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Research

Digital Fabrication Laboratories: Pedagogy and Impacts on Architectural Education

Abstract. This paper discusses the role of the new digital fabrication laboratories in architectural education, as an opportunity to introduce practical exploration along with scientific content. It includes a historical review of practical instruction in architecture, a description of digital fabrication labs, and a comparison between pedagogical methods in engineering laboratories and in digital fabrication labs. The paper ends with a reflection about the impact of the introduction of this type of labs on architectural education.

Introduction

Since the late 1990s a new type of laboratories started to appear in the leading architecture schools, initially called "rapid prototyping labs", and later referred to as "digital fabrication labs".[1] But, aside from the use of digital technologies, how do these laboratories differ from the traditional model shops, and why are they called laboratories, instead of simply "digital fabrication workshops"? Should they focus mainly on research, development or instruction? Which are the pedagogical methods used to teach in these labs and how they can be integrated into the architectural curriculum? Finally, how are these laboratories related to other practical instruction spaces, such as the studio and the science labs, and what can be the consequences of their introduction in architecture schools?

To answer these questions, this paper presents a review of practical instruction in architectural education in Western history, and looks at the types of laboratories and the educational methods for practical instruction used in the neighboring field of engineering. The aim of this work is to help architecture schools define the objectives of their digital fabrication labs, and to propose a way of incorporating practical instruction in these labs within the curriculum, with adequate pedagogical methods in each phase of the learning process. The paper ends by discussing the possible changes that may be introduced in the architectural practice as a result of this new way of teaching.

A review of practical instruction in architectural education

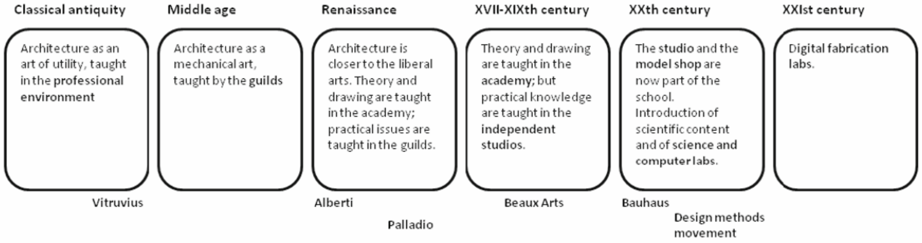

Fig. 1. Practical instruction in architectural education over time

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Fig. 2. Three examples of practical instruction in different periods: in a medieval guild, in Jean Louis Pascal's independent architecture studio in the nineteenth century, and in a Bauhaus workshop in the early twentieth century

Fig. 3. Digital fabrication lab: students gather around the laser cutter; removing a model from the 3D printer; assembling a model with rapid-prototyped parts

In classical antiquity the arts were divided into different categories. The liberal arts, which were exclusively intellectual, were only practiced by free citizens (thus the name "liberal"), while all the other arts, which involved manual work, were practiced by slaves [Jaeger 1986]. Aristotle separated the "arts of necessity" from the "arts of pleasure". Architecture and the figurative arts were not considered part of the superior arts; they were considered arts of necessity, and thus were taught in professional practice, outside of the great philosophers' academies. One of the first initiatives to change this situation was Vitruvius's treaty, *De architectura libri decem*, which would influence the formation of the "modern concept of a broad liberal arts education" of architects [Vitruvius 1999].

In the first universities, in the Middle Ages, the liberal arts taught in the Trivium and the Quadrivium were, respectively, grammar, logic and rhetoric, and arithmetic, geometry, music and astronomy. The "arts of necessity" were then called "mechanical arts", and included blacksmithing, navigation, agriculture and hunting, as well as medicine and architecture (the exact list of mechanical arts varies according to time and author). These arts were then taught at the guilds, the professional associations, with technical – not scientific – instruction, and without any links to philosophy, science or to the other higher arts.

This lower status of architecture would change only in the Renaissance. Between the sixteenthth and the seventeenth centuries the figurative arts – painting, sculpture and architecture – stood between the liberal and the mechanical arts, becoming closer to science, literature and mathematics, and more distant from crafts. The role of architects such as Alberti, Leonardo and Brunelleschi was very important for this shift. In *De Re Aedificatoria*, Alberti defines architecture as a product of design (*lineamentis*), giving it an intellectual dimension. With drawings – including the recently invented perspective – and scale models, architects gained control over the production of the building, and with treatises like Alberti´s and Palladio´s they were freed out from the guilds' masters, and architecture became a generalizable science, with its own grammar and theory.

However, the academy was not created to substitute the apprenticeship system, but rather to introduce two novelties: a theoretical discussion about art and architecture, and the drawing as a way to define the building *a priori*. Practical instruction continued to be provided by professional associations and private workshops for many centuries. At the École de Beaux Arts in Paris, for example, studios would be incorporated in the school only in the second half of the nineteenth century.

In the twentieth century, after World War I, the Bauhaus in Weimar was probably the most successful example of the incorporation of the professional workshop in the academic education of architects. Its pedagogy was rooted in the traditional apprenticeship system, and proposed re-integrating technical and aesthetic issues through intense work in production shops: "crafts work was seen as an ideal unity of artistic design and material production" [Bauhaus Dessau Foundation 2011]. Each workshop had two masters: a master of form, "an artist responsible for the design and aesthetic aspect of work", and a master of crafts, "a craftsman who passed on technical skills and abilities".

Between 1923 and 1928, László Moholy-Nagy established what is nowadays considered the essence of the Bauhaus method, promoting the integration of art, science and technology. He was an enthusiast of the qualities of materials and tried to derive aesthetic value from the new industrial production techniques. His ideas were later published in *Von material zu architektur* (1929) (translated into English as *The New Vision* [1938]), which would become an important reference for the modern design method. In his book he proposed the "merging of theory and practice in design" [Moholy-Nagy 1938: 5] and described his educational method:

> Teachers and students in close collaboration are bound to find new ways of handling materials … materials through actual experience of its properties, its possibilities in plastic handling, in tectonic creation, in work with tools and machines such as is never attained through book knowledge in the usual school exercises and the traditional courses of instruction [1938: 23].

Although the Bauhaus was a very influential example in architectural education, after World War II many professional schools were incorporated into larger universities, and had to introduce more scientific content in order to gain scientific respectability, as described by Herbert Simon:

> It is ironic that in this century the natural sciences almost drove the sciences of the artificial from professional school curricula, a development that peaked about two or three decades after Second World War [1998: 111].

In engineering education, for example, science and mathematics were gradually added to the curriculum. Soon "the practical aspects of engineering generally taught in the laboratory began to give way to the more academic, theoretical subjects" [Feisel and Rosa 2005: 122].

Like engineering schools, architectural programs were also gradually transformed through the inclusion of scientific content, losing part of their traditional hands-on educational methods. This process culminated with the Design Methods Movement in the 1960s, in which the architectural design process was extensively studied in a scholarly way. New "scientific methods" of design were developed and tested, in response to the new, highly complex architectural programs. The movement was influenced by developments in the fields of operational research, artificial intelligence and computer technology. Its main objectives were 1) to design better, by understanding the process of design; 2) to externalize the design process, allowing large teams to collaborate; 3) to allow repetitive parts of the design process to be automated by the computer [Gregory 1971].

A new type of practical instruction was thus added to architectural education – the science laboratory – which can be defined as:

> a place where scientific research and development is conducted and analyses performed … [using] a vast number of instruments and procedures to study, systematize, or quantify the objects of their attention. Procedures often include sampling, pretreatment and treatment, measurement, calculation, and presentation of results … (*Encyclopaedia Britannica*, 2011).

In the traditional architectural studio and model shop, work was usually not carried out in a scientific, systematic way. Design was usually exploratory, based on trial and error. The new science laboratories in architecture schools were used for the demonstration of physical concepts in architectural applications, such as acoustics, lighting and statics, but also for the scientific study of the design process. It is not clear when and in which field the denomination "design laboratory" first appeared, but nowadays many architecture departments include a laboratory with this name, where research about the design process is conducted.

Another type of laboratory that was introduced in architecture schools in the past decades was the Computer-Aided Design (CAD) lab. In the 1970s the first CAD-specific courses were offered in computer labs; in the 1980s computers started being installed in the studios for 3D modeling, and in the 1990s they were already very common in the studios, with an emphasis in advanced visualization [Mitchell 1990]. At that point, the popularization of 3D modeling and rendering made physical scale models almost disappear in many schools.

In the same way that computers became part of the design studio in the 1980s and 1990s, in the 2000s computers became part of the model shop. Since the late 1990s some schools started introducing rapid prototyping and other computer-controlled machines in what would be later called "digital fabrication laboratories". Initially, these facilities included just smaller rapid prototyping machines for producing scale models automatically from CAD models, but soon there was an interest in the new post-industrial methods for the production of full-scale prototypes and building parts.

Digital fabrication laboratories in architectural education

The introduction of digital fabrication technologies in architectural education is a recent, yet quickly-implemented phenomenon. As stated by Rivka Oxman and Robert Oxman "fabrication labs in education, which were rare even just a few years ago, are today commonplace" [2010: 23]. However, the origins of these laboratories in architecture schools have not been well documented.[2] The first experiences in the use of digital fabrication for architectural prototyping and model-making were the result of the collaboration with mechanical engineering laboratories, which were already using these techniques for product development. As early as 1994, Mitchell and McCullough were already proposing the use of "rapid prototyping" and "numerically controlled fabrication" for making scale models and for producing building parts, directly and indirectly:

> …increasingly, it is feasible to use rapid prototyping devices to generate physical scale models from digital information [1994: 461].
>
> Rapid-prototyping machinery can be used not only for direct transformation of CAD models into fabricated objects, but also to produce moulds and dies needed to reproduce those objects in other materials or in multiple copies [1994: 432].

But acquiring computer-controlled machines is not enough for turning a model shop into a laboratory. The essence of a laboratory is in the scientific approach to experimental work, which necessarily includes systematization, the use of control variables, the elaboration of conjectures, and the documentation of all processes.

One of the first digital fabrication laboratories in an architecture school was set up by Professor William Mitchell at MIT′s School of Architecture and Planning in the late 1990s. The laboratory′s first acquisition was a fusion deposition modeling (FDM) machine, followed by a laser cutter. The first applications of these machines were producing scale models related to Ph.D. students' researches and to graduate elective subjects specially created for exploring the new techniques. Water jet cutters and computer numerical control (CNC) router machines were also available through an agreement with the Mechanical Engineering Department. As the methods and parameters for using the machines were gradually assimilated, a larger number of students started using them, more machines were acquired, and the laboratory became the Digital Design Fabrication Group (http://ddf.mit.edu), where nowadays many courses are taught and research projects are conducted.

The methods, parameters and examples of applications developed by pioneer digital fabrication labs like MIT′s made it feasible for other schools to implement their own labs. As the word spread, the price of machines decreased, and new, less expensive techniques became available, architecture schools started creating their own digital fabrication laboratories.

An important aspect of these new resources was their motivational power, as acknowledged by Marc Schnabel in an eCAADe round table on CAAD education, in 2001:

> 3D Modellers, 3D Scanners, immersive Virtual Environment and Rapid Prototyping are used to assist both students and teachers to explore and study architectural creativity in a new way that enables a deeper involvement into design-issues. Since production time and cost are fairly eliminated, students do not become too attached to a design, which is the outcome of long training of IT-applications, modelling and production. A solution can not only be altered as quickly as new ideas emerge but also experienced virtually or real [Mark, Martens and Oxman 2001: 210].

The "ideal computer curriculum" proposed by Mark, Martens and Oxman included, in the advanced level, a "Computer Aided Manufacturing and Robotics" course, which included "the possibilities of numerical control processing, rapid prototyping and building component manufacturing" [2003: 170]. In the same paper the authors discuss two different strategies for introducing new technological contents in the architectural curriculum: one that integrated digital design topics in existing courses, and another one in which the topics were offered in specific, mandatory courses. The authors concluded that the first strategy was more efficient because "it is essential that an architect's education continue to be focused on issues of building and place".

However, it is still necessary to provide instructions for students regarding the use of the machines and their specific software, and to introduce digital fabrication concepts, such as the three types of computer-controlled production processes – additive, subtractive and formative [Lennings 1997] – because this knowledge can have an impact on design decisions. For this reason a better option may be to include specific courses on digital fabrication in the beginning, and progressively integrate this content in more advanced architectural design studios.

Types of laboratories: research, development and education

Feisel and Rosa [2005] define three types of engineering laboratories, with different objectives: research, development and education. According to them, **research laboratories** "are used to seek broader knowledge that can be generalized and systematized", thus contributing to the overall knowledge in a field. In research projects the use of the digital fabrication laboratories is often combined with the use of equipment from other science labs, such as wind tunnels. An example of this type of research is described by Prata-Shimomura et. al. [2011]. In order to study the characteristics of natural ventilation in different types of urban patterns, Prata-Shimomura produced a scale model of an urban area using a laser cutter. The precision of the model was crucial to the success of the experiment, since a difference of just a few millimeters could change the results in a 1:1000 scale completely. The technique allowed the precise installation of Pitot tubes and anemometers in some surfaces of the building models, through the automated punching of holes, for measuring wind pressure and turbulence. The understanding of urban ventilation gained with this project can be applied in many future urban design projects.

The objective of **development laboratories** is to obtain experimental data to guide professionals in designing and developing products. This type of laboratory is also used to gather specific measurements of performance, "to determine if a design performs as intended" [Feisel and Rosa 2005: 121]. One of the first uses of digital fabrication equipment for product development was carried out by Frank Gehry's architectural firm in the project of a fish sculpture in Barcelona, in 1992. Shelden [2002] describes how the design team used a laser cutter to produce models for testing the fitting and assembly of the parts, and identifies this moment as a key point in the digital revolution in architecture. Digital fabrication labs can also be used for developing building systems and materials. Loveridge [2011], for example, describes the development of a new aluminum foam material in collaboration with materials and fabrication researchers. The material will not be used uniformly throughout objects; the idea is to use different densities, parametrically defined, in areas that are more and less subject to stress.

According to Feisel and Rosa, while the objectives of research and development laboratories are clear, the objectives of **instructional laboratories** "need to be better defined through carefully designed learning objectives" [2005: 121]. It is possible to say that the same applies to digital fabrication labs. The learning objectives in these laboratories are seldom made explicit. The present cost of rapid prototyping and digital fabrication equipment limits the size and number of pieces of equipment that an architecture school can acquire and maintain. For this reason digital fabrication labs often serve simultaneously as the three different types of laboratories described above. Research, development, instruction and even the production of scale models for traditional design courses often overlap in these spaces. Thus, most digital fabrication labs in architecture schools cannot be classified as a specific type of laboratory.

In order to increase the possibilities, many digital fabrication labs from architecture schools have established partnerships with industry and carry out design (development) projects with students (instruction), using scientific methods to derive new knowledge (research). Vogiatzaki-Spiridonidis, for example, has created

> a consortium of schools of architecture and small to medium sized enterprises activated in the area of digital manufacturing … [to] establish an exchange of experiences, information knowledge and expertise regarding the contemporary trends and specific demands of architectural creation between teachers, researchers and enterprises [2009: 5].

The information transmission in this type of partnership works in both ways: students get closer to the production actors in the real world, and at the industry gets in touch with the outcomes of the research being carried out at the university. In projects like this education, research and development activities are completely integrated.

Pedagogical methods in laboratory instruction

An important issue regarding laboratory instruction is related to the **pedagogical methods used**. As early as the first decades of the twentieth century John Dewey, one of the greatest American educators, proposed the introduction of experimental work from children's to adults' education, as a means to revolutionize education. However, in order for his proposition to be effective, he emphasized the need for using scientific methods:

> I see at bottom two alternatives between which education must choose if it is not to drift aimlessly. One of them is expressed by the attempt to induce educators to return to the intellectual methods and ideas that arose centuries before scientific method was developed. … Nevertheless, it is so out of touch with all the conditions of modern life that I believe it is folly to seek salvation in this direction. The other alternative is systematic utilization of scientific method as the pattern and ideal of intelligence exploration and exploitation of the potentialities inherent in experience [Dewey 1997: 85-86].

Dewey also stated that his emphasis on the scientific method did not mean that specialized techniques needed to be used necessarily. He affirmed that scientific method "provides a working pattern" for experiments, but educators should be sensible enough to adapt these methods to different situations, subjects and level of maturity of the students. This is what makes experience effectively educative.

Another important issue in experimental education is related the the objectives of the educational laboratory, which need to be clearly defined. In a colloquium organized in 2002 by the Accreditation Board for Engineering and Technology (ABET), the American accreditation organization for programs in applied science, computing, engineering, and technology, some of the objectives of the engineering instructional laboratories were outlined [Feisel and Peterson 2002]. These included instrumentation to use tools, working with models, learning to do experiments in safety, developing psychomotor capabilities and sensory awareness, collecting and analyzing data, designing and assembling systems, developing creativity and a sense of ethics, and practicing teamwork and communication skills.

In design studios recently taught in digital fabrication labs, students are usually shown working with CNC routers and 3D printers, making models, designing and assembling building systems, working in teams and presenting the results to reviewers, thus meeting most of the objectives that a laboratory should have. Although these studios are unquestionably motivating for students and can produce good results, some of the objectives of instruction laboratories listed above are usually not made explicit, such as the scientific methods used in the design process.

The different instruction styles in science laboratories are the theme of an interesting and lively debate among educators and psychologists. Dickey and Kosinski [1991] affirm that the traditional laboratory pedagogy is not effective because it is too similar to traditional classroom methods, which are based on the transmission of information. To solve this problem, they propose the concept of "inquiry labs", in which students have to plan and perform their own scientific investigations, instead of blindly following a cookbook. Sweeney and Paradis emphasize the role of "scientific inquiry labs" in the preparation of future researchers:

> Science is, by its nature, a hands-on, inquiry based discipline. Students are unable to fully appreciate the scientific method and the essence of scientific inquiry unless they have the opportunity to acquire and analyse data first-hand [2004: 195].

However, this type of approach may not work in all levels. Kirschner et al. [2006] have shown that guided instruction is also important, based on the differences between the cognitive loads that can be absorbed by expert and novice students. Controlled experiments are limited and do not necessarily stimulate the use of creativity, but they are necessary in courses for beginners. The "minimally guided approach" (also known as "discovery learning, "problem-based learning", "inquiry learning", "experiential learning" and "constructivist learning") is more efficient when used with intermediate and advanced students.

In a study about engineering education, Sheppard et al. [2009] proposed the categorization of laboratory instruction in three levels (fig. 4). For novice students, laboratories are typically used to gather data related to physical evidence in order to contextualize theory. Students in this level must follow the instructor's directions strictly, step by step, in order to reach the desired results, which will demonstrate a concept. In physics courses, for example, classes typically consist of an introductory lecture in which a theoretical principle is introduced and demonstrated. Next, students must do some exercises in order to understand the mathematical description of the theory. The last step consists of developing laboratory simulations that illustrate the same phenomenon. In these structured or "controlled experiments" students can validate the concepts learnt by testing them with different parameters and conditions.

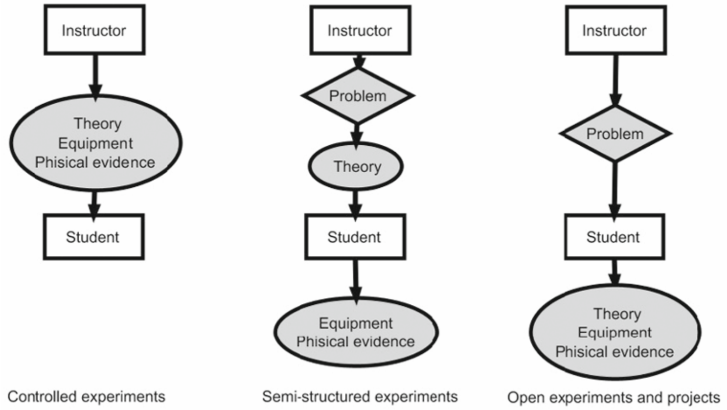

Fig. 4. The three models of laboratory instruction; adapted from [Sheppard et al. 2009]

This initial guided instruction approach is not very commonly used in digital fabrication laboratories (nor in architectural education in general), and could be the reason why students find it difficult to develop their design experiments in a more systematic and scientific way, often recurring to trial and error.

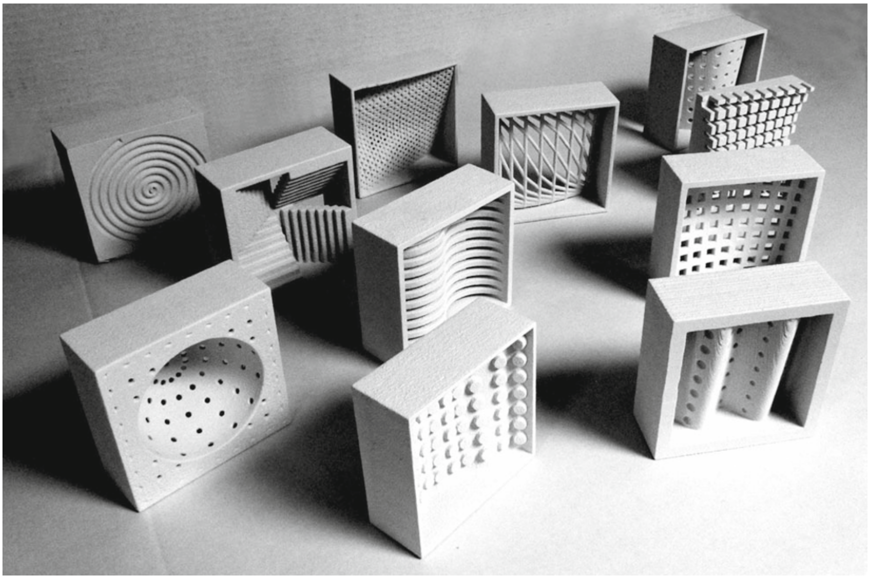

Fig. 5. 3D printer experiment

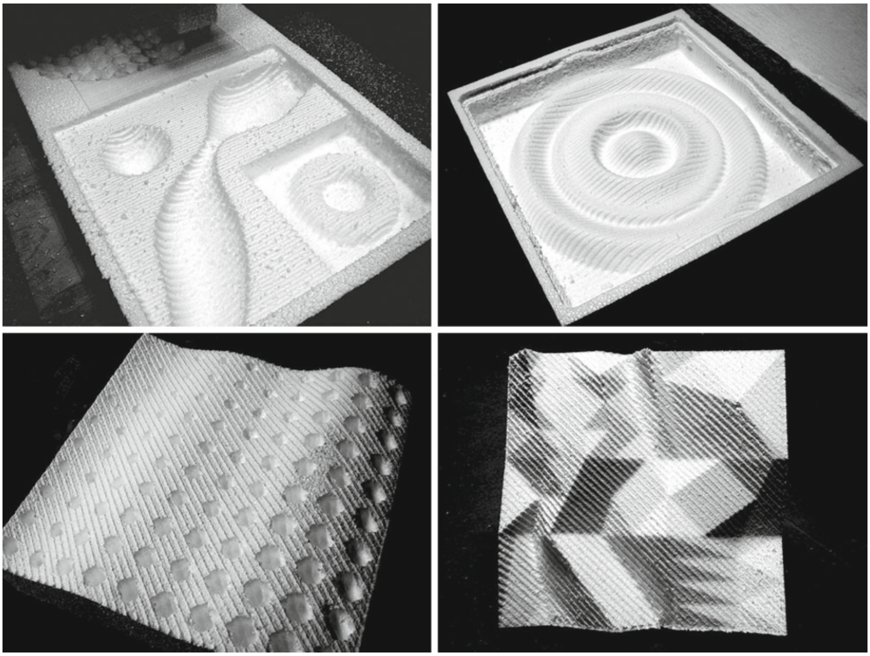

Fig. 6. CNC router experiment. LAPAC, University of Campinas

In digital fabrication labs basic knowledge about the different production methods can be taught in introductory workshops, in which students are asked to develop simple models to explore the specific capacities of each machine. Fig. 5 shows an exercise developed by students from an introductory digital fabrication course taught by Celani and Pupo in which they were asked to develop a 10 x 10 x 5 cm model to be fabricated in a 3D printer, in which they used parametric software to experiment with different wall-widths and feature dimensions. Fig. 6 shows a similar exercise, in which students worked on a standard block of material, varying the type and diameter of tools and experimenting with different milling strategies (such as spiraling, diagonal or orthogonal toolpaths) and parameters (such as vertical and lateral step distances). Different textures could be obtained with the very same geometric model. The result of the milling process with different parameters could be previewed virtually before being sent to the CNC router. With this type of exercises students learn to define parameters and gain confidence in the use of the different machines available in the lab.

The next step in laboratory instruction, still according to Sheppard et al. [2009], consists of allowing students to solve practical problems. In this case students are told which concept to use, but they need to decide on how to use the available equipment to perform a given task. This type of exercise is known as “semi-structured experiment”, because only concepts and objectives are given, but no methods are suggested. Semi-structured experiments are more motivating than controlled experiments, because they involve problem-solving, which results in intellectual satisfaction. They make students more pro-active and more confident in the use of concepts, but in order to perform this type of exercise students must have been previously taught how to use laboratory equipment properly.

To work in this level in a digital fabrication laboratory the instructor can challenge students to develop a geometry that can only be produced with a specific type of machine. For example, students can be asked to decide how to build a small ball inside a perforated sphere, or to define the best digital fabrication method for producing a model of a spatial structure. Each student or team will come up with a solution, and some of them will be found to be unpractical, which generates an interesting discussion [Duarte et al. 2011].

A good example of this intermediate approach is described by Mark [2003]. In this design studio students were first taught to write G & M codes for generating CNC tool paths. Next, they had to produce models with three different methods: using CAD commands to generate the geometry and standard CAM software to automatically generate toolpaths, which required a trial-and-error process to achieve the desired results; using CAD scripting to generate the geometry, thus having more control over the toolpaths automatically generated by standard CAM software; and programming directly the CNC pathways as part of the design process, which allowed “greater control over how the forms are shaped and how the materials are fabricated” [Mark 2003: 339].

With advanced students it is possible to use a much more open technique. “Open experiments” can be used to teach how to deal with complex problems. In this type of experiment only concepts and a brief description of the problem are given. Students must define the objectives of their experiment and the means to achieve them. Often they also need to search for new concepts which have not been already introduced by the instructor [Sheppard et al. 2009], or to use interdisciplinary knowledge. Once students are familiar with different production methods and machines and their characteristics, they can develop architectural designs taking these into account. Plus, by this point they have developed a sense of scientific systematization of procedures, which can help them be more efficient in their design explorations.

An example of this approach can be found in another course taught by Mark [2007]. In this final year architectural design studio students were asked to develop a lightweight oceanfront structure for seasonal use in a coastal island. The structure had to be retractable and covered by a tension membrane, taking into account wind forces and with minimal environmental impact. After defining a preliminary design, students worked with animation software to simulate the transformations of the structures. Some students used CAD scripting to generate their shapes. Next, they used finite element analysis software to simulate the fabric movement and stresses, which helped in selecting the best option for the moveable parts. They then built a physical model in the digital fabrication laboratory to study the movement of the structure and the collision between movable parts. After this, changes were introduced, new computer analyses were carried out, and new physical prototypes were produced. This process was repeated several times, until the project was considered finished. Finally, students used fluid dynamics software for an initial study of the structures' performance, followed by wind tunnel testing with digitally fabricated models. According to Mark, the shift between digital and physical representations, which was facilitated by the use of digital fabrication techniques, was the most important characteristic of the studio:

> As design moves increasingly from paper documentation to computer mediated direct fabrication of architectural projects, greater opportunity exists to associate visual representations on a computer with more dynamic and physical modeling methods. The initial development of a project may involve a wide search of design schemes that seem plausible when simulated with special effects tools. This technology doesn't catch, however, the full range of specific problems of construction, degrees of movement and interference checking realized in rapid prototyping [2007: 226].

In this example, since the problem proposed was very open, students developed significantly different structures, with different types of movement. However, all the projects had in common a scientific process of form optimization through the use of different analysis tools, including digital fabrication, wind tunnel and computer programs.

Discussion: The impact of digital fabrication laboratories on architectural education

We have seen a historical review of practical instruction in architectural education, and the evolution of the field from an exclusively practical profession to the status of a respectable science. Through history, architecture was progressively transformed from a lower art into a highly theoretical discipline. From a hands-on activity, design became a prescriptive activity, in which models and drawings are used to foresee reality, and in which everything must be resolved before the construction process.

Next, we have looked at how practical instruction was swept out and then reintroduced in the professional careers in the twentieth century, and how scientific methods were introduced in architecture, transforming its nature to an even greater extent. We have described the characteristics of digital fabrication labs, and seen how they can be introduced into the architectural curriculum. Finally, we have described the educational objectives and pedagogical methods of science laboratories' instruction, divided in three levels of progressively more open experiments, and we have presented examples that illustrate how digital fabrication labs can effectively implement the concept of a scientific laboratory and be at the same time a place for creative exploration.

In some schools, the initial impact of digital fabrication laboratories in architectural education was simply the increase in the number of physical models produced [Duarte et al. 2011]. The reason for this was probably the fact that digital fabrication was introduced in specific courses, and not as part of the design curriculum. It is important that students learn to use the machines and understand the concept behind each different digital fabrication strategy in specific courses; but in senior years digital fabrication content should be incorporated in architectural design studios and combined with other technologies, such as parametric modeling, CAD scripting, programming and the use of equipment from other science laboratories, such as natural light simulators, wind tunnels, and computational analysis tools.

As digital fabrication labs become more common in architecture schools and are assimilated by design instructors, they can promote changes in architectural education, allowing students to become closer to the production process and to have a better control over building parts and materials.

Oxman and Oxman [2010] have suggested that the recent interest in fabrication techniques is related to a "cultural shift" in the order in which buildings are defined in contemporary architecture. According to them, in the modern tradition the design process started with the definition of form by the architect alone, followed by the definition of the structure and the material in collaboration with engineers. In a recent phenomenon they call "the new structuralism" material and structure have acquired greater importance in the design process, with form emerging as a consequence of working with the right material in the correct way. In this method structural engineers are present from the very beginning of the design process, working side by side with architects. They describe the recent emergence of interdisciplinary research groups, such as the Arup Advanced Geometry Unit and Smart Geometry, who have developed new design methods with a scientific approach, based on advanced mathematical and computational techniques.

In this scenario, the authors see a new challenge to architectural education: "How do we educate architects to function as material practitioners?" [Oxman and Oxman 2010: 23]. They point out the need to redefining the knowledge base of the architect, which now must necessarily include advanced geometry and "digital enabling skills", and they acknowledge the role of digital fabrication laboratories in this new educational agenda: "Fabrication is not [just] a modeling technique, but a revolution in the making of architecture" [2010: 23].

In summary, it is possible to say that digital fabrication laboratories have a potential of promoting experimental methods in architecture together with a scientific approach, which is the basis of contemporary architecture practice. To achieve this, the explicit use of scientific methods should be encouraged. In fact, this is the reason why they are called "digital fabrication **laboratories**" and not simply "digital fabrication **workshops**". We just have to wait now to see what kind of architects will come out from these new schools, and what type of changes they will impose on architecture.

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Notes

1. The reason for this change is probably related to the fact that mechanical engineers define rapid prototyping as a layered manufacturing process [Volpato 2007], thus restricting the use of this expression to the use of additive machines, such as 3D printers. Other authors, such as Lennings [1997], define RP as "a process that automatically creates a physical prototype from a 3D CAD-Model, in a short period of time" [1997: 297].
2. A search for the keywords "laboratory", "rapid prototyping" and "digital fabrication" in the *Journal of Architectural Education* databases, for example, did not return any entry.

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