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Virtual to Physical: Integration of Design Computing and Digital Fabrication in Architectural Pedagogy

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Abstract This study examines the significance of digital fabrication of scaled physical models in the digital design process and highlights the integration of design computing and digital fabrication in architectural education. Advances in CAD/CAM technologies have increasingly influenced building design and construction practices by allowing the production of complex forms that were once difficult to design and construct using traditional technologies. At the advent of digital architecture, schools of architecture introduced digital technologies to their curriculum, focusing more on design computing than digital fabrication, preventing students from completely mastering digital technologies. The significance of digital fabrication for scaled physical models as a design media within the digital design loop is discussed. Two case studies of leading schools of architecture that are successful in building the bridge between both areas are given. These focus on the curricular structure to integrate both areas within design studios. Finally, a curricular structure offering students a balanced approach to these areas of knowledge is proposed based on what was learned from these case studies.

Keywords: Physical Model; Design Loop; CAD/CAM; Fabrication; Integration; Curriculum

1. INTRODUCTION

Digitally-driven architecture is raising new design possibilities. Advances in CAD/CAM technologies are radically changing the way of designing and constructing buildings and narrowing the gap between what can be designed and what can be built. The final result of this digital architecture, characterized by a dynamic transformation of three-dimensional structure, is highly dependent on not only the designer's aesthetic sensibilities but also the designer's expertise in using digital technologies. Schools of architecture the world over introduced digital technologies to their curriculum with a focus on computer based visualization at the advent of digital architecture (Kvan et al. 2004). They failed, however, to give the same attention to digital fabrication, limiting student's skills in exploring the quality of complex space to two-dimensional rendered perspectives on a computer screen. This imbalance between design computing and digital fabrication resulted in students having an incomplete mastery of digital architecture. This study emphasizes the significance of digital fabrication for scaled physical models as not only representation tools but also a design tool in the digital design loop and aims to highlight the need for a balance between both areas in architectural education. In Section 2, the scaled physical model is re-evaluated under the digital architecture context and the need for digital fabrication for physical models is discussed. Section 3 investigates the curricular changes in two leading schools of architecture that combined design computing and digital fabrication education and integrated them with design studios in a successful manner. Section 4 proposes a curricular structure that offers a balance of knowledge in both areas as a general pedagogical approach.

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2. THE PHYSICAL MODEL IN DIGITAL ARCHITECTURE

(1) The physical model in the architectural design process

There are different methods to represent and explore three dimensional architectural spaces. The first basic method documenting spatial organization includes two dimensional drawings such as plans, elevations and section rendered on a two dimensional medium. The second method includes drawings showing space rendered three dimensionally: perspectives, isometrics and axonometrics. These can show the depth of different volumes and often help in the understanding of

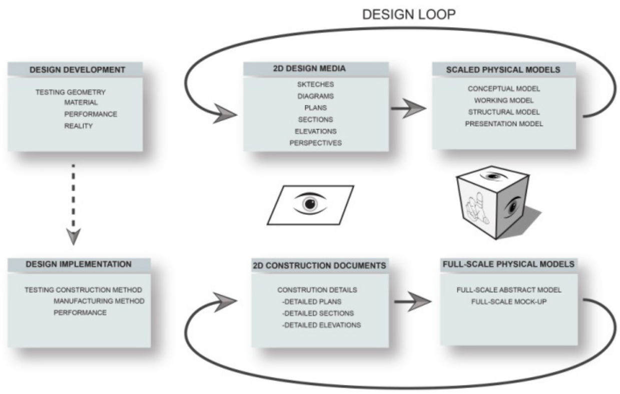

Figure 1. Typical relationship of design media in design loop

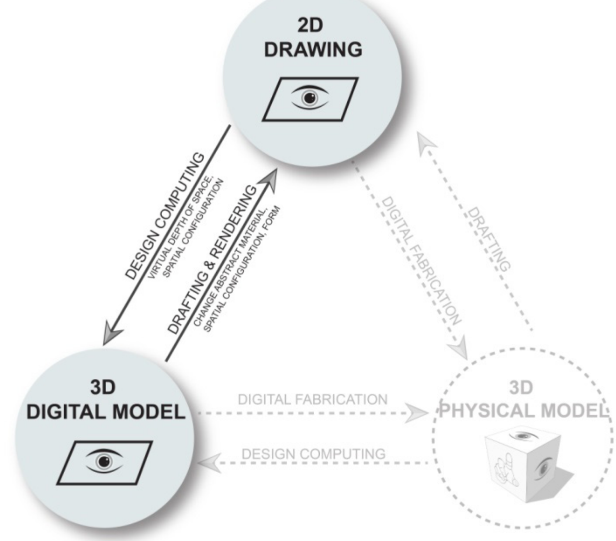

Figure 2. Incomplete design loop with little feedback from physical models

spatial configuration by showing plans, elevations and sections concurrently. These are still expressed, however, on a two-dimensional medium. The third method is a three dimensional scaled model made in a physical manner. Physical models share a greater success in aiding complex visual relationships because the physical model and the viewer share three-dimensional space and its tactility in the same reality (Porter and Neale, 2000). A scaled physical model is considered by most as the best way to describe spatial quality to others including clients and consultants and is very useful to the architects as a design tool. Physical models not only help the perceptual process but also function as design aids. Hensel and Menges (2006) stress that physical modeling can function as: a platform for form-finding and performance analysis; scaled rapid prototypes, testing the geometry and linking between assemblies of elements; or 1:1 scale prototypes, investigating the manufacturing methods and performance and behavior capacities of the design (Hensel and Megen, 2006). At the same time, scaled physical models hold more potential in indicating new design directions, helping to check deficiencies in design and in their refinement curb the effort of imagining various problems only in drawing (Morris, 2006). It is clear that physical models as a design medium offer a continuum in the perceptual and design generative processes. They enable a designer to better understand complex space through a tactile experience and provide a designer with more feedback within the iterative loops of the design process shown in Figure 1.

(2) Limits of virtual model

The introduction of CAD (Computer-Aided-Design) into architectural design enabled architects to explore topological and non-Euclidean geometries that were previously impossible to execute manually. Since the late 1980s digital computer modeling through CAD as an effective tool to experiment on complex forms has become pervasive in all aspects of architectural education and practice. In the early stages of digital architecture, however, computer-generated images often seduced students and architects with quick and unrealistic images. Architects have focused on the production of free form design as computer generated images and less as physical products (models or building) and come up with curvy, almost sensual images of free form designs made for magazine covers, ignoring the complexities of construction or any potential as a materialized construct (Saas, 2006). From this lack of materiality, some theoreticians, critics, and designers would find the space of digital models negatively immaterial, threatening the tectonic thinking of architecture (Mitchell, 1998). On top of the lack of materiality, the digital models and images generated on a two dimensional media reveal limits of the perceptual process. Allen (1998) addresses that the digital model assumes that a very narrow range of perceptual mechanism comes into play in the experience of architecture: a tunnel-like camera vision, ignoring the fluidity of the eye and the intricacies of a peripheral vision-not to mention that rest of the body, so the computer simultaneously collapses and increases the distance between the architect's two-dimensional representations and the building's three-dimensional reality (Allen, 1998). Spatial exploration through virtual model only with little tectonic thinking and a limited perceptual process cannot complement the iterative design process. Reiser and Umemoto (2006) point that the material computation will always generate richer and more singular expressions than the emulation programs derived from them will produce. A design loop with little feedback from physical models would make little contribution to the computer-generated logical process of design as shown in Figure 2.

The selective students' works from a architecture design studio taught by the author in 2011 and 2012 are provided below to examine the exemplary output of the incomplete design loop. This design studio was inspired by Dale Chihuly, an avant-gardist in the development of glass as a fine art. Students were encouraged to explore the space for a glass exhibition and workshop through reinterpretation of the transformative aspect of glass making. The first project developed multiple continuous curved surfaces as an extended space that blurs the boundaries between programs, between vertical and horizontal elements, and between building and context. The student was inspired by the different types of forces applied in the transformative process of glassmaking: pushing, stretching, and twisting. An early computer model built in Rhinoceros was used for conceptualization and form generation. The building form was very fluid and seductive. It is, however, difficult to understand the spatial configuration created by the continuous curved surfaces through traditional

Figure 3a. Computer rendering

Figure 3b. Model photo

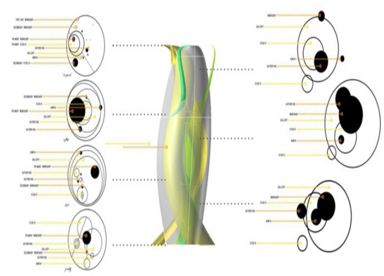

Figure 4a. Computer-generated diagram

Figure 4b. Model photo

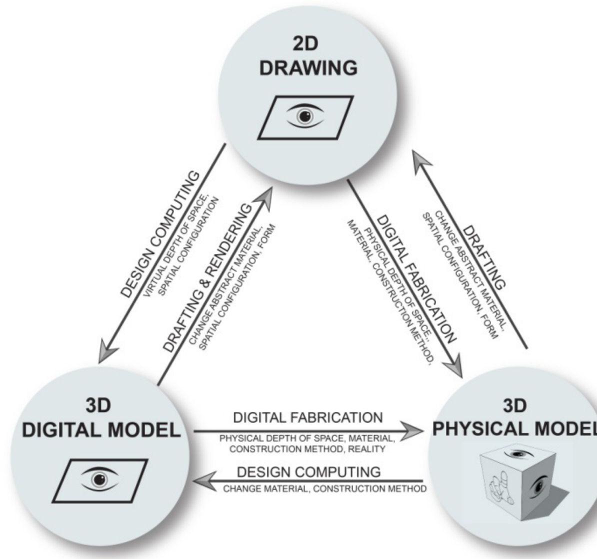

Figure 5. Complementary design loop with feedback from physical models

architectural drawings and even multiple renderings at a glance. During the semester the student has shown drawings without complete physical models unfortunately due to limited knowledge on how to create multiple continuous curved surfaces in physical manners. The feedbacks from physical models were lost within the cycles of design experimentation. A final physical model didn't successfully show the design intent and spatial quality that other drawings and renderings delivered as shown in Figure 3a and 3b. The second project explored multiple twisted and curved interior spaces enclosed by a single curved exterior envelope to create a unique user's experience while circulating through the program. The student was fascinated by the change of relationship between different programs and people's interaction between the exterior and interior based on what the student interpreted as the way air and heat drive glass transformation. The design process began with an analysis of program adjacency and interactions, and modeling their transitions utilizing Rhinoceros. This provided interesting spaces explaining the idea as shown in Figure 4a. In the next step of developing the conceptual idea into a real three-dimensional space, limited modeling techniques for curved surfaces didn't offer the student freedom to explore new spatial opportunities during the design process, and ended up simplifying the form into something that didn't deliver the author's initial design idea convincingly as shown in Figure 4b.

(3) Digital fabrication in digital architecture

In the pre-digital era, traditional designing and building techniques were entirely based on Euclidean geometry (Lynn, 1999). The introduction of CAD into digital architecture enabled architects to generate and manipulate a topological geometry of continuous curves and surfaces that exist outside of Euclidean geometry. Architects soon found difficulties, however, in giving real spatial materiality to these complex forms in scaled physical models and buildings with traditional fabrication and construction methods. Saas (2006) indicates that at the onset of digital architecture few expressed the ability or desire to build outside of known Euclidean shapes as opposed to contemporary architects who have demonstrated that it is possible to design and build variations of Euclidean shapes as free-standing or interrelated designs (Saas, 2006). Objects at this level of complexity in digital representation could not be processed with manual fabrication techniques to their materiality (Kolarevic, 2005a). The advent of CAM (Computer Aided Manufacturing) that makes digital data control fabrication tools enabled architects to handle the structures and forms in that level of complexity, and then to give physical reality either in scaled models or in full scale construction to these seductive images that used to exist in virtual space only. The current innovations of CAD/CAM are narrowing the gap between visualization and building with a seamless transition between design and construction. CAM/CAM technologies opened up new opportunities by allowing production and construction of very complex forms that were, until recently, very difficult and expensive to design, produce and assemble using traditional construction technologies (Kolarevic, 2005b). Physical models that have been employed in the design loop at key stages of project development rebuild the relationship between means of design as well as representation of different dimensions via CAM development. CNC fabrication provides a vital link between the virtual and physical model and integrates digital fabrication with the design process, allowing a more direct exploration of the relationships between material, form and performance (Menges, 2012). In short, CAM technologies restore the role of physical models within the design loop in digital architecture. Figure 3 shows that the integration of digitally fabricated physical models into the iterative design loop of a computer aided design process would raise new possibilities for innovation in the digital design process where feedback between the virtual and physical reality is critical (See Figure 5).

3. ARCHITECTURAL EDUCATION TOWARD DIGITAL INTEGRATION

The comprehension capacity of designers strongly relies on the design world that the design medium they prefer to adopt can construct (Rowe, 1987). Accessing these generic tools enables architects to create their individual design instruments and thus generates diverse forms of expression (Gramazio and Kohler, 2008). Digital fabrication for scaled physical models as design media uses different types of fabrication tools including a laser cutter, a 3D router, a thermal former, a 3D rapid prototyping equipment, and combinations thereof. From a design generative point of view, different fabrication methods open up possibilities in offering new design directions. The distinctive effect of working models from each fabrication method during design development is the offering of a different perspective on forms, structure and materials to designers in the design loop. The possibilities and restrictions of fabrication technologies can potentially become generative drivers integrated into a computational design framework (Menges, 2007). It is critical for designers to understand how to translate a computer-generated virtual model into a digital language that CAM can understand and have the ability to choose the correct fabrication tools for constructing a design. It is therefore necessary for digitally savvy architects to understand how these tools work, which materials they are best suited for, and where possibilities lie (Iwamoto, 2009). Unfortunately, at the onset of digital architecture schools of architecture overlooked the significance of integrating digital fabrication into the curriculum, resulting in asymmetric curricular development. Architectural education and practice can benefit from the strategic integration of digitally fabricated models into the design process: where specific forms and goals require specific modeling tools (Globa et al., 2012). In order to educate future designers to be capable of facing design challenges with a balanced skill set of both design computing and digital fabrication, a critical perspective on changes to the academic structure is required.

(1) Research methodology

The following sections investigate two cases of leading schools of architecture that bridge the gap between design computing and digital fabrication in a successful manner, focusing on the change of curricular structure the schools went through to integrate both areas into the curriculum and design studios. The selections of the schools for analysis were based on the Architecture School Guide 2009: Schools that excel in digital design and fabrication[1]. The curriculum of the M.Arch I program is chosen since it is oriented to those who haven't had a solid architectural education background that includes design computing and digital fabrication. The comparisons between the course structure in 2005 when digital fabrication began to be incorporated into the curriculum and that of most recent years are made based on descriptions of courses offered and the course syllabuses made available at each school.

Collected courses for comparison are categorized in the areas listed below:

- Area of study
- Digital courses vs. non-digital courses[2]
- Mandatory vs. elective digital courses per area of study
- Computing-oriented vs. fabrication-oriented vs. combination courses of the two per area of study
- Semester of course offering

The subsequent analysis focuses on the changes below:

- Overall relationship among areas of study
- Number and ratio of digital courses by area of study
- Number and ratio of computing-oriented vs. fabrication-oriented vs. combination courses of the two per area of study
- Criteria of computing and fabrication for different areas of study
- Number and ratio of mandatory and electives in digital courses
- Curricular sequence of mandatory computing and fabrication courses

The analysis of these changes shows how these two schools value the relationship between computing and fabrication and incorporate this within their curriculum. The interviews with faculty and former students are provided to investigate each school's unique approach to the curricular integration.

(2) Case Study-1: Taubman College, University of Michigan

The main curricular framework for three-year master's program of Taubman College at the University of Michigan has a series of rigorous core design studios that are integrally linked to other areas of study. As seen in Fig. 6, there was a significant change in the curriculum between the 2004-2005 academic year and the 2011-2012 academic year. There were 8 areas of study in 2004-2005: Design studio, Design Fundamentals, History/Theory, Structure, Construction, Architectural Representation, Sustainable Systems and Environmental Technology, and Urban and Landscape Design. In 2011-2012 Digital Media was added to these existing eight areas of study. The significant increase in the number of courses in Construction represents a strong interest in material research newly infused with digital capabilities. The introduction of Digital Media with a focus on design creates a reorganization of computing courses that in 2004-2005 belonged to the area of Architectural Representation and demarcates two realms of computing: Computing courses providing more design generative instruments moved to Digital Media, and those on drafting and graphics remained in Architectural Representation. Conversely, the area of Architectural Representation focuses on non-digital courses strengthening traditional representation skills and hand-drawing (See Figure 6). The change of design computing and digital fabrication courses across different areas of study is illustrated by the fact that in 2004-2005 there was only one digital fabrication course without design computing in Construction while in the academic year of 2011-2012 there were several digital fabrication courses, among which two taught design computing concurrently in the same area of study as shown in Figure 7. Some of the digital fabrication courses in Construction are integrated with computing courses in the area of Digital Media as shown in Fig. 6.

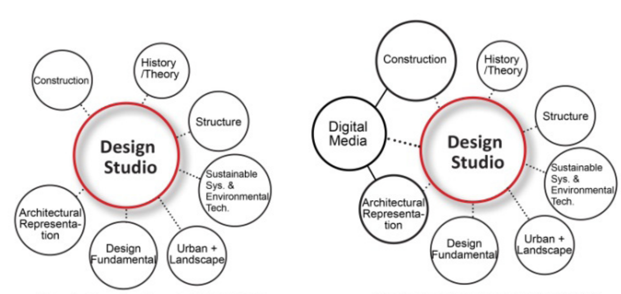

Figure 6. Change of curricular structure at Taubman College

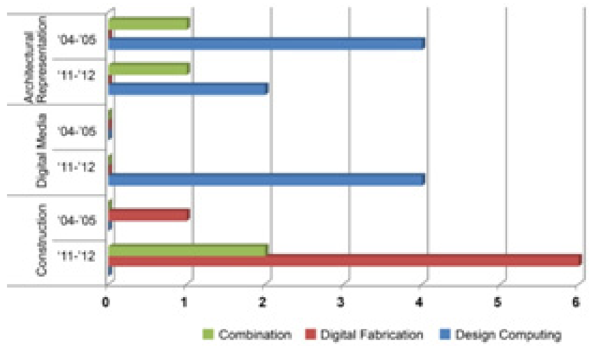

Figure 7. Change of computing and fabrication courses by area of study at Taubman College

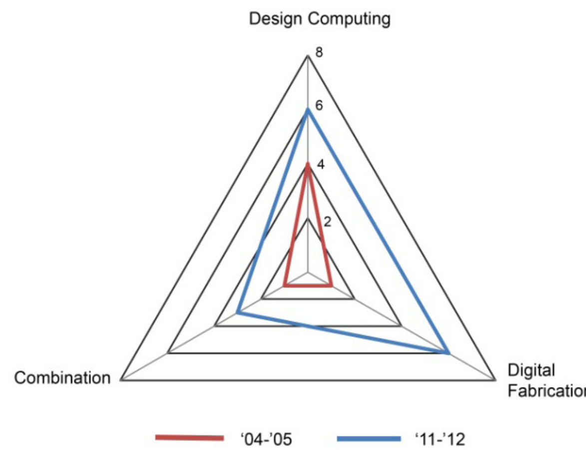

Figure 9. Change of overall number of computing and fabrication courses at Taubman College

Glenn S. Wilcox, an assistant professor of Architecture, comments on the pedagogical approach to achieve the integration of digital computing and fabrication during an interview in July 2012:

> *Some courses integrate fabrication tools into the process of computing classes and so try to achieve computing skills and their material ramifications within one course. In the end of this integrated course, students can learn basic fabrication tools….. There is also the collaboration between computing class and the fabrication class. For instance, students can work on one project by taking a computing class first, and then a fabrication class later. Michigan has support at the administrative level as well. The budget will be provided for combining seminars and studio.*

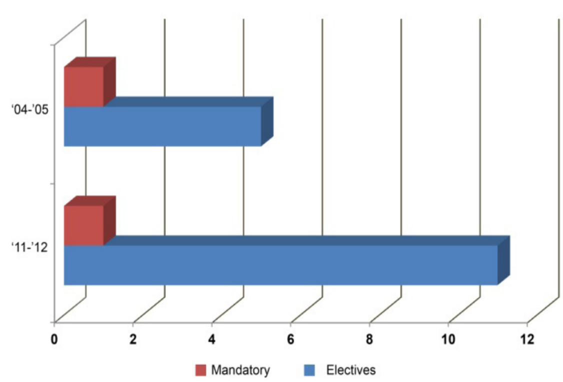

Figure 8. Change of mandatory and elective digital courses at Taubman College

It is also interesting to note that the number of mandatory courses didn't change even though the number of digital courses offered increased by almost 100% as shown in Figure 8. There is one mandatory course in Architectural Representation providing design computing and digital fabrication at the same time. The time of mandatory course offering is the second semester in both 2004-2005 and 2011-2012. The college doesn't require all students to master digital fabrication skills but offers many electives to those who want to do so and provides basic digital technologies of computing and fabrication in the first semester right after classes teaching traditional representation skills. Kyle Sturgeon, a former graduate student of Taubman College and a current director of advanced studios at the Boston Architectural College addresses during an interview in July 2012:

> *At Michigan, none of the digital fabrication courses except for a couple are required and the single representation course carries much of the weight in introducing digital representation software. However, Michigan faculties have a strong affinity for the technical tools available to architects and integrate them into the work of the studios and seminars. It is culturally 'in-the water' and there is a level of craft and representational skill that is expected by virtue of the studio environment and the level of work produced by peers. There are many electives that are consistently offered that focus specifically on digital technologies. Digital fabrication is available to all students. The cultural expectation is that students will choose to pursue or expose themselves to these technologies because it is a major characteristic of the school.*

On top of the general increase of digital courses by 150% across different areas of study, digital courses that placed more emphasis on design computing in 2004-2005 were reconfigured to provide balanced importance with design computing and digital fabrication in 2011-2012 as shown in Figure 9. Digital Media, Construction and Architectural Representation focus on a distinctive area of study and at the same time are integrated in the aforementioned way to support Design Studios, enabling students to acquire a balanced skill set including digital modeling, fabrication and traditional hand-drawing, and to utilize these skills in their Design Studios.

(3) Case Study-1: Southern California Institute of Architecture (SCI-Arc)

The main curricular framework of the three-year master's architecture program at SCI-Arc consists of a series of rigorous core design studios that are linked to other areas of study. There were remarkable changes in the curricular structure between the 2005-2006 academic year and the 2012-2013 academic year as shown in Fig. 10. There were 4 areas of study in 2005-2006: Design Studio/ Soft Tech (visual arts)/ Hard Tech (technology)/ History, theory and humanities. Soft Tech (focusing on design computing) addressed and encouraged the development of visual communication techniques driving design work. Hard Tech focused on the exploration offered by science and technological arts by developing a critical base of knowledge in material technology. These two areas of study introduced the latest technologies- from advanced digital modeling tools to equipment for digital fabrication- alongside traditional methods such as constructed and freehand drawing and woodworking. In the 2012-2013 academic year the previous course structure was reconfigured into four different areas of study: Design Studio/ Cultural Studies/ Applied Studies/ Visual Studies by redistributing the previous courses falling into Hard Tech and Soft Tech under Applied Studies and Visual Studies. The Visual Studies program takes a central role in the education of communications techniques and required skill set offered across the SCI-Arc course curriculum. It responds to the constantly evolving paradigms of architectural communication, introducing new tools ranging from advanced digital modeling and animation to the equipment for CNC processes. On the other hand, Applied Studies explores the way of making physical environments through materialization of abstract ideas into the spatial form of building context (See Figure. 10). The increase of courses offering design computing and digital fabrication by 100% suggests that SCI-Arc sharpened its focus on digital architecture. The courses offering digital fabrication with or without design computing were increased from two to eight in Visual Studies and from six to thirteen in Applied Studies as shown in Figure 11. Hsinming Fung, a director of Academic Affairs comments on the increase of digital fabrication courses as pedagogical approaches that SCI-Arc highlights at during an interview in August 2012:

For 8-10 years SCI-Arc has been a pioneer in using digital technologies. In the beginning, digital technologies were representational tools or just rendering tools. In other words, software was dictating design. Particularly it controlled design. But I believed that software should be just a tool and should not limit design. So students should learn different applications. SCI-Arc's pedagogy is learning out of building, not rendering. It is tied to approval of a concept, testing ideas beyond the screen or paper. You have to understand properties of the material and figure out how to build with it, which computers cannot do. The intelligence of how to put these things together is what we need to teach. The changes of design software and curriculum have to address that. We don't teach techniques and take a look at it as an instrument to help students. Teaching design is most important. Teaching tools is secondary.

Herwig Baumgartner, a professor of Design, also stresses the importance of the digital fabrication process as a design tool during an interview in August 2012;

Digital fabrication and the process of making objects have been a central part of our process because models do a really good job at approximating reality. We use them less as a final product for presentations but as a prototype to develop and explore materiality, specifically facts and color. My studio considers physical models as a working tool for progress models at different scales. For me the model-making process is a hybrid of different techniques. Each different technique makes a model look different. It looks a lot richer and complex in terms of understanding its parts. This is why my studio really emphasizes it and thinks it is as important as drawings.

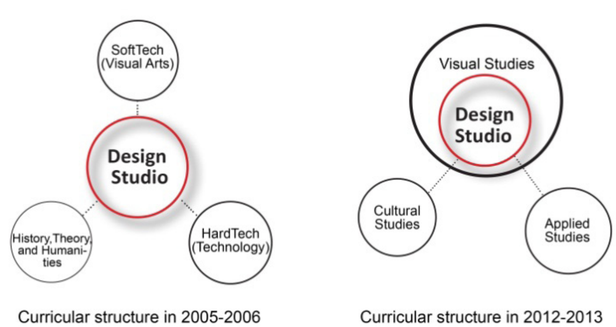

Figure 10. Change of curricular structure at SCI-Arc

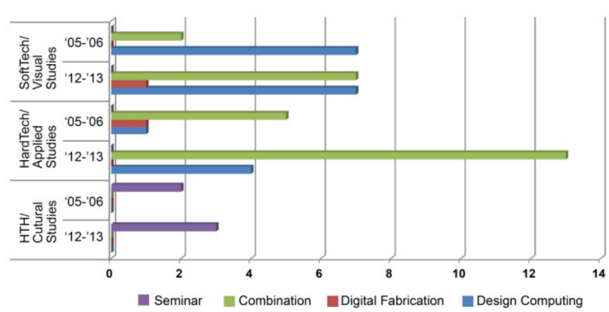

Figure 11. Change of computing and fabrication courses by area of study at SCI-Arc

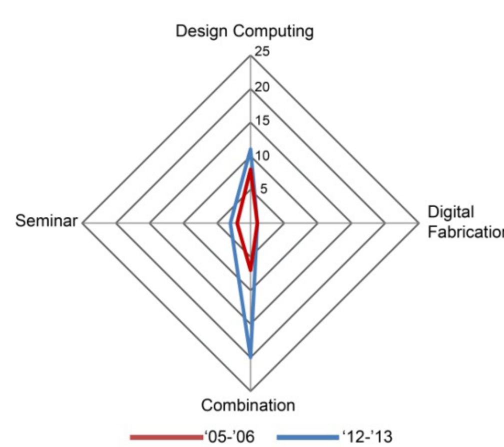

Figure 12. Change of overall number of computing and fabrication courses at SCI-Arc

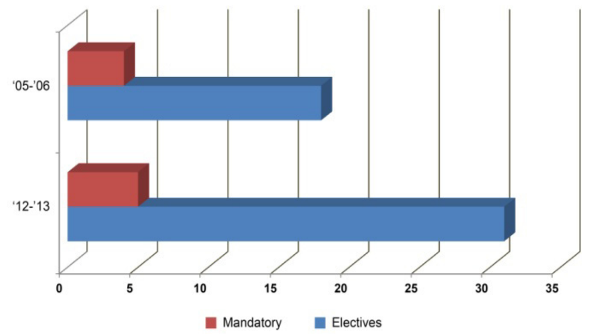

Figure 13. Change of mandatory & elective digital courses at SCI-Arc

SCI-Arc not only emphasizes the significance of digital fabrication but also stresses the importance of its integration with design computing by continually improving courses offering design computing and digital fabrication concurrently regardless of the area of study. The number of combination courses increased from seven in 2005-2006 to twenty in 2012-2013 as shown in Figure 12. Another change in SCI-Arc's curriculum is the slight increase of mandatory courses in Visual Representation encompassing computing and fabrication from two in the 2nd and 3rd semesters in 2005-2006 to three in the 2nd, 3rd and 4th semesters in 2012-2013. Even though the number of mandatory courses didn't increase significantly, the elective courses increased significantly by 160% as shown in Figure 13. This shows that SCI-Arc doesn't require all students to master digital fabrication skills but offers many electives to those who want to deepen their knowledge of design computing and digital fabrication. It is also interesting to observe that the characteristics of the digital fabrication courses are distinctive by area of study. Seunghyun Kim, a graduate of the program in 2011, points out during an interview in August 2012 that digital fabrication in Applied Studies focuses on assembly and material behaviors at full scale while digital fabrication in Visual Studies is geared toward the exploration and representation of form at a physical model scale which can be utilized in Design Studio. Baumgartner comments on the pedagogical approach to achieve the integration of Visual Studies and Design studios;

> *The courses of Visual Studies are parallel to design studios and support them. They are coordinated with studios to help students learn tools to use in studios. Seminars and Design Studios are parallel and connect to each other as well. What is taught in seminars is coordinated between them to better tie them together. There is also strong collaboration among the faculty teaching Core Studios, Visual Studies and Applied Studies. Faculties meet before each semester and discuss what is successful and less successful as well as what to improve, and then exchange ideas with administrators.*

In summary SCI-Arc emphasizes digital fabrication courses in order to realize its pedagogical goal of learning from building. The broad distribution of design computing and digital fabrication in the curriculum and the large number of courses that teach the two

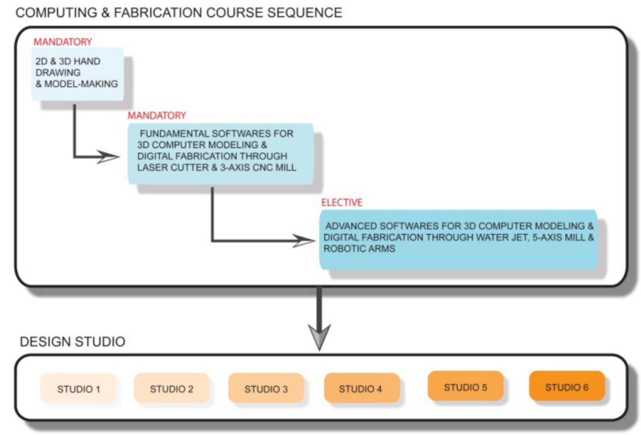

Figure 14. Proposed sequence of computing and fabrication courses

simultaneously enable students to acquire a balanced set of digital representation skills for use in producing both design process and final presentation images and models.

(4) Learning from two case studies

Digital innovation can be found not only in each schools' resources, including computing software and fabrication tools, but also within their curriculum. In spite of unique pedagogy per each school, the invaluable innovation direction in common can be found. The main framework with a series of rigorous core design studios integrally linked to other areas of studies did not change in both schools. The courses of visual representation run parallel to design studios and support them. They are sequenced and coordinated with studios to help students learn tools applicable to design work as shown in Figure 14. The sequence of visual representation courses first explores understanding and generating two and three dimensional forms in manual methods through traditional hand-drawing and model-making to develop design logic and skills before acquiring digital modeling and fabrication skills. The second course introduces the exploration of key three dimensional forms through digital media, which encompasses the fundamental fabrication techniques using a laser cutter and a CNC mill. Lastly, advanced modeling, rendering, and fabrication techniques covering joinery using a combination of equipment including a water jet, plasma cutter, and robotic arms are offered. The most remarkable curricular change is that the number of courses offering digital fabrication increased. This conspicuous increase of digital fabrication courses provides students with more opportunities to acquire a balance of skills between computing and fabrication. Both schools encourage collaboration between courses of two realms. Another interesting fact to note is that the number of mandatory courses covering both areas didn't change significantly while the number of electives increased remarkably. The knowledge of fabrication has been included in mandatory courses implying that fabrication skills are considered to be part of the skill set that students must have. The schools offer many electives to those who want to master design computing and digital fabrication. Courses of visual representation covering design computing and digital fabrication are offered in the early stage of the curriculum as required sequences since these become useful tools for students later in their schooling.

Each school, of course showed the curricular differentiation which deserves extra attention: Tauman College encourages integration between a computing course and a fabrication course. Conversely, Sci-Arc looks for the integration within a single course by offering more combination course. It is interesting to note that Sci-Arc provides courses focusing on two different character of digital fabrication by the area of study: one is geared toward the exploration and representation of form at the physical model scale and the other investigates assembly and material behaviors at very large or even full scale.

4. PROPOSAL OF COURSE STRUCTURE

Important changes have been made to curricula worldwide in the last decades to accommodate new demands, opportunities and potential in construction, professional and process. New strategies need to be developed to demonstrate the impact of media techniques in understanding the way designs can be visualized and processed in order to support design thinking (Kvan et al. 2004). The curriculum at most schools at the advent of digital architecture, however, gave less attention to digital fabrication. These two areas of digital architecture have not evolved in tandem, resulting in an imbalance of students' knowledge. The previous section illustrated the curricular changes of two leading schools of architecture that bridged both areas in a successful manner. This section proposes a new course structure as a broad pedagogical approach to help students acquire advanced and balanced skills in both areas via two methods based on learning from the previous section: integration of design computing and digital fabrication, and integration of both areas with design studios. A continuous education in design computing and fabrication is needed across semesters and areas of study. Students are strongly advised to have the skills listed below as prerequisites before taking a digital architecture class:

- Working in free-hand and hard-line format with knowledge on principles of two-and three-dimensional geometry
- Orthographic drawing
- Axonometric projection
- Perspective
- Architectural diagramming
- Physical modeling by hand

(1) Integration of design computing and digital fabrication courses

This approach is already used by leading schools of architecture, but is proposed here as a broad guideline for schools that have yet to adjust their curriculum but are beginning to consider integration of both areas. Regardless of whether integration is achieved within one course or two individual courses, the course should offer knowledge on both areas concurrently because this will help students relate the knowledge of one area with the other easily, actively providing feedback in the design loop compared to courses offered in a separate sequence. This course needs to provide students with various exposures to computing software and fabrication equipment as working design tools beyond the technical level of tutorials. This will enable students at the end of the course to explore complex forms and spaces and to physically visualize their designs. Listed below are the basic characteristics of the proposed course combining computing and fabrication:

1. The course will address creating a smooth workflow from the exploration of digital modeling tools to fabrication using a diverse array of fabricating machines to best represent design intentions and materiality at different scales. The course will successfully build the bridge between digital modeling and fabrication.
2. Rather than focusing on specific digital computing tools and fabrication machines, students can learn extensively about the inherent nature of each tool and choose the correct tool and process to suit their particular design intentions at the end of the course.
3. Exercises and workshops provide students the opportunity to work physically with a wide variety of tools and materials.

As learning outcomes students are expected to acquire the ability to (1) use design computing tools, (2) find proper fabrication tools, materials, and techniques, and (3) translate intangible data into physical materials through the fabrication process. The focus is on what students will be able to do and how students will show what students know. Two options can be suggested as methods to integrate both areas as shown in Figure 15. The first option (option A.1) is to offer design computing and digital fabrication concurrently in one course. Students in this course would learn design computing for digital models and digital fabrication to give these digital models a physical reality. This option would be easily administered since coordination requirements between both areas are minimal. Students can also achieve maximum feedback from the design loop because they can work on the same design for both areas. It requires the course instructor, however, to be familiar enough with computing and fabrication to teach these subjects. There also may not be enough time in one semester to offer in-depth knowledge in both areas. In this case the course can be extended into another semester as a sequenced course. The second option (option A.2) is to offer two individual courses: design computing and digital fabrication respectively. Students can thus learn both areas of digital technology separately but concurrently in one semester. Having separate courses gives the ability for each to have a larger allotment of time for the two respective areas of digital architecture. This method is advantageous in that it doesn't require a course instructor who is proficient in both areas of study. This option, however, requires more coordination of the contents and schedule of the two courses so students can use the knowledge they acquire in one course in the other course, benefitting the design loop. The key to the success of this option is close coordination between the two.

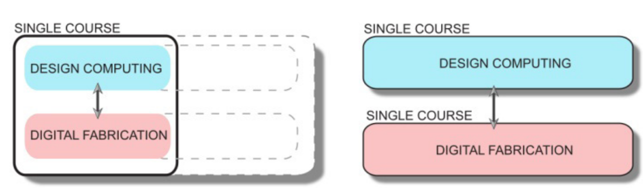

Figure 15. Proposed integrated structure of computing and fabrication courses

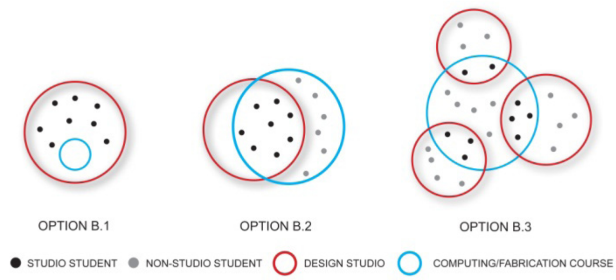

Figure 16. Proposed relationship of computing and fabrication course to design studio

(2) Integration of design computing/digital fabrication with Design studios

Students should be required to learn fundamental design computing and digital fabrication skills during early phases of the curriculum so students can take advantage of those skills as design tools and apply them to the subsequent design studios. The curriculum should be required to provide knowledge of not only computer-aided documentation and modeling but also introductory digital fabrication skills. Further integration of both areas with design studios would be ideal so students can take advantage of the skills they learn through other areas as tools to support design studios (See Figure 16). As represented in Fig. 16 three options can be suggested as methods to integrate computing/ fabrication with design studios while keeping the same number of credits that students can take. The first option (option B.1) has tutorials on computing/fabrication as a part of a design studio. All students of a design studio have the same tutorials that are provided within studio hours, either from the studio instructor or from another source outside the studio. This option would be easily administered because coordination requirements between studio and computing/fabrication tutorials are minimal. It requires the studio instructor, however, to be familiar with computing and fabrication enough to teach the students. Additionally, the time dedicated to design studio and tutorials, respectively, can be limited since both should share one semester. The second option (option B.2) overlaps a computing/ fabrication course and a design studio as represented in the diagram. This option requires all students in a studio to take the required computing/ fabrication course while it is also open to other students.

Students can have more time for design and tutorials since the two courses are offered separately and don't share the same block of limited time. If a computing/ fabrication course and a design studio explore the same final product, students can have a higher quality of final work. One tutorial offered through a computing/ fabrication course can be used for both courses. This option needs more coordination between a design studio and computing/ fabrication course since the pedagogical direction, course schedule, and contents to be covered can be different with either instructor of the two courses. The studio instructor doesn't need to be proficient enough to teach computing and fabrication skills and the fabrication instructor doesn't necessarily need design skills. From this point of view, this option makes it easier to hire instructors than the first option. The computing/ fabrication course can also have many more students than design studio. Multiple classes of computing/fabrication will be provided, depending on the number of design studios that would require the course. The inclusion of the design studio's focus into computing/fabrication may cause the studio to govern computing/ fabrication courses, possibly resulting in less diverse projects and students outside of the studio not liking the overall direction of the computing/ fabrication course. The third option (option B.3) provides the chance for multiple overlaps between the computing/ fabrication course and studios for the sake of more flexibility. As seen in the diagram, not all students in the design studio are required to take the associated computing/ fabrication course, which is good for those who already have knowledge of computing/ fabrication. Students can come to computing/ fabrication courses from different design studio with various types of projects. The diverse character of this option would limit the possibility for a specific design studio to govern a computing/ fabrication course. This option would be able to have the same merits regarding the quality of the final product, the amount of time for tutorials and design, and less stringent hiring requirements as option B.2. The multiple relationships between computing/ fabrication courses and design studios are more complex than option B.2., so it will require more coordination between them. The size of computing/ fabrication classes should be large enough to accommodate students from multiple studios and non-studios.

5. CONCLUSION

Educators in architecture must incorporate new technological and social developments within the curriculum in order to prepare students for the changing world of practice (Lynch, 2004). In the same vein, this paper discusses the significance of digital fabrication for scaled physical models as tools for representation, but also as design generative in the digital design loop, and to maintain balance between both areas of digital technologies in architectural education. The physical model as design media is still significant in the relating the virtual and physical worlds. The integration of digitally fabricated physical models into the iterative design loop of a computational design process would raise new possibilities in the digital design process, where the feedback between virtual and physical realities is critical. In order to educate future designers who can take on design challenges with balanced skills of both design computing and digital fabrication, a critical change in the perspectives surrounding academic structure is required. Case studies in two leading schools of architecture have shown how their curricular structure has changed to bridge the gap between design computing and digital fabrication, and successfully integrated them with design studios. The number of courses offering digital fabrication increased to achieve a balance with design computing. The courses of both areas run parallel to design studios, and are coordinated to support so students learn tools applicable to design projects. These courses are offered in early stages of the curriculum in a required sequence, giving practical tools for students to apply in their later schooling. It is important to integrate courses offering design computing and digital fabrication, rather than to simply increase the number of courses, because it can teach students efficient processes of taking a model from digital form to the operation of machines that brings a virtual model to physical reality. Finally, the course structure for the integration between both areas and design studios was proposed as a broad pedagogical approach for students to acquire balanced skills in both areas and apply them in their design work. It is critical that rather than focusing on specific digital computing tools and fabrication machines, students can learn extensively about the inherent nature of each tool and choose the correct tool and process to suit their particular design intentions at the end of the course.

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FIGURE CREDITS

Fig.1- Fig.2, Fig.5- Fig.16: Created by an author

Fig.3a & 3b.: Marco Montoni, Interface: Chihuly Gallery and Workshop, Boston Architectural College, 2012

Fig.4a & 4b.: Angela Sarno, Interface: Chihuly Gallery and Workshop, Boston Architectural College, 2012

ENDNOTES

1 http://www.architectmagazine.com/education/digital-design--fabrication.aspx

2 For the purpose of this research, digital courses are defined as courses offering algorithm-based computer modeling or CAM knowledge and design studio requiring them as main design tools. Courses teaching computer-aided representation are not included in this category.

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