Educating New Generation of Architects

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Abstract. Recently the developments in and the extensive use of digital design technologies have brought about fundamental changes in the way architects design and represent. As a result of the changing architectural design practise, there have been significant changes in architectural curricula to accommodate new demands, opportunities, processes and potentials provided by advance digital design tools and fabrication-based design techniques. Based on this new demand in design education, a number of additional subjects have been introduced in architectural curricula facilitating the experimentation of free-form /complex design artefact, building components and material attributes. Reported in this paper is the experience of the students as well as a commentary on the quality of the outcomes they achieved whilst confronting this new learning experience. Based on the analysis of collected questionnaire answers, this paper will document the issues that the students experienced during digital design development, the modelling and assembling level as well as in the process of fabrication.

Keywords. Digital architecture; fabrication; design teaching and learning.

INTRODUCTION
Emergent modes of computer aided design and manufacturing technologies have transformed the current processes of architectural design practise into a new understanding of the design realm by facilitating the creation of complex geometries, with greater accuracy, faster finishing and increased automation. The potentials of algorithmic programming, generative design and parametric design for architecture have been demonstrated through the works of some of the well known designers of our time. A unique and innovative approach to the process of delivering complex building projects (Shelden, 2002) and design artefacts have been developed such as in Gehry Partners, Greg Lynn and Herzog de Meuron. CAD/CAM (Computer Aided Design / Computer Aided Manufacturing) tools and CNC (Computer Numerically Controlled) technologies which started to be used in design profession, provide many new possibilities for the development of industrial manufacturing, creating free-form / complex design artefact and building components. In particular, CNC technologies have the capacity to significantly alter and enhance the relationship between architect and material through the means of digital fabrication (Booth, 2009).

As a result of the current scene of architectural design practise, there have been significant changes in architectural curricula to accommodate new demands, opportunities, processes and potentials provided by the advance CAD technologies (Kvan et al. 2004) and the fabrication-based design techniques. Based on this new demand in design education, number of additional subjects have been introduced in architectural curricula facilitating the experimentation of free-form / complex design artefact, building components and material attributes,
as well as experiencing the digital design processes and production. We offered students a new subject to facilitate the understanding of digital design processes including experimenting on parametric, algorithm, morphology, form and the material attributes of designing. We advocate the digital design studio which includes both components of solving a design problem such as in a design studio and software learning focusing on the implementation of the skills on a design task.

Reported in this paper is the experiences of the students as well as a commentary on the quality of the outcomes they achieved whilst confronting this new learning experience. A comprehensive questionnaire were developed and used at the end of the course for students to reflect and evaluate their design and production experiences. Based on the analysis of collected questionnaire answers, this paper documents the issues that the students experienced during digital design concept development and 3D modelling as well as in the process of fabrication. Our observations and the outcomes of the studio show that the students managed to learn the modelling software, to design the artefact and construct the models during the course in a satisfactory level. The paper also considers how this initiative will prepare the new generation of architectural design students to learn digital design processes and to develop skills of using CAD/CAM technologies and fabrication techniques as the new kind of design medium.

THE DIGITAL ARCHITECTURE AND FABRICATION STUDIO

Following the concerns above, an elective course is offered as an undergraduate subject in a newly established Architecture Program in International University of Sarajevo (IUS), Bosnia and Herzegovina in 2010 and 2011. The weekly studio included one-hour theoretical, 3 hours computer-based and 3 hours fabrication-based studios in the Architectural FabLab at IUS for 14 weeks. The course served as an introductory subject in teaching digital architecture, CAD/CAM tools, rapid prototyping and fabrication-based design techniques. The course attracted 25 architectural design students who are in their final year of the graduation.

Course aim and setup

The aim of this course was for students (1) to understand and develop the essential skills and knowledge of digital design and fabrication; and (2) to develop the understanding and hands-on experience of fabrication technologies. The course content has two major components: (1) understanding of the principles of digital fabrication in relation to material's properties, and (2) understanding of the digital design processes. In order for students to develop the understanding of processes and production, firstly, relevant techniques and concepts such as sectioning, contouring, tessellating, folding and forming based on (Iwamoto, 2009) were introduced and discussed. Secondly, students are provided extensive tutorials and home works in terms of understanding of form generation in Rhinoceros 4 and scripting in Grasshopper (learning operation of commands, 3D surface making commands, NURBS, solids, surface manipulation and analysis, scripting etc.) in the computer-based studio. In the computer-based studio, the students acquire the necessary skills and knowledge to create and manipulate the models. Since the students do not have the previous scripting experience, they started to learn the basic knowledge of scripting and they altered / edited several existing scripts in Grasshopper. Finally, the students are given the opportunity to experience CNC milling and laser cutter in the Architectural FabLab of IUS with the supervision of a technician. In the fabrication-based studio, a design project was used as the major assessment item.

In order for the students to develop and practise the digital design skills in Rhinoceros and Grasshopper, they experimented several fabrication techniques and materials through several assignments.

Skate park design project

With weekly supervision in design development supplemented by tutorials for technical skill devel-
development, the digital design project titled “Skate Park Design” provided opportunities for students to (1) experience and practice design in Rhinoceros 4.0 and Grasshopper, and (2) develop and apply assembling principles and technical skills for production. The design brief requires students to use a ‘rib’ structure [1] to model the park and then to finish it with covering the surface materials with the following restrictions: (1) the park will be in a diameter of 30m or should fit in 35m x 35m square; (2) the maximum height is 3m; (3) the park should be a combination of curved surfaces; and (4) the park should be in a closed loop.

Matrix of modules
The major assignment, named as ‘matrix of modules’ provided opportunities for students to (1) create a design object using tessellating techniques, and (2) experience chosen material’s attributes, and (3) hands-on experience of fabrication in the Architecture FabLab. ‘Matrix of modules’ assignment includes designing and fabricating a Lattice in the giving specifications that should fit in a prism: 40cm x 40cm x 10cm. The size of the lattice module in a cell should be 10cm x 10cm x 10cm. To produce the matrix, the lattice module should repeat itself for four times in each direction. A pattern could be linear, quadric, sinusoidal, gestural etc.

QUESTIONNAIRE RESULTS
To understand the effectiveness of digital design learning, this study collects and analyses the evidences from students’ perception, and reflects on our own experiences in planning, conducting and evaluating the digital architecture and fabrication studio. We adopt a quantitative research approach to study students’ perception using a comprehensive questionnaire. At the end of the studio, students who successfully completed the fourteen weeks studio were asked to answer the questionnaire. The questionnaire consists of two parts of 45 questions in total.

Technical features (answered on a five-point Likert scale): the questions of part one aim to evaluate the performance of various technical features of digital design tools and production.

Open questions: the second part of the questionnaire continues with a set of open questions in order to develop more in-depth understanding of students’ perception and expectation of digital design and fabrication tools in design learning. Students reported and discussed issues ranging from the design representation and documentation, creativity, process, to the production and the materialisation of the design ideas.

The sample size of the study is quite ideal with 25 from a class of 24 students responding. 36% of the participated students are female. 45% of the students have four years CAD experience. However, 100% of the students experienced digital design and fabrication tools such as Rhinoceros and Grasshopper for the first time. 100% of the students have a personal computer and only 13% of them do not have internet connection at home, which implies that the students are quite well computer literate. The students can be therefore considered as both expert designers and CAD users.

We summarise the questionnaire results indicating the students’ evaluation of the digital architecture and fabrication studio for design learning in the following sections.

Design support
Students thought, overall the subject is worthwhile: 27% of the students rated their experiences as strongly agreed, and 45% of the students were agreed. 73% of the students satisfied/very satisfied with the design decisions and solutions that came out of the digital design session in Rhinoceros. Students divided about comparing digital design tool (Rhinoceros) to parametric design tool (Grasshopper). 36% of the students rated their experiences with the digital design tool as superb, 45% of them as neutral. 63% of the students rated their experiences with the parametric design tool as neutral, 36% of them as not very effective.

Although, 54% of the students rated their performance of thinking in 3D increased, they largely
divided regarding the usefulness of the digital design tools. As indicated in the following direct quotes from the students, their opinions are often conflicting, reflecting on both the strength and weakness of digital design and fabrication tools and in relation to features of general CAD applications that are familiar to them.

“...Rhinoceros is easy to use, but I am not sure about its efficiency. Do we really need to know this program in our future career? It is for so abstract forms. Maybe good for industrial design but, not architectural design. I am happy to know it. I hope it will be useful. But Grasshopper is hard to understand. General idea of it is understandable. But I do not understand how to know what I need next to achieve my task”.

“I like to design with curves in Rhino, because it is not possible in Sketch-up. Computer programs is perfect when I do not need to model –psychical model which I draw. Sketch-up is very useful to understand the volumes at the beginning of design process. And it is easy to use, and quick. AutoCAD is also good to draw, because of its simplicity, and let you decide everything about your design by yourself”.

“We learned ArchiCAD but I do not prefer to use ArchiCAD because of its failure, especially when we take section and it is not a fast way to design, it is not simple program. In ArchiCAD we need to consider everything in the beginning of the design process. With Rhinoceros, I was able to design very complex forms, I like that”.

Figure 1
Used medium for the design development.
Modelling support
63% of the students considered the model making with the CNC machines as “effective/very effective”, as a tool to realise design ideas. The comments agreed on the comparison of the effectiveness of the CNC machines with the conventional model making tools. 45% of the students rated “not effective/not very effective”, 45% of them rated as neutral regarding the effectiveness of the model making with hand-tools such as knife-blade. 68% of the students rated as very satisfied/satisfied with the outcome that came out of the fabrication process in Lab.

As indicated in the following direct quotes from the students, their opinions are on the strength and weakness of CNC cutter and Laser cutter in relation to features of conventional model making tools:

“...I found it amazing how the laser cutter operates, as it cut the timber. I also like very much the colour of the burnt timber, you cannot achieve that look using knife and blade”.

“I think the assembling is a little hard and time consuming”.

“I improved my digital model using several scripts which I borrowed from different resources...the possibilities of the process seems endless...but I have to construct it a point using sectioning technique”.

Summary
The above results of the questionnaire indicate consistency in the user perception and tool preference during the digital architecture and fabrication studio. The results together with our observation on and discussion with the students reveal some challenging characteristics, especially the issues related to the affordance of new design and production technologies. The fabrication and design process have directly impacted on the overall satisfaction of students. The outcomes of the digital design and fabrication studio as illustrated in the next session clearly indicate that the students are able to design, develop, assemble and fabricate the design idea to a satisfactory level. However, the questionnaire result and our observations show that students have been frustrated with various issues emerging during the digital architecture and fabrication studio including: lack of programming and scripting knowledge, lack of understanding the assembling procedure, lack of understanding the material’s properties and difficulty of transferring an abstract design idea into a concrete form.

OUTCOMES OF THE DIGITAL ARCHITECTURE AND FABRICATION STUDIO
The following section includes snapshots of the outcomes of the studio.

Skate park design
Students are encouraged to use variety of media for the design of the skate park, as illustrated in Figure 1. Most of the students started to design by sketching using pen-paper. With the completion of the sketches and deciding the layout of the skate park they modelled it in Rhinoceros. The key element of the task is to fabricate the park using the cardboard, so making the curve surfaces stands as a challenging task. The sectioning technique is applied for making the model, as illustrated in Figure 1. Rather than construct the surface itself, sectioning uses a series of profiles, the edges of which follow lines of surface geometry.

Since students do not have programming background, they tend to employ existing scripts in their design. We also encouraged them to find an existing script, modify / alter and use it in their design process. The students investigated Rhinoceros’ wiki, and forum pages to find out the possible ways of modelling, assembling and fabricating the curved surfaces. Some students applied the RhinoScript as provided on the rib structure tutorial to form the base surface of the skate park, as illustrated in Figure 1. Some students also used the graphical algorithm editor, Grasshopper, tightly integrated with Rhinoceros’s 3-D modelling tools, to form and create the assembling layout of the skate park.
Matrix of modules
Using a matrix of modules to create a lattice wall is the major assignment item, as illustrated in Figure 2 and 3. The task requires students to think in 3D space elaborating the spatial adjacency of the elements, the connection of each module, assembling and fabricating.

The tessellating technique is used for making the lattice wall which is a common architectural design element to provide sun shade and visual separation of spaces. The tessellating which exists since the ancient Roma and Gothic architecture is a collection of pieces that fits together without gaps to form a plane or surface. In architecture, the term refers to both tiled patterns on buildings and digitally defined mesh patterns. The task requires elaborating on the joints and the relationships of each module.

This design task does not only include the form generation based on a module which will come together and form the lattice wall, but also it requires the understanding of types of materials and their attributes. Students are given opportunity to explore several materials such as PVC, timber and cardboard, as illustrated in Figure 2 and 3. Each studied material has its own values in terms of the hardness, softness and the combustion degree etc. and behaves differently during the cutting process.

CONCLUDING REMARKS
Many design schools around the world have been adapting digital design concepts in their curricula. In relation to design education and pedagogy, the theoretical, computational and cognitive approaches of design computation and digital design have been studied by researchers (Knight, 1999, Oxman 2006, Cuff 2001). Oxman (2008) stated that “in design theory, the decline and transformation of root concepts such as representation, precedent-based design, typologies, and other principles of the past generation are in the process of being replaced today by a new body of design concepts related to models of generation, animation, performance-based design and materialization. These are design concepts deriving from the synergy between emergent technologies, design and architectural theories”. In relation to those new design concepts, the design pedagogy requires further investigations.

In general, there are two views of teaching digital design; a course adjunct to a design studio (Oxman, 2008), or a course offered independently of a design studio (Marx, 1999). Our approach of digital design teaching is based on an approach which combines those two views. In the digital architecture and fabrication studio, students are offered new learning experiences including learning new skills of using software - prototyping tools and implementing this knowledge and skills on a design task at the same time.

Based on the above results and our observations, advance digital design and prototyping tools as the emerging design teaching platform for the new generation of architects remain to be challenging. As indicated in the questionnaire results, students are overall satisfied with the digital design and fabrication experience. In addition, the students commented on the quality of the design outcomes. Besides the above findings regarding students’ perception on the digital architecture and fabrication course, the paper concludes with the following remarks.

Framework of the course
In terms of the structure of the digital architecture and fabrication studio, the content of the course comprised (1) teaching the digital design concepts (generative design, computing, parametric design etc.), (2) operation skills of the modeling software and prototyping tools, and (3) implementing those skills and knowledge on the design tasks. Our previous teaching experience showed that a course offered independently of a design studio would only benefit on the development of the technical knowledge of using particular software. Thus the lectures in which students would be exposed to several fabrication and digital design concept related issues should be used as the grounding for integrating the knowledge. Following the building up of digital design concepts, the development of various skills is
necessary. Thus, a set of tutorials in which students would gain knowledge of and practice in using the CNC technologies should be formed. These technical tutorials should provide the basic knowledge about how to operate a particular piece of software. Finally, students should be given opportunities to apply the knowledge and skills that they have developed during the course, so different sets of design and fabrication tasks should be given.

**Digital design process**

Working with the digital medium requires a different kind of thinking. Different from the basic principles of design teaching such as typologies, graphical representation, contextual and conceptual design explorations, digital design requires algorithms, computing, morphogenesis, form explorations, materialization and production techniques. Students should be exposed to those concepts and techniques by giving a chance to explore design artifacts in digital and in physical form.
**Required skills**
Interdisciplinary working becomes essential. Thus the generation of architects should develop a variety of skills that include architecture-related skills (place design, formation, generation and performance), digital design skills (modelling, imaging, fabrication, scripting and programming), and generic design skills (problem-solving, decision making).

**Model making**
Models have a fundamental role in the practice of architecture. Within the process of architectural design, models are suggested as an essential tool in the realisation of habitable built form. Making the model represents the concretization of ideas, by getting as close as possible to the actual construction of a design idea. By using 3D scanning and rapid prototyping techniques, the designers are able to go back and forth between digital and manual modes, thus taking advantage of each one during the design process. The design task should have the component of model making including the explo-

*Figure 3*
Lattice design examples, the material is card board.
ration of fabrication techniques such as sectioning, forming, folding, tessellating and contouring.

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REFERENCES
