



XIV del 1 al 5 de diciembre de 2008  
CONVENCIÓN CIENTÍFICA  
DE INGENIERÍA Y ARQUITECTURA

ANIVERSARIO  
44  
cujae  
2008



Gráfica Digital  
Integración y Desarrollo

La Habana  
1 al 5  
Diciembre  
2008

# Teaching Architectural Design through Computer Modeling, Rendering and Digital Fabrication

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**Abstract**—The paper examines the process of introducing the rudiments of architectural design and computation through computer modeling, rendering and digital fabrication. The scope of the paper is educational. The context of the paper is the teaching of an introductory course to Design Computing. Computational concepts from the digital modeling, rendering and fabrication techniques developed for the course, as well as the students' response, are discussed in the paper.

**Key Words**—Computational Design, Computer Modeling, Digital Fabrication.

## I. INTRODUCTION

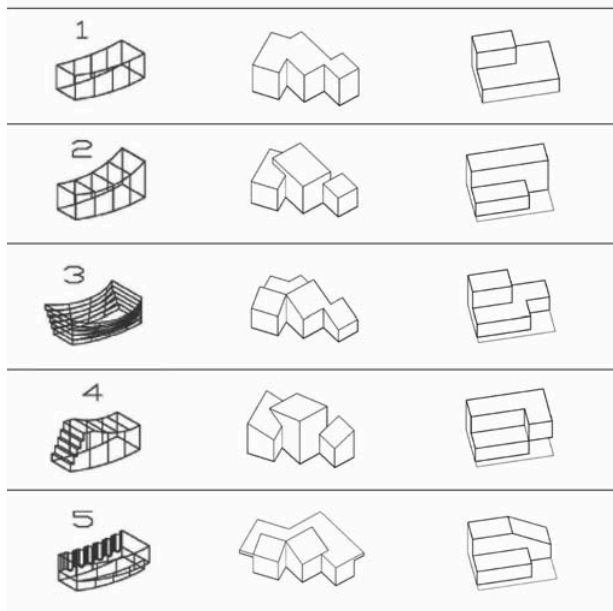
This paper concerns how computational methods and means affect the design education. The teaching of an introductory course to computational design is used as case study. The objective of the course was to teach architectural design with CAD: 3d modeling, rendering and rapid prototyping. The paper presents the content of the course, analyzes the performance of the digital tools within the educational context and discusses the students' work, and the ideas that this work stimulated in class. The presentation is critical of design and teaching principles and of production methods.

The descriptive and productive contribution of computation in design has been studied for decades [1], [2]. The use of generative methods in design confines a new domain in thinking [3] but also, in design education [4], [5]. Finally, rapid prototyping and digital fabrication have been used as transferring mechanisms between the physical and the digital domain [6], [7], [8]. Particular to this study is the use of digital fabrication from virtual models and drawings.

## II. MATERIALS AND METHODS

A case study is presented: the teaching of an introductory course on computational design, to a group of sophomores at the Massachusetts Institute of Technology the Spring 2007-08. The group included thirteen students, nine of which were majoring in architecture and four in computer science. Students were required to design a summer cabin at Cape Code, Massachusetts. Cape Cod is known as a place for artist retreats. There one finds a collection of summer cottage rentals. The design objective of the exercise was to propose a new beach front cottage. The program demanded built in furniture for one person to live for a week. The total cost of materials (plywood, studs and concrete base) was limited to \$10,000. By building a series of digital models for their designs, the students performed a series of explorations with computers and digital fabrication. In the Spring 2007-08, special emphasis was also given in the use of spatial relationships that the students had to make explicit in their process. This presentation follows the organization of the course. It is divided in four stages: modeling, rendering, production, re-design. The stages proceed sequentially. First, the students articulate and model the designs abstractly as an arrangement of forms by employing a small number of spatial relations. Second, the students examine the properties and the performance of the configurations of interior space. Third, the designs are elaborated by obtaining detailed construction components and physical parts for manufacture with a digital fabrication device. Fourth, specific construction details or arrangements are redesigned, remodeled and reconfigured.

TABLE 1  
EARLY EXAMPLES OF DESIGNS BASED ON SIMPLE SPATIAL RELATIONSHIPS



Arrangements with solid forms, based on simple spatial relations. Student work (columns from left to right): S. Goshenur, I. Winder, M. Naydekova.

#### A. Modeling

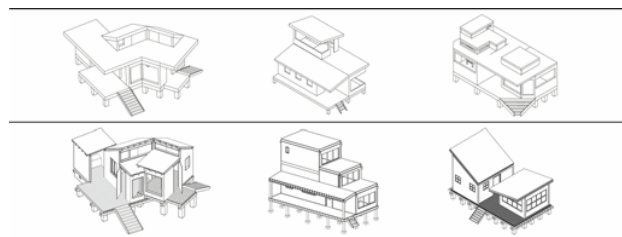
At the modeling stage the students summarize the functionality of their cottage and begin to think on its appearance and organization. Sketches and diagrams, digital and physical models are used. First, all information related to the site is analyzed and documented. Three features of the site are recorded in particular: a) the direction of the wind, b) the approximate direction of sun rays at 9am, 12noon and 6pm, and c) the views. The first drawings deal with the organization of a tentative floor plan for the cottage. The main cottage space cannot exceed 10' wide by 10' long, while the overall coverage cannot be more than 400sf maximum (20' x 20'). The building program includes: a) sleeping space, b) reading space, c) activity space, d) toilet and sink, e) entry. Lines are organized in hierarchies of weights, groups of elements are placed on distinct layers and architectural symbols are inserted to indicate the elements on the plan.

Second, the students explore schematic 3D models and propose easy constructible forms. This usually means forms built of flat sides (curves are avoided, since they are harder to construct). Starting with a tentative arrangement the students have to propose four design variations. Then, solid modeling is used to construct building parts for one of the schematic design alternatives. The overall form of the cottage reflects the previously completed study. The modeling process involves building an initial solid shape from the plan (extrusion of plan), and using other solids to subtract or add shapes on it. The students select a form from the produced set of design alternatives to use as the basic design schema. Then, they

subtract windows and doors, and they add a floor and a roof (see Table 2, up). The external overall form of the cottage is designed as a basic block model. The model is organized into 6 distinct layers: a) ground surface, b) floor, c) walls, d) roof, e) window openings, door openings, f) details (stairs, etc.)

Third, the students begin to consider architectural detail. Their models obtain elements of construction. The cottage should be constructed out of wood on a concrete foundation. The details of window frames, doors and structural members (studs), are also modeled in this phase. The students adjust the plan and the overall form of the building around the adjustments made. After gaining sufficient understanding of the basic form and its physical makeup they create a 3D representation of their cottage in full detail. They use the information of the preceding stages to build new more informed models that contain construction details. For the most part, each student has to create a completely new model. (see Table 2, down). Further, the students have to test the interior for spaciousness and light. For example, if a room is small they have to find ways to make it seem more spacious, without adding square footage. And also, the choice of window openings should demonstrate that the sunlight entering the room is under control.

TABLE 2  
EXAMPLES ON SOLID MODELING AND DETAILING



Schematic models (up) and models presenting construction details (down). Student work (columns from left to right): I. Winder, M. Naydekova., X. Xiao

#### B. Rendering

At the rendering stage the students prepare a set of renderings of their CAD model in 3D Studio Max. First, they learn how to compose the lighting so that the overall form, shadows and details are appropriately illuminated. Using virtual cameras they create views and they print them on paper and bring them in class for discussion. Surface depth is achieved through appropriate selection of "artificial lights" and by placing lights imaginatively. Richness in the variation of tones and shadows, as well as shadow depth, is achieved through thorough testing.

Second, the students explore the use of natural light. Insufficient lighting causes eye strain and creates an unpleasant environment. Excessive lighting causes heat and creates a need for shading. The students learn how to create a balance of direct and diffuse natural light. They select a specific area of their cottage to test various lighting applications and the performance of light on surfaces. Then, they build four alternative window designs and they test them,

aiming at serving the needs of the selected area in the best possible way. In this process of testing they build an interior stage set and orient it in a direction that suits their lighting needs. Using radiosity in 3D Studio Max the students perform a daylight study on one area of their model at 12 noon in the months of June, July or August. The testing of the four window designs happens from the same view point in space. The results often show that the cottage may have to get reoriented so that the sun light enters from the desired direction. One analysis model is selected, to study for heat gain and excessive lighting on surfaces, in 3D Studio Max. For this purpose the students create shields, reflectors or initiate changes in the window color or the window frame design, to limit the direct glare and increase diffuse light. Finally, they build four alternative solutions for shading, reflection, etc., while keeping the window design unchanged.

Third, the students begin to consider the importance of materials and textures in design representation as well as in construction. Texture mapping makes renderings more convincing, because it enhances the sense of scale and depth. The students learn how to align and set up materials on a surface of a digital model. Their objective is to get texture map scale and alignment correct through trial and error. They create one texture mapped image for their cottages and they describe in detail their intents for the materials of the cottage.

TABLE 3  
DAYLIGHT STUDIES AND TEXTURE MAPPED RENDERINGS



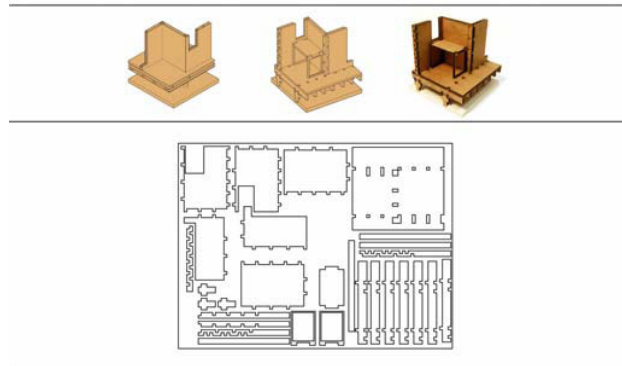
Daylight study (up) and texture mapped image (down). Student: A. Kotova

### C. Production

At the production stage the students focus on the transfer of their CAD models to physical models by using rapid prototyping devices. They have to merge the available design and construction information in a new model. A precise construction model for assembly is produced. For this purpose, the students construct a series of 3D physical models from their digital models. More specifically, they build accurate physical models of selected areas and details of their cottage by using rapid prototyping technologies (in this case, the laser cutter and the 3D printer). First, a construction model is built from models that contain design and construction information. The use of this new model is construction at a

specific scale. Each piece of the construction model corresponds to a component of the building. The construction model includes all the appropriate components for the assembly of the physical model. The components are cut on the laser cutter from a single sheet of material (see table 4).

TABLE 4  
EXAMPLE OF MODEL EXECUTED IN THE LASER CUTTER



Three phases of a detail (up, left to right): construction detail, construction model, physical model. A sheet ready for cutting (down). Student: A. Kotova

Second, it is constructed the top part of the building, at a specific scale, out of masonite, 1/8" in thickness, which is substituted for wood on the laser cutter. Starting with a building model as a solid shape, the inner and outer surfaces are remodeled as sheets of material with specific thickness. All components generated in 3D are translated and sorted for fitting within the boundaries of a single sheet of the material. The order on each sheet is optimized for minimum waste in cutting. The component jointing is made by tab and slot, included in the design of each component. Permanent jointing is sustained by friction between components, so that in the assembly phase minimum quantity of glue is used to put together the models. Special attention is given on fabrication accuracy, fitting and overall composition of the models.

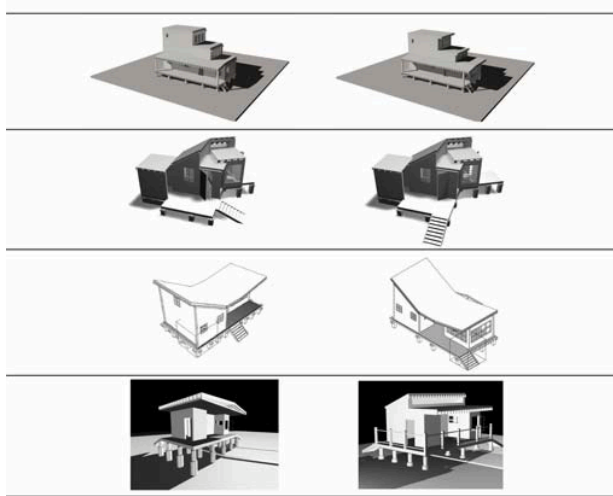
Third, it is built the lower part with the 3D printer, out of plaster and it used to represent the ground plane and the supporting, foundation blocks. By performing the above three steps, the students learn how to work with fairly precise rapid prototyping devices, and become familiar with construction techniques and details, such as joinery etc.

### D. Redesign

In the previous three stages of modeling, rendering and production, the students complete a design for their cottage. In the re-design stage, they are asked to fully demonstrate their design intentions and construction methods. By using 3D modeling, computer rendering and rapid prototyping this final stage aims to convince that the cottage is functional, well designed and that it can be constructed for less than \$100,000 (the cost of a 400sf cabin). The redesign phase goes beyond the presentation purposes. It permits students to revisit all the previous stages and resolve any pending design issues. The

redesign areas or components that received negative design or technical evaluation, but they do not have to reconfigure the entire cottage. They carefully review their work with the instructors and they consider fixing areas that are weak in appearance, or construction. They also make sure that their design decisions match the goals in their design statement of purpose. Three are the main goals of the redesigning phase: achieving better clarity of design, demonstrating the design process, and proving sufficient level of technical understanding. The new designs (redesigns) are referred to as "Scheme 2", as opposed to prior design solutions are referred to as "Scheme 1". That is, first ideas appear as "Scheme 1", while design improvements as "Scheme 2".

TABLE 5  
EXAMPLES OF REDESIGN



First ideas (scheme 1) appear on the left column, while design improvements (scheme 2) appear on the right column. Student work (top to bottom): M. Naydekova, I. Winder, X. Xiao, R. Reder

### III. RESULTS AND DISCUSSION

In the presented case study, young students created design descriptions in CAD, namely drawings and 3D models. The models were used for performance testing and for 3D printing or laser cutting. A key aspect of the proposed educational process was that the students, in all four stages: modeling, rendering, production and redesign, had limited time to focus on a single technical issue: i.e. the modeling, the rendering or the fabrication component etc. Instead, they had to move from one objective to the next efficiently, having in mind the end goal, the design.

At the modeling and rendering stage the students had to move beyond the use of a single software package. They had to move from AutoCAD, or Rhino to 3D Studio Max back and forth, as needed. As a consequence, they had to abandon the notion of "the single model". Multiple representations had to be constructed for different purposes, while revisions and redesign of components was a common task. The students had

to exercise their skills in digital modeling while having very specific design and construction tasks. The level of complexity was intentionally kept moderate: complex geometries and technically advanced construction details were avoided. At the "modeling" stage the students complained for the interface of the software we used, which was AutoCAD or Rhino. The students found the structuring of the interface cryptic and the tools difficult to access. Similarly in rendering" the students appreciated the basic interface of 3D Studio Max and its ability to handle the model or the virtual cameras and lights easily, but they found the accessing of the rendering tools unintuitive. The quality of the work both in modeling and rendering was initially low. Over time, after repeating specific modeling or rendering routines their skills became better and the results too.

The production stage was aiming at linking design modeling with digital fabrication. Production refers to the transfer of a design to a physical model starting with a 3D digital model [8]. This process takes into account specific material and machine constraints as part of the design input and translates the 3D digital model to a set of components. The result is a model built exclusively of components for assembly at a specific scale, while joineries are built based on the relationship between component geometry. At the production stage the students faced problems in transferring their design and construction information into the production model. Geometric complication found in descriptions, was an obstacle in fabrication because it made difficult the determination of the components. Further, the methods used to build the earlier 3D models were found inefficient in transferring the information into physical larger scale production models for assembly. The students found difficult to transfer the construction details and to take into account the tolerance of the material. Several tests became necessary to achieve the desired accuracy and the required degree of friction in component jointing.

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