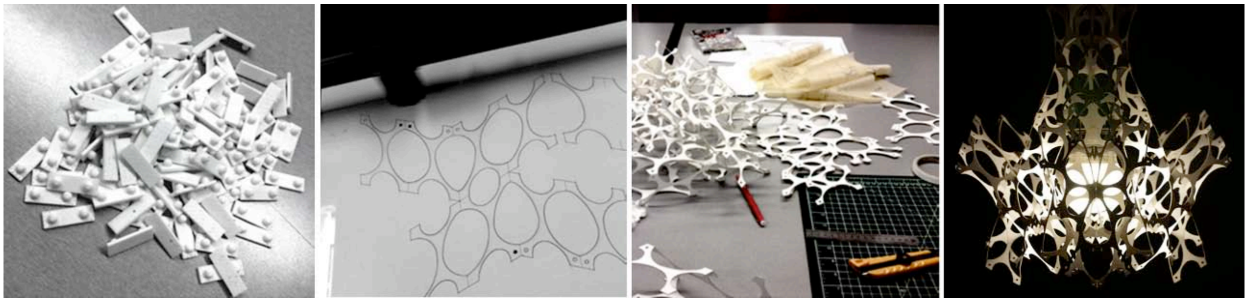

Fig. 1: (Left to Right) 3D prints of connection pieces, laser cutting of frames, assemblage of elements, and final light

Detail Understanding

With the depth of detail and information that virtual models afford contemporary architectural practice, including animations, scheduling, cost estimation, and contract documentation, it is difficult to imagine losing sight of the finer components of detailing and assembly.[14] The contemporary design process transcends seductive architectural imagery and mandates an awareness of the fundamental manner in which materials come together. In Vitruvius' *"Ten Books on Architecture"*, the great Roman architect outlined the three principal qualities of architecture as durability, utility, and beauty.[15] Through digital fabrication, students not only have the ability to tangibly understand the latter component, but also explore dimensions of materiality and functionality in their design work. The performance and behavior of elements and their assembly may be better investigated through digital fabrication.

A notable project leveraging this component of digital fabrication is a third year steel design project that asked students to consider developing a steel structure but also explore the performance and assembly of components in a detailed manner. Students immediately understood the value in rapid prototyping connections with the three dimensional printer as the consistency of a homogenous construction in the ABS printer was analogous to the relative homogeneity of steel construction. With the ability to fabricate prototype connections and understand the physical constraints and loads they dealt with, students gained insight into many properties of construction and detailing they otherwise would not have encountered simply on a computer screen. One student was able to develop an interesting steel hinge detail on a floating platform by exploring the kinematic properties of the connection through an operational prototype including range of motion, structural support, and required detailing that could not be derived from a computer simulation (Figure 2).

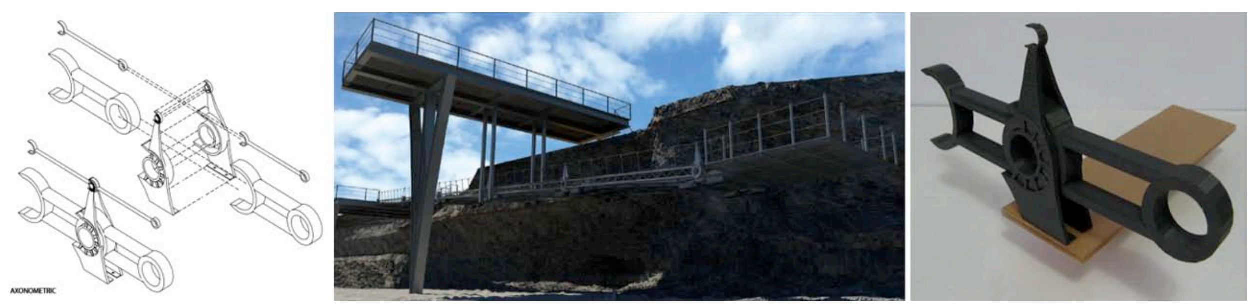

Fig. 2: (Left to Right) A CAD model of the detail, a rendered view of the connection in context, and an operable developmental prototype from the 3D printer used for design development of the hinge

Integration of an Iterative Design Process

Digital fabrication allows students to develop a rich cycle of design creation, critique, and consolidation. This iterative model of design is critical for students to develop their designs by gaining insights into their designs from third parties. In order to best articulate one's intentions, the medium becomes critical in design discourse. The cyclical ETC design process described by Robert McKim in "*Experiences in Visual Thinking*" consists of a clear process whereby designers *Express* their ideas, *Test* them, and then *Cycle* through alternative design strategies.[16] At this point in history, the cyclical design process has become a more robust system where design iterations may emerge with greater speed and ease, thereby allowing for multiple alternatives to better hone design ideas. Contemporary modes of digital fabrication are currently both accessible and quick which is essential in an iterative design process. The power of the computer has enabled students to develop a representation of their ideas yet it is often this visualization that often compels students to believe their designs are "finalized". The pristine quality of digital imagery or physical model is perceived as complete whereas a sketch is merely seen as a foundational communication medium. Contrary to this mode of thinking, all these media should be considered as modes of representation and subject to alteration and a basis for discourse.

An example of how digital fabrication has enriched the iterative design process is a project that called for students to develop interior green wall systems that would support and sustain vegetation to either address food security issues or improve indoor air quality. Rather than rely on a cycle of virtualized conjecture and discourse on a design, students were encouraged to develop incremental prototypes to showcase a proof of concept for their designs. Students not only were driven to articulate the design intention, but also had to demonstrate an evolutionary process whereby physical prototypes were used to indicate appropriate operation. In the case of one particular design, students had proposed a hydroponic system which relied on a steady circulation of nutrients dissolved in water. Though the computer imagery and sketches idealized the flow of the solution, the physical prototypes allowed students to refine the design to accommodate for the actual flow, but also methods of connection and assembly. In the process of design development, students had to present their work to a variety of consultants including professors with backgrounds in green roof design and structure. Without the prototypes, a host of issues in the design would not have been surfaced in the iterative design process thereby potentially compromising the design's performance (Figure 3).

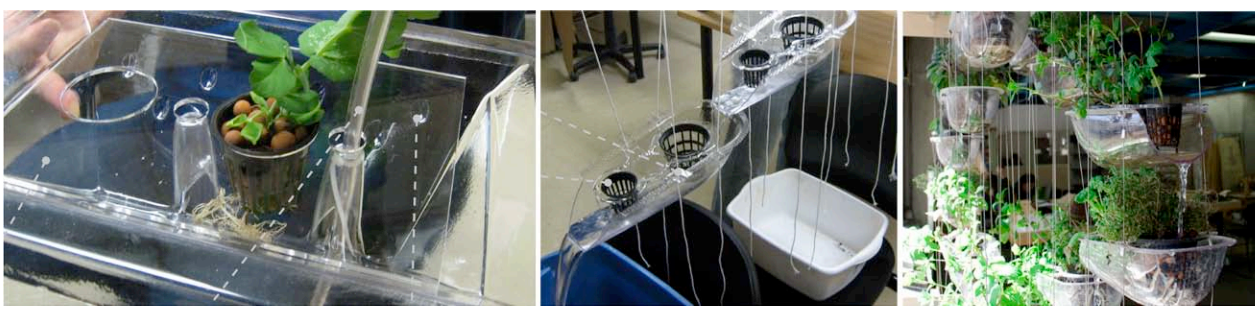

Fig. 3: (Left to Right) A sample of iterations of a hydroponic irrigation system over the course of a month from an initial vacuum formed tray configuration, to a basket configuration, to a fully secured assembly

Mass Production

The study of architecture and design is not limited to a high level macroscopic view, rather it demands that students have a great familiarity with the realities and modes of production. Additionally, an understanding of cost effectiveness through economies of scale in time and money, though often a neglected component in academia, is imperative for students entering the "real world" of professional practice. An awareness of production is critical for architecture. The past two decades have been cited as one which has empowered students to investigate extremely complex geometries with a mandate that architectural pedagogy integrate awareness of fabrication and manufacturing processes. Timberlake and Kieran argue that the "Preoccupation with image and failure to look at process has led entire generations of architects to overlook transfer technologies and transfer processes."[17]

There are several benefits in focusing on well-detailed individual components including cost effectiveness, ease of erection or fabrication, and reduced entropy in the design and construction process. The aggregation of articulate base units allow for an enhanced rigor on prototypes for mass production. Several published reports have indicated that by intimately bringing architecture students farther down the production process, these designers are able to critically examine their ideas as an aggregation of elegantly manufactured components as opposed to monolithic pieces devoid of sensitivity to construction and feasibility.[18] In a fourth year installation project, students were presented an opportunity to create interactive installations that had to cover a preordained surface area. Rather than examine the design from a large scale level and subsequently refine details and production as a secondary process. A spectrum of design iterations emerged yet a consistent theme running through the projects was the of tessellation of a series of base units in order to expedite limited resources including manpower, time, and budget. From a motion-sensing membrane that twitched based on traffic, to a triangulated vacuum formed touch screen, to an array of acoustic-sensitive pulsating orbs, to a responsive entryway, students developed interesting designs that emerged from an awareness of the production of the base components.

Fig. 4: (Left to Right) Examples of component-based interactive installation designs including a motion-sensing membrane, touch screen display, pulsating acoustic-sensitive array, and response entryway

Stakeholder Accessibility

Unlike many other professions architecture requires its practitioners to have the ability to not only cater to multiple agencies in order to produce their work (such as contractors, planning agencies, and engineers), but also communicate and relate to a spectrum of stakeholders (ranging from clients, governmental agencies, and local residential groups). Beyond the practical scope of industry, within academia students are also required to also express their ideas within a theoretical framework. That architects and artists from Piranesi and Escher to Marcos Novak and Lebbeus Woods have conjectured architectures that only could exist on paper serves to highlight a tradition of design thinking that encouraged discourse.[19] Unfortunately these deeper levels of meaning are not as well received or as accessible for conventional audiences whereupon the presence of a tangible, physical model conveys intentions at a fundamental level all people are familiar with. Design pedagogy is not an esoteric realm. The ability to communicate ideas at an accessible level is an invaluable asset for students to appropriate while in school. Digital fabrication methods have allowed designers to not only facilitate the iterative design process, but also produce tangible components that may be understood with greater ease to a wider audience. Various user groups from different backgrounds may better understand a project and discuss issues pertaining to a concept that is physically available. Rhetoric may express ideas but tangible objects generate discussion.

The liberation from production capacities enables a greater design focus while providing a platform for both design conceptualization and greater accessibility to wider audiences. Innovative design and interesting hypothetical design exercises often make for interesting posters, however to the general public and a general audience, physical models allow them to penetrate beyond the veneer and better understand the nuances and sensitivities a designer may be entertaining. At the same time, as the innovations of contemporary architecture design push the boundaries of form and technology, reproduction of these complex designs with conventional methods of representation would be extremely difficult to execute with precision and accuracy. The synergy of digital fabrication technologies and representation has been instrumental in liberating students in their design work. This is most evident in the realm of design presentations and competitions. An example of this within Ryerson University's Department of Architectural Science is the competition work executed in a second year landscape course which not only demonstrates an aspiration to explore innovations in design while at the same time physically demonstrating these principles to an a general audience through an intuitive and approachable medium – the physical model (Figure 5).

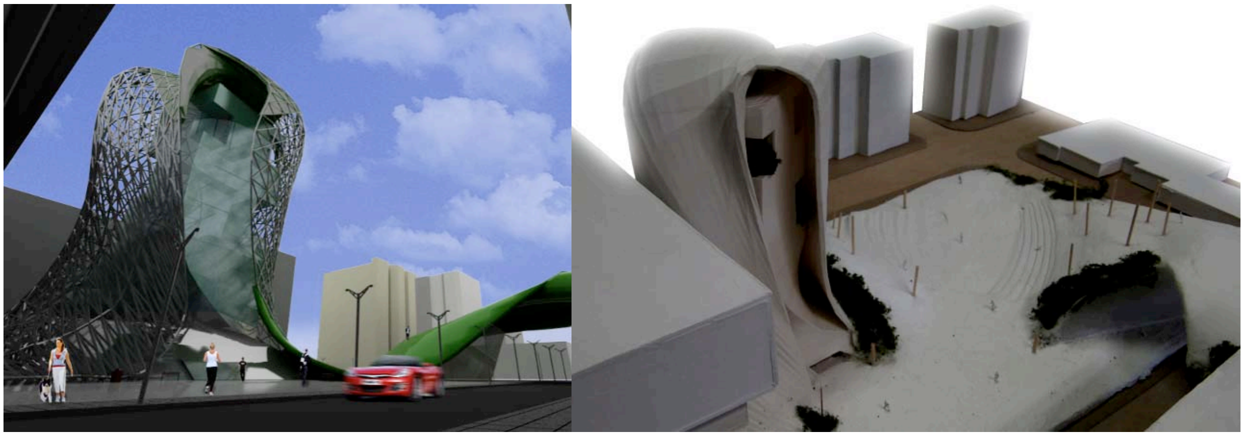

Fig. 5: (Left to Right) A second year landscape design project allowed students to not only present imagery from a CAD model alluding to a complex form but through a three dimensional print and laser cut model rendering the design more tangible to a diversity of stakeholders on the judging committee

CONCLUSION

From a pedagogical perspective, unlike the didactic model commonplace in many technical courses, the education that occurs in an architectural design studio arises from an amalgam of various learning models from experiential-learning to practice.[20] The spectrum of learning modes must have a corresponding variety of developmental and communication media. It would therefore be inappropriate to constrain students' educations to only technologies used since the inception of the first built condition. Where architectural computing precipitated a paradigm shift in the modes of communication and pedagogy in academia and industry over the past two decades, digital fabrication currently is adopted as the next evolutionary step in pedagogy and practice. Once thought of as beyond the realm of feasible implementation for financial or technological constraints, digital fabrication technologies have experienced significant drops in capital investment and improvements in user interface and accessibility.

The sampling of projects highlights the potential these fabrication technologies open up to students such that they may go beyond the representational capacities rapid prototyping has to offer and gain greater insights and sensitivities into their design work and education. Tangibility of design work, detail development, production consideration, enhanced stakeholder accessibility, and a greater productivity in the iterative design process are among the many reasons why digital fabrication serves to add an additional dimension to design pedagogy and process.

Student Contributions:

Figure 1: "*Instruction Toward Illumination*": Hsiao-Chung (Anthony) Chieh and Ho Suen (Winnie) Lam
Figure 2: "*Detail Fabricatin":* Jonathan Wong and Calvin Fung
Figure 3: "*On Form and Growth":* Kayeon Lee, Nicolas Boutin, Farah Kabir, Farhan Durrani, Jessica Gibson, Richy Seto
Figure 4: *"Floor Wall Ceiling":* Kyle Anderson, Donna Behrouzian, Freddie Chan, David Feenstra, Calvin Fung, Donna Ghorashi, Faiyan Khan, Robert Morrone, Maria Ng, John Payne, Aamir Shaikh, Regina

Shing, Michael Sirlois, Iris So, Ghazal Taikandi, Sarah Wendland, Kwan (Leo) Wong, Bernard Wun, Andy Yeung, Hyebin Yoon, Hsiao-Chung (Anthony) Chieh, Ho Suen (Winnie) Lam, Michael Lanctot, and Nadia Qadir

Figure 5: *"Urbanica"*: Dadin Duldul, Wasif Ahmed, Abdul-Moiz Khan, Rowena Domingo, Aileen Soria, Jason Paulos, Sheliza Khan, Esteban Fernandez

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