Inserting computational technologies in architectural curricula

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ABSTRACT
This chapter describes two case studies concerning the introduction of computational design methods and technologies in new undergraduate architectural curricula, one in Portugal and the other in Brazil. In both cases the immediate goal was to introduce state-of-the-art technologies in the curriculum to promote creative design thinking. The ultimate goals were to fulfill the criteria of intellectual satisfaction, acquisition of specialized professional skills, and contribution for the economic development of society that should underlie university education. The chapter describes the theoretical framework, the various courses and labs that were devised and implemented, as well as the strategies used to implement them. Then it presents the final results and concludes with a discussion of the pros and cons of each strategy. The main lesson drawn from both efforts was that cultural and organizational aspects are, at least, as important as technical aspects for the successful integration of computer media in architectural education.

INTRODUCTION
The insertion of “new technologies” in architectural teaching and practice has been everything but smooth. The meaning of the term itself is ambiguous and tends to be reduced in a very simplistic manner to the use of the computer or, even more simplistically, to the use of CAD software. Not surprisingly, the issue divides educators and professionals alike and prompts them to take extreme positions. On one side, one finds those who tend to assign a central role to the computer; on the other, one encounters those who refuse to admit that it can have any role at all. Reality, nevertheless, demonstrates that the role of the computer can facilitate the resolution of certain design problems but may jeopardize the solution of others. Time and experience permit to categorize problems and so the contact of architectural students with new technologies in the early stages of their learning and training process is important. This chapter describes two cases concerned with the integration of computational design methods and technologies in undergraduate curricula in new programs in architecture, one at the Technical University of Lisbon School of Engineering (Instituto Superior Técnico – IST, TU Lisbon) in Portugal, and another at the School of Civil Engineering, Architecture and Urban Design of Campinas State University (Faculdade de Engenharia Civil, Arquitetura e Urbanismo da Universidade Estadual de Campinas – FEC, UNICAMP) in Brazil.

In their paper “The Ideal Computer curriculum” Mark, Martens & Oxman (2005) discussed how devising an architectural curriculum in the digital age is a matter of finding a balance between the need for integrating state of art technology and the demand of keeping traditional subjects to meet the requirements of professional accreditation. They identified a list of computer courses that could be included in the architectural curriculum organized into three levels: basic, intermediate and advanced. Then they identified two different strategies to integrate computer courses in the architectural curriculum,
one that was set within the framework of the typical curriculum structure and another that displaced a
great number of traditional courses. Finally they gave examples of possible curricula for each of the two
cases. In the first curriculum, most of the digital design topics were integrated in existing courses, except
for two mandatory courses in geometric modeling and structural analysis. By contrast, in the second
curriculum, most of the computer topics were offered in seven separate mandatory courses. In both
curricula, students could take additional, elective courses on computer-related subjects. They concluded
that the first strategy was better because the latter “would not likely prepare students well for a career in
architecture as the profession is likely to demand.”

The IST case described in this chapter is closer to the first curricula described by Mark, Martens
& Oxman (2005) in the sense that it includes fewer computer courses and the CAD content is
better intertwined with architectural content, although not by including computer topics in
traditional courses but the reverse. The IST curriculum includes only three mandatory courses,
two in the first years and one in the last year, and no elective courses on computer topics.
Although the title of the first two subjects make reference to CAD, computer topics are taught by
addressing architectural problems, such as how to model and describe a building (CAD I) or how
to write a program to generate a certain type of architectural forms (CAD II). And in the last
subject, (CAAD) the goal is the development of architectural design projects with the use of
computer technologies. This means that all the courses have a creative component.

At UNICAMP the curriculum includes four mandatory and five elective CAD courses, but although their
objective is to allow students to incorporate computer technologies in their design process, their focus is
still mainly instrumental. In fact, in none of these subjects the development of a design project with the
use of different technologies in an integrated way is carried on, like in the IST case. Each CAD subject at
UNICAMP concentrates on a specific computer topic (e.g. rapid prototyping, animation, generative
systems, etc.) and small projects are carried on in each subject more with the objective of fixing specific
concepts than with the objective of showing the use of technologies in an integrated way. In other words,
students are left with the responsibility of putting the parts together. Thus, this curriculum is closer to the
second case described by Mark, Martens & Oxman (2005), because it includes more CAD courses but
CAD topics are less intertwined into design content as a whole.

However, the most remarkable feature of both cases is that the computer is not seen as a mere
representational device, but as a potentially conceptual tool and so all the effort in setting up both
curricula was placed on enabling such use of the computer, first by gradually building students’ skills and
then approaching design problems using different media, including computers.

Another difference between the two cases lies on the strategies used to integrate the computer courses.
The process of integrating the courses was dynamic and, in fact, one may distinguish three different
moments in the process of integration: (1) before the interventions described in this chapter; (2) after such
interventions, when the delineated strategies were put in place, and (3) a few years on. When the IST
program was created in 1998, there were two computer courses and the strategy initiated in 2000 was to
change their contents and add a studio course. The peak of this strategy was reached in 2004 when
students in the revised curriculum reached the fifth year and took the studio. Then the process backlashed
under the pressure of traditionally oriented instructors who did not accept that the computer could be
more than a representational tool, and the studio was taken out of the curricula. In the IST case, computer
courses were first introduced in the undergraduate program and only later were they introduced in
graduate programs, mainly because this was the order in which these were created at the school. When the
Unicamp program was created in 1999, there were already five mandatory computer courses. The strategy
was the opposite from IST, as changes in the curricula were first implemented at the graduate level by
setting up classes in which the computer was used as conceptual tool, a process initiated in 2002. By
linking the work in such classes to ongoing research, namely theses, it was possible to demonstrate the
potential of the computer to go beyond representation capabilities. Then such changes were introduced at
the undergraduate level in a gradual manner, driven by demand of students and then instructors. Currently, there are five computer oriented mandatory courses and five electives courses at the undergraduate level but computer topics have permeated other courses as well.

Such differentiated strategies were crucial to the difference in outcomes. The IST curriculum led to noticeable results faster (publications, design and scientific awards, etc.) but was rejected by traditional teaching staff who pushed the beginning courses to intermediate years and cancelled the advanced course, whereas in the Unicamp case the opposite is true. The argument laid in this chapter is that the success of the integration of computers in architectural education depends not so much on the number of courses, but on how computers are used and how they are introduced into the curricula following a process in which cultural and organizational aspects are, at least, as important as technical ones.

THEORETICAL FRAMEWORK

In setting up the new curricula, five theoretical references were taken into account. Almost two decades ago, Akin (1989) identified two different viewpoints regarding the role of computers in architecture. One, supported by early computer enthusiasts and pioneers, argued that the computer would eventually replace the architect. The other viewpoint, hold by more conservative designers, defended that it could merely add to existing design capabilities. Akin, however, was in favor of a third view, which considered that new technology "continues to change the way we design, rather than to merely augment or replace human designers” (p.301). The belief in this view was the starting point for the design of the new curricula described in this chapter. The work of early pioneers who used the computer in the design of buildings with success made evident that turning the back to the new technologies was not the solution. As a result, some schools introduced CAD courses in their programs, but usually only in the last years of their curricula. The computer was then used as a drafting tool in the last stages of the design process to produce accurate or presentation drawings. Only when the goal shifted into giving students the opportunity to use the computer as a conception tool, rather than a mere representation device , was it considered desirable to include CAD education in the early years of formation.

The second reference was Schon’s theory of the reflective practitioner. (Schon 1987; Schon & Wigging, 1992) In his texts, Schon puts forth an approach for educating competent professionals so that they are able to tackle complex and unforeseen problems in their practice. He describes designing as a conversation with the materials of a design situation. Working in some visual medium - drawing, in the experiments reported in the texts - the designer sees what is ‘there’ in some representation of a site, draws in relation to it, and sees what has been drawn, thereby informing further designing. In this see-move-see cycle, the designer not only visually registers information but also constructs its meaning, that is, identifies patterns and assigns meanings to them. Schon elaborates on the conditions that enable this cycle to work effectively, and thus draws some recommendations for design education and for the development of computer environments. In Schon’s approach, to be able to construct visual representations of a design context is a key element of an effective designing process. Accordingly, hand drawing is an essential skill in traditional design education. The goal in setting up the CAD curricula was to promote the kind of process described by Schon, but with computer-based media.

The third references was Mitchell and McCullough’s (1994) diagram showing the integrated use of digital media for surveying, representing and fabricating buildings, (Figure 1, top) which showed the emerging relationships between the building, and its drawings, physical model and digital model, and illustrated the possible translations among the various representations. The fourth reference was Mitchell's (1975) categories of models for representing design problems: analogue, iconic, and symbolic, which we reinterpreted in a diagrammatic form similar to the first diagram. (Figure 1, bottom) The proposed extended combination of the two models is shown in Figure 2 with the computer-related courses included in the two curricula addressed in this chapter. The iconic digital model or just digital model may include geometry, textures, and lights. The symbolic digital model or computational model refers to the
codification of architectural forms into a computer program. The analogue digital model or virtual model refers to the simulation of buildings in the real world as well as in imaginary worlds. A virtual model can have different degrees of simulation and its basic version may be obtained from the digital model by adding the fourth dimension (time, movement). The two curricula presented in this chapter were set up to ensure that students had the opportunity to learn and experiment with all the translations among the different representations. This meant that they had to be given access to both the capabilities found in traditional design studios and those offered by digitally-mediated design. The specific courses in which students had the first contact with the translation mechanisms involving digital media at each school are identified in the diagram.

Finally, the fifth reference was the work of Wojtowicz, Chen, Mitchell and others (Wojtowicz et al., 1992, 1993; Chen et al., 1994) on the virtual design studio. These authors describe the theoretical and the practical aspects, as well as the methods and the infrastructure required for setting up and undertaking design studios using new information and communication technologies. Over the years, other authors have approached this topic using the latest technology, but the principles and set up have remained more or less constant. For a detailed reference on their work see the Cummincad archive of research papers. (http://cumincad.scix.net)

To complete the set up required for the digital and virtual design studio, the courses mentioned above needed to be complemented with a sophisticated infrastructure.

At IST, part of the infrastructure was common to the entire school, including wide network access and online course information. In fact, the school is connected to the e-U, an European-wide wireless network that links all the universities and permits anyone to login from any campus, regardless of the institution of origin. In addition, the school has implemented and turned mandatory to place the contents of all courses online using a system developed locally called Phoenix. The remaining infrastructure was specific to the Program in Architecture and included advanced geometric modeling, rapid prototyping, virtual reality and video-conferencing laboratories. Their installation began in 2005, although somewhat similar facilities from other departments were used before.

At Unicamp an online teaching environment called Teleduc was created in 2001 and had been used by most courses since then, so the University had already assimilated the culture of remote collaborative environments when the changes reported in this text took place. In regards to rapid prototyping and digital fabrication technologies, a laboratory started being set up in 2007, through investments that targeted research and graduate education specifically; not undergraduate teaching. This is due to a characteristic of the public funding policies in Brazil, where research in technology is considered a priority. The courses and the labs at each of the two schools are briefly described below.

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**Figure 1.** Precedent theoretical models for integrating traditional and digital media: at the top, a diagram adapted from Mitchell and McCullough (1994); and at the bottom, a diagram reinterpreting Mitchell’s design problems representation models (1975).

**Figure 2.** Proposed theoretical model for integrating traditional and digital media: diagrams combining and extending the diagrams in Figure 1 that show the various models and processes of conversion among them used in the design process. The diagrams also identify the courses in which such processes are addressed or utilized at IST (top) and at UNICAMP (bottom).

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THE TU LISBON IST CASE, PORTUGAL
The undergraduate program in architecture was created at Instituto Superior Técnico, the Technical University of Lisbon (TU Lisbon) School of Engineering, in 1998, with the aim of providing a technology-oriented education in architecture. This sort of orientation was non-existent in other architectural schools in the country, and specifically at the School of Architecture (FA), which maintained its beaux arts tradition when it was incorporated in TU Lisbon in 1979. The creation of the new program led to the unusual situation of having two programs in architecture at the same university but the goal was to have a technology-oriented program and an art-oriented one. The new program was initially set up as a five-year professional degree to guarantee accreditation by the architectural association. Courses were organized into five categories: basic sciences, design support systems, building technology, history and theory, and architectural design. When the program was set up, it included only two computer-related courses: Computer Programming and CAD. The first was a required course in all the degrees offered by the school, and it consisted of a C language programming class. The second course consisted mainly of an Autocad-based 2D drafting course. In addition, there was a GIS course and computer-based surveying techniques were taught in a traditional course called Survey of Buildings.

It did not take long for problems to emerge. The contents and exercises of the programming course were the same across all the degrees and had no architectural content. Architecture students complained that they did not perceive how programming skills could be applied in designing and they saw no point in taking the class. As a result, many dropped and failed. The CAD course was offered in the second year. In this course, AutoCAD was taught in the manner used to teach civil engineering students. The teaching methodology consisted of enumerating AutoCAD commands and showing how they worked. Then students were given 2D drawings and were asked to copy them using AutoCAD. Students saw little motivation in copying drawings and some dropped the class. Those who finished it used the acquired skills to develop accurate drawings in their studios, but the computer was not used in a creative way. When it became clear that things were not going in the desired direction, it was decided to change the curricula. This happened two years after the program was initiated and led to the strategy described herein.

CAD classes had been introduced in architectural curricula for the first time in the country at TU Lisbon's School of Architecture (FA) in 1986. First, they were offered as an extra-curricular course to senior undergraduate students and then as a mandatory class in the last two years. As time went by, these courses tended to be offered in earlier years. So, following the idea of introducing computers early in architectural formation, drawn from the theoretical references listed above, it was decided to maintain the courses in early years but to reformulate them, first by swapping their contents, so that students learnt first how to draw with the computer and then how to program. The idea was to use a scripting language of an existing CAD package in the programming course so that exercises could have architectural content. Finally, a computer-based studio was created in the last year to take full advantage of the computer and architectural skills that students had learnt in previous years. The resulting courses, CAD I, CAD II, and CAAD are described below, followed by a description of the labs that were created to support them.

The IST program accepted 50 students each year, divided into two cohorts of approximately equal number. This means that CAD I and II had between 25 and 30 students, including those who failed these courses in previous years. The CAAD Studio was offered as an alternative to a traditional design studio, which permitted that the number of students taking the course could vary between 8 and 24 students each year, depending on the specific content of the course and students’ interest. For instance, when the course was offered as a remote collaborative design studio, the maximum number of accepted students was just 12.

**CAD I: Geometric Modeling and Visualization, 1st semester, (4h x 14 weeks)**
This course is the first in the series of three devised for the new undergraduate Program in Architecture at IST with the intention of proving students with state of art designing and representation skills. It introduces the fundamentals of geometric modeling and visualization techniques while presenting students with the most common hardware and software solutions. In the proposed approach, the computer is not understood as a mere electronic version of traditional drafting media, but as a tool that creates new opportunities to architectural and urban design. Students are asked to select a building, to construct its virtual model and then to manipulate it creatively for analyzing and describing its architectural qualities. The goal is to teach students about architectural qualities and in doing so get them to learn how to model with the computer.

Students can work in teams of two and work proceeds through a series of 5 small exercises that build up to a final project: 2D and 3D modeling, image processing, realistic rendering and web design. In previous years, students selected buildings from World famous architects or local city landmarks. In the latter case, the work in the class is articulated with a research project that is being developed in collaboration with a firm, which aims at developing a 3D model of the city for research and practice purposes.

**CAD II: Programming and Digital Fabrication, 2nd semester (4h x 14 weeks)**

This course introduces the theoretical and practical fundamentals for the exploration of computational aspects of architectural form and knowledge. The basic concepts of computer programming are addressed using Autolisp, Autocad's scripting language. Students are expected to acquire the basic skills required for developing their own design tools. As such, students are introduced to various paradigms for encoding and computing with architectural forms – parametric design, shape grammars, genetic algorithms, and cellular automata – as well as different techniques for producing them through rapid prototyping – cutting, additive, and subtractive processes. Students are asked to select a class of forms and encode them into a computer program.

Like in CAD I, students can work in teams of two and work proceeds through a series of 5 small exercises that build up to a final project: batch, parametric and rule-based programs, web design, and rapid prototyping. In previous years, students work addressed both historical themes, for instance a program for generating Romanesque churches (Figure 3), and contemporary themes, for instance, a program for generating twisted towers and decomposing them into discrete parts for fabrication.

*Figure 3: CAD II: programming and fabrication. Program for generating Romanesque churches (Ricardo Mesquita, 2003/04): from the digital model to the 3d physical model produced by FDM.*

**CAAD: Computer Aided Architectural Design Studio, 9th and 10th semesters (2 x 4h x 14 weeks)**

This course integrates the skills acquired in the previous two courses while introducing new tools, such as advanced geometric modeling, rapid prototyping, virtual reality, remote collaboration and structural analysis. It aims at exploring the use of advanced computer-aided design and production techniques to address complex problems and develop innovative solutions in collaboration with the industry. It may have the format of a remote collaborative design studio open to senior students in Architecture and Engineering of at least two universities, and the specific topic varies each year. For instance in one academic year, the problem was to design a technology-oriented cultural centre that included non-regular double-curved surfaces made of ceramic elements. In another year, it aimed at conceiving innovative ceramic roof coverings. For detailed accounts of these studios see Duarte, Caldas & Rocha (2004) and Caldas & Duarte (2005), respectively.
More recently, the studio addressed the customization of mass housing. This studio built on previous research aimed at devising a methodology for designing housing systems. (Duarte 2005; Benrós & Duarte 2009) This methodology encompasses a design system, a building system, and a computer system. The design system encodes the rules for generating solutions tailored to specific design contexts. It determines the formal structure and the functional organization of the house. The building system specifies how to construct such solutions in accordance with a particular technology that is suitable for the context. Finally, the computer system enables the easy exploration of solutions and the automatic generation of information for fabricating and building the houses. It was the first time that this methodology was used in its full extent. In the CAD II class, students had already developed programs for exploring solutions for housing design systems conceived by other students in a more traditional way. However, in the CAAD Studio the conceptual and temporal separation between conceiving the design system and developing the program were blurred, and students conceived the design system by developing a computer program (Figure 4). This was exactly the sort of approach that was sought when these classes were devised. Computer-based media has become a way of stimulating creative design thinking and engaging students in a reflective practice as proposed by Schon.

Regardless the specific themes, the key ideas in the studio are to use advanced media both for designing and exploring solutions at the conceptual design stage and for producing the information needed to build them at the construction detailing stage. In addition, students are asked to develop the protocols required for geographically distributed, multidisciplinary design teams to operate effectively. In short, students are expected to operate within the context of a virtual design studio. Students are arranged in groups of up to 3 and the number and content of the exercises depend on the specific topic of the studio.

Figure 4: CAAD: Computer Aided Architectural Design. Design system for customized housing conceived by programming it in Autolisp. (Luís Rasteiro, Joana Pimenta, and Pedro Barroso 2005/06). Explanation of how rules are applied in the generation a solution, partial universe of design solutions, view of a street generated using the program, and FDM models of solutions.

ISTAR Labs: IST Architecture Research Laboratories

The ISTAR Labs are the infrastructure created specifically to support courses with CAD content in the IST undergraduate Program in Architecture, as well as courses and research in graduate programs. Lab here means a room with specific technical equipment where courses can be taught or research can be undertaken. The goal of the IST Architecture Research Laboratories (ISTAR Labs) is to enrich architectural higher education through information technology and research. The ISTAR labs investigate how such information technologies can be integrated in the design process. These labs represent a fundamentally new strategy for professional education in general and architectural design programs in particular – a strategy that employs educational technology to build upon the established strength of the studio method, and the design community experience with it. The strengths of the studio method are its problem-oriented focus by engaging students in complex ill-defined problems that require creativity and cross-disciplinary work. The proposed strategy is to create a robust research environment and a rich online environment that complement the physical studio environment. The ISTAR Labs encompasses two main labs: the Bioclimatic Architecture Lab (LAB, after the Portuguese acronym) and the Computational Architecture Lab (LAC) (Figure 5), addressed in his chapter. LAC includes four modules briefly described below. For a more detailed description see the URL http://www.civil.ist.utl.pt/istar/.

Advanced Geometric Modeling Lab

The advanced geometric modeling module possesses the tools for the development and manipulation of digital models for analysis and visualization purposes. Some of the available tools include wide spread software such as Architectural Desktop, Photoshop, 3D Studio, but also more sophisticated software such Mechanical Desktop, Autodesk Revit, Rhino and Catia.
Rapid Prototyping Lab

The rapid prototyping module includes both rapid prototyping and 3D digitizing facilities. Rapid prototyping enables the production of physical models from digital ones, whereas 3D digitizing accomplishes the opposite. Both techniques can be used in the study of design and construction solutions that cannot be accomplished with the traditional means due to shape complexity. These solutions include new building forms for aesthetic innovation and pleasure, but also for better technical performance. The solutions rapid prototyping and 3D digitizing solutions available are those considered appropriate for a teaching environment for being cleaner, for not demanding special security measures, for possessing easy maintenance. Such solutions include: a laser cutter, a milling machine, and a vinyl cutter, all falling into the category of subtractive process, and an FDM 3D printing machine, which is an additive process. The available solutions can be complemented by more sophisticated solutions that exist in other IST laboratories.

Virtual Reality Lab

The virtual reality module enables the creation of virtual models from digital ones, with different degrees of immersion and interaction. Virtual models can be used for conveying solutions to clients, for studying the impact of large-scale architectural and urban interventions, for testing and experiment with innovative constructions techniques in a degree not allowed by physical and digital models. The big advantage of virtual reality is that the user can experience the built environment in a way that is closer to reality without actually having to build it. The lab includes a desktop solution, and a room unit. The desktop solution can be used by a single user, and it allows only a small degree of immersion and user interaction with the environment, whereas the room unit can be used by several users at once and allows a higher degree of immersion.

Remote Collaboration Lab

The remote collaboration module provides the means for enabling distance teaching, learning, and working. An important part of the work involved in the design of a building is done in collaboration. Traditionally, such a collaboration required participants to be co-located. Later, technological evolution would then introduce synchronous and asynchronous means of communication, such as fax machines, telex, and phone. More recently, other forms of communication emerged such as e-mail, video-conferencing, and Web-based applications. The goal of this lab is to study how such new forms of communication affect and should be used for effective design collaboration. It includes several wide spread desktop solutions for videoconference through IP, and one mobile larger unit that enables both IP and ISDN communication.

THE UNICAMP CASE, BRAZIL

The Architecture and Urban Design course at the State University of Campinas (UNICAMP), Brazil, was created in 1999, with a curriculum that emphasized the relationship between building technology and design. In its very beginning it accomplished the need for making students proficient in the use of the computers by means of five different IT subjects throughout the six years of the program. This was considered an innovation, since most architecture courses in Brazil have only one or two CAD subjects, usually for 2D and 3D computer drafting training. However, even in this avant-garde environment, in the original curriculum CAD was seen merely as a representation tool, as in most schools in Brazil. As a result, in 2003 the course was criticized by the State Education Council, who suggested that a young, innovative pedagogical project should not give CAD a secondary role. In response to this criticism, in the

Figure 5: ISTAR, IST Architecture Research Laboratories: views of the advanced geometric modeling, rapid prototyping, remote collaboration, and virtual reality facilities included in the computational architecture laboratory.
The past five years the CAD curriculum at UNICAMP has progressively evolved, introducing new CAD-related issues, such as BIM, digital fabrication, and the use of computers in the creative process.

The Unicamp program accepts exactly 30 students each year, organized into one single cohort. Mandatory courses typically have 30 students and elective courses may vary between 10 and 20 students. Classes are held at a computer laboratory equipped with 40 desktops and/or at the rapid prototyping laboratory, LAPAC, which is described below. The present CAD curriculum at UNICAMP includes four mandatory subjects, plus 5 elective courses:

**AU301: Introduction to IT and computer graphics, 1st semester (2h x 15 weeks)**

The objective of this subject is to level freshmen students in terms of their ability to communicate ideas properly, using digital media for visual, textual, numerical and hypertext explanations. The subject includes the introduction to graphic design and raster and vector graphic representation concepts. Students are asked to develop graphic projects about a central theme (an architectural work) with the use of image processors, desktop publishing, mind map and web design software. At the end of this class students are ready to communicate their ideas using digital media.

**AU302: CAD drafting and modeling, 2nd semester (4h x 15 weeks)**

In this course students are introduced to CAD systems, BIM concepts, digital geometric modeling, parametric modeling, and definition of classes of objects. They are encouraged to develop architectural models in 3D, from which they can automatically generate 2D representations. At the end of this subject students are supposed to be ready to develop their design projects tri-dimensionally. However, this subject must also prepare them for the production of traditional bi-dimensional architectural representations, such as construction documents and detailing.

**AU303: CAD in the creative process, 3rd semester (2h x 15 weeks)**

The objective of this subject is to introduce computational design concepts. After an introduction about the history and definitions of computer-aided design, generative strategies, such as symmetry, parameterization, randomness, substitution, hierarchical systems, recursive application of rules, performance-based and constraint-based design, and evolutionary computation are introduced. Students develop short design exercises in the computer using CAD scripts, CAD plug ins and on-line applications that implement shape grammars, fractals, parametric design, cellular automata and genetic algorithms. Programming is simply presented as a tool that allows the implementation of generative strategies, but it is not taught in this course.

**AP314: Modeling and animation, 5th semester (4h x 15 weeks)**

This course develops students' ability to use CAD software for representation purposes. It includes 3D modeling, rendering and animation.

**AU120: Integrated collaborative design (BIM), 10th semester (6h x 15 weeks)**

This course is a studio in which course collaborative design instruments and environments are introduced and used to develop a design exercise. The course includes methods and organizational strategies for integrated collaborative design and design coordination. Case studies of projects developed by multidisciplinary teams, with a high level of control of activities and budget are presented. Students develop a design project in a collaborative way, using BIM software and a virtual collaborative design environment.

**Elective courses**

In addition to the mandatory courses above, the school also offers five elective courses, namely *Information and Communication Technologies in Design (CV909), Rapid Prototyping and Digital Fabrication (AU910), Integrated Design in 4D CAD (AU911), Design Automation and CAD Programming (IC061), and Generative Design Systems (IC069)*. The two last subjects are graduate
subjects that can be taken by senior undergraduate students. The goal of these courses is to complement
the skills acquired in the mandatory courses and enable the students to explore in a deeper way the use of
new media in architecture and urban design. The programming course was once offered as an
undergraduate elective, but half of the students dropped it, even though programming was introduced
within an architectural context, through CAD scripting. As a graduate elective, only a few undergraduate
students show interest in the subject. Some of the possible reasons for this have been discussed by Celani
(2008).

Besides, digital technologies have been introduced in other subjects that are not necessarily part of the
CAD curriculum. Such is the case, for example, of a subject called Topography and Geographic
Information Systems for Architecture. This is a traditional topography course into which digital media
was introduced. Besides the usual content, concepts of remote sensing, Global Positioning Systems and
Geographic Information Systems are presented. The same happened in a subject called Architectural
core models. In 2009 rapid prototyping and digital fabrication technologies were first introduced in this
course. Students developed scale models with the use of 3d-printing and laser-cutting. As a final project,
they produced a collaborative sculpture made of CNC-cut parts (Figure 6).

Figure 6: Students assembling the collaborative sculpture (left) and the sculpture displayed at the School
of Civil Engineering, Architecture and Urban Design.

Unfortunately, the school's limited number of faculty members in the field of computation makes it
impossible to offer the electives with the desirable frequency. In order to overcome this limitation, extra-
curricular activities related to the field, such as invited lectures and workshops, have been offered as a
way to encourage students to further develop their computational design skills. Another strategy used has
been the development of individual undergraduate research projects that are carried on at the digital
fabrication lab. Some of these projects are described below.

LAPAC – Automation and Prototyping for Architecture and Construction
Laboratory

In 2007-2008 a rapid prototyping and digital fabrication laboratory was created in the school. The goal of
this lab is to provide the technological means for supporting the courses listed above. The lab includes a
laser cutter, a CNC milling machine, and a 3D printing machine (Figure 7), in addition to several
modeling and simulation software. For a more detailed description of the lab see Pupo & Celani (2008),
and http://www.fec.unicamp.br/~lapac/.

Figure 7: LAPAC’s rapid prototyping machines.

The use of the new machines was first introduced to senior-year students, as a new resource for producing
scale models (Figure 8). The enthusiasm of the students with the new available techniques made them
increase the number of physical models produced during the design process, thus contributing to the
quality of the outcome. After this experience, rapid prototyping was introduced in the Architectural
Models subject (4th semester), which now includes both traditional and automated fabrication techniques.
Students now can use the laboratory for producing models for any architectural design studio they are
taking.

Figure 8: Scale models produced by senior-year students.
A strategy that has been used is the offering of one-year undergraduate research scholarships. This type of research consists of individual or small team projects about anything students are particularly interested in, under the advice of a professor. The only requirement to develop a research project in the digital prototyping and fabrication lab is that the student must overlap his or her personal interest with the use of the available technologies. For example, a student interested in accessibility developed tactile maps using rapid prototyping techniques; another student interested in origami conducted a research about how to make origami using the laser cutter; a student interested in historical architecture produced scale models of her favorite buildings, and so on. As a result, these students deepen their knowledge about technology and its applications in architecture (Celani, 2008).

The results are presented to other students during an annual interdisciplinary seminar at the University. On top of a cash stipend, students are given credits in their academic records as an extra incentive. Some of the research projects conducted by undergraduate students at LAPAC are shown in Figure 9.

Figure 8: Research Project #1: The hand-made model being 3d-scanned; Research Project #2: One of the models produced in this research, with the 3d-printer; Research Project #3: The presentation model of the campus; Research Project #4: The tactile map; Research Project #5: The wind-tunnel experiment, with the laser-cut model; Research Project #6: The dry ice experiment with the 3d-printed model; Research Project #7: The laser-cut scale model of the wind reactor-generated shape (Eduardo Corradi); Research Project #8: CNC-cutting the concrete mold’s parts (Danilo Higa da Rocha); Research Project #9: A scale model of a sculpture, 3d-printed from the 3d-scanned file (Laura Cancherini); Research Project #10: A screenshot of Photomodeler software showing the digitations of a capital (Luciana Iódice).

RESULTS

When the new curriculum was devised at IST, the goal was to provide students with state of the art computer technology and prompt the use of such a technology in a natural way in the design process. When the courses and labs were created the expected results were: (1) to support architectural teaching and research; (2) to investigate how computers and information technology can be integrated in the design process; (3) to create a research environment that supports creative and innovative design teaching and practice; (4) to develop new expertise oriented towards new architectural and building solutions; (5) to provide technology-oriented consulting services to the AEC industry. These results were achieved to a certain extent. The technology was successfully integrated in the architecture program and use of the skills that students acquired in the described courses extended to other courses. The courses and the labs have served as the basis for developing several master and doctorate theses. The work of students has led to innovative and creative approaches with recognized results. For instance, one student won the FEIDAD Award in 2005 and another got the Best Paper Award at the 2007 CAAD Futures conference. In addition, several patents were obtained, some of which have yielded new products for the construction industry that are now being commercialized. This, in turn, has prompted the industry to take the initiative to commission new projects. Finally, the courses and the labs contributed for increasing the students’ employability, particularly by firms known for their technology-oriented approaches. Interestingly enough, students’ good results in the technology-oriented realm did not collide with their design skills, as they also obtained significant results at this level. In fact, both the students who took the CAAD studio and those who took the alternative traditional studio got awards in design competitions over the years.

However, despite the good results, the strategy followed at IST back-lashed. The preeminence of the computer-based classes, particularly among students, led instructors who were in favor of a traditional approach to fight against computer-oriented classes. The argument was that before students learnt how to use the computer before, they should learn how to draw, and that free-hand drawing skills were essential to architectural design thinking. Our argument was that students should learn free-hand and computer
drawing in parallel so that they could become proficient in both techniques and use them naturally in the design process. We believed that computer-based means of representation could support design thinking in a way similar to that of hand drawing. Traditionally oriented instructors outnumbered technology-oriented ones and the result was they voted to move computer classes to later years of the program in architecture. At the end of this power struggle, the computer-based classes were reduced to only two, with the first being offered only in the 5th semester (third year). The CAAD studio first became an elective course and then it was cancelled. The GIS course also was cancelled.

This outcome is not so surprising if we consider that, according to literature in management, (Beamish, 2008) to successfully introduce any new technology into an existing organization, one must conquer the support of the organization’s members. No technology can be successfully introduced without such a support. Cultural and organizational aspects play a role in the process that is as important as those of technological aspects. Despite the fact that the new program in architecture was created inside an engineering school with the goal of enabling a technology-oriented formation, the prevalent culture of the community of architecture instructors had a different orientation. Obviously, the sheer struggle for power also influenced the course of events. Instructors with no background in technology and specifically in computers saw the raise of computer technology as a threat to their position and their interests and so acted accordingly.

One possible way of avoiding this negative reaction that has been followed in recent years is to team up technology-oriented instructors with traditionally oriented ones. When both become responsible for the success of a class, particularly a studio, they have no option than putting their differences aside and work together. In addition, while one concentrates on the successful teaching and use of the technology, the other can make sure that design aspects are not overlooked and neglected. Obviously, this strategy depends on the willingness of the two instructors to work together in first place, but this is something that head of the program is in good position to overcome.

At the time these events were taking place, a graduate student from UNICAMP was spending a period of study at TU Lisbon as part of her Ph.D. studies on prototyping and fabrication technologies. She was interested in how such technologies could be introduced in the curriculum at UNICAMP, who was in the process of implementing its own laboratory to strengthen the role of technology. As a result, digital fabrication technology was implemented into mandatory and elective subjects at UNICAMP. There the strategy was first to make digital fabrication technologies available to students outside the formal curricula and then led students to transport these technologies into the formal courses and use this as drive to change the existing courses and create new ones.

At UNICAMP the curriculum changes were based on the assumption that the introduction of computational design theories and techniques would naturally result in the use of new technologies in the design process and in the increase of design creativity. With the introduction of rapid prototyping techniques students started to give more importance to physical models in the creative process, which was a great contribution to their design outcomes. The number and quality of scale models was increased, along with the quality of the designs. However, the use of IT still remained restricted to representation issues for most students, even in students who had taken CAD programming and generative design elective subjects.

One possible reason for this is the fact that all the new subjects have been introduced as complements to the course's main core, which is still formed by traditional architectural design studios, as in most schools. In these studios instructors usually teach design in the same way they are used to work in their professional practices, which does not include the use of state-of-the-art design computing techniques. This has shown us that changing the school's design culture is as important as creating laboratories and introducing new subjects.

A strategy that has been adopted to overcome this limitation is offering workshops to the faculty and creating discussion forums about the use of the new techniques in the creative process. Another
possibility would be to introduce CAD programming and generative design techniques earlier in the curriculum, as mandatory subjects linked to a design studio as done at IST.

**DISCUSSION AND CONCLUSIONS**

In her paper “Theory and design in the first digital age” Rivka Oxman (2006) proposed a theory of digital design that tried to map the different levels of interaction of the user with digital media and integration of the computer into design. Oxman identified four components of digital design - representation, generation, evaluation, and performance - and four types of interaction with increasing levels of integration - interaction with non-digital representations, interaction with digital constructs (e.g. a CAD model), interaction with a digital representation generated by a mechanism (e.g. a rule-based generated CAD model), interaction with a digital environment (e.g. interaction with the coded rules that generate the CAD model). Then she identified eight main models of design, being the first, the paper model, in which the user interacts only with non-digital representations. In the second model, called CAD descriptive model, s/he interacts with a CAD model, an explicit representation of a particular form. In the third, the generation evaluation model, the designer also makes use of analytical simulation techniques that are predictive models of design. In the fourth, called formation model, s/he interacts with dynamic representations for form generation such as in parametric design and scripting, rather than with its explicit representation. In the fifth, the generative model, s/he interacts with more complex mechanisms of form generation like shape grammars. The difference between formation and generative models are basically in the level of knowledge embedded in the process used to generate architectural form. The sixth and seventh are performance models, in which the formation and generative mechanisms are coupled with performance-driven techniques, so that the form is the result of the manipulation of these mechanisms to obtain a form with a specified performance. The eighth is a compound model that combines all the other models.

According to this theory, the TU Lisbon IST and Unicamp cases represent two different approaches for integrating digital technologies in architectural curricula. They both aimed at achieving the compound model identified by Oxman but they followed two radically different strategies.

In the IST case, the strategy was to introduce digital technologies early in the formation process at the undergraduate level, starting with the CAD descriptive model (CAD I), then the generation evaluation and the formation models (CAD II), and finally the generative and performance-based models (CAAD). In the latter case, not all the models were explored at once in the same course every year because it was not feasible in just one course, but the idea was to explore some of these models every year so as to form students with varied skills over time. The implementation process was top down, with the few mandatory courses being forced into the curriculum. It permitted to achieve noticeable results faster (awards, etc.) but it caused a negative reaction on the behalf of traditional teaching staff. At the end the computer-related classes were pushed back to latter years of the curricula.

In the Unicamp case, the original curriculum, created in 1999, was similar to Martens & Oxman’s second curriculum, because there were many computer courses, but they were not integrated in the design curriculum. When the digital fabrication laboratory was created, the strategy was to introduce digital technologies at the graduate level and then to permeate gradually the undergraduate design curricula. This was accomplished by offering workshops to undergraduate students outside the curricula who then transported these techniques to the design studio. Eventually there was also a demand for the creation of separate courses on these topics, mainly because the design teaching staff did not possess the required skills. The implementation process was bottom-up, with several mandatory courses being added gradually to the curriculum. It avoided a negative reaction but took longer to achieve visible results. At the end more courses on computer topics are offered at Unicamp then at the beginning at IST.

The Unicamp case shows that Martens & Oxman’s ideal introduction of computer technologies within the design curriculum is not always possible, because it requires design instructors who are ready for this type of approach. In certain cases the introduction of digital fabrication facilities along with research projects,
workshops and elective courses may be more efficient because it allows the students themselves to carrying the new contents to the design studio.

Both the experiences at UTL and UNICAMP have shown that it is important to introduce CAD subjects as early as possible in the architectural curriculum. This includes not only representation skills, but also fabrication and generative knowledge. Adding computational design subjects in the curriculum and creating rapid prototyping and digital fabrication laboratories is important. However, the greatest challenge to the real revolution in CAD curriculum is changing the design culture in the school. This has been true for the two programs described herein, despite of all their differences.

In the seminal paper "The theoretical foundations of Computer-aided Architectural Design", Mitchell (1975) proposed different levels for the "division of tasks between human designer and machine". According to him, the "least ambitious level of use of the machine is to allocate to it only tasks of representation", which is followed by "the task of evaluating solutions produced for consideration by the human designer". Unfortunately, in most of the architectural curricula these are the only functions given to the computer.

The automated generation of design alternatives by means of computer programming (not just by the use of black-box software!), even if just for small, well-defined, design problems, represents a far more ambitious pedagogical use of the machine, and thus should also be included in the architectural curriculum. To be able to develop this type of application, students must learn alternative ways of representing design problems – not just the graphic ones – since computers operate with symbolic representations. It is important to introduce these skills early in the curriculum, so students can get used to them and start developing their own algorithms. In the beginning of their education they may use these skills just to automate repetitive procedures, and as they become more experienced in design they can start using them for design exploration. In theory, the capacity to automatically generate a great number of alternatives may contribute to the discovery of novelty and the increase of creativity.

This proposal may look contradictory to Schon´s theories about the importance of visualizing and manipulating shapes for reflecting on design problems. However, graphic diagrams play a fundamental role in the definition of symbolic representations, allowing one to establish parametric relationships. Besides, nowadays graphic representations can be used even for developing computer programs. "Visual programming" environments, such as Grasshopper, bring symbolic representations closer to the architect’s way of thinking.

Still according to Mitchell (1975), "The most ambitious potential level of use of the machine is to attempt to develop systems capable of dealing intelligently and flexibly with ill-defined problems; that is of displaying the capabilities characteristic of a good human designer." (p. 149) In order to develop this kind of skill in architecture students, it would be interesting to encourage interdisciplinary work with computer sciences and engineering students.

In summary, we have described two approaches to introducing new technologies in architectural curricula, each with its own pros and cons. It is hard to say which is better as the success of the approach depends on the specific culture of the institution and its social and technical environment, as well as on the ability of the “technology promoter”—the person or people in charge of leading the process and teaching the computer-oriented classes—to undertake extensive, sometimes painful, negotiations. If one has the social skills and the willingness to undertake such negotiations, one might be able to avoid the type of backlash described in the IST case and, therefore, one might be better off following a similar approach as it leads to visible results faster. Otherwise, it might be wiser to follow the approach described in the Unicamp case and let students and time get there.

In conclusion, the introduction of technologies in an integrated way in any architectural curriculum has to take into account the school’s traditions and the faculty’s beliefs. Different paths, sometimes not so direct, may be necessary in each case. The whole enterprise needs to have the participation of the entire
community, so that new technologies can be really integrated in the architectural education and not seen as an interference, a threat, or a luxury, whether in specific CAD subjects or within the design studio.

More information on the courses and the labs can be found at http://www.civil.ist.utl.pt/~dac/ and www.fec.unicamp.br/~lapac.

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