Lean thinking and rapid prototyping: towards a shorter distance between the drawing board and the construction site

Gabriela Celani A. D. Granja & E. Pinheiro
Architecture and Building Prototyping Laboratory, School of Civil Engineering, Architecture and Urban Design, State University of Campinas (UNICAMP), Brazil

Ariovaldo Denis Granja
Technology & Construction Management Group, Architecture and Building Prototyping Laboratory, School of Civil Engineering, Architecture and Urban Design, State University of Campinas (UNICAMP), Brazil

Érica Pinheiro
Graduate Program in Civil Engineering, School of Civil Engineering, Architecture and Urban Design, State University of Campinas (UNICAMP), Brazil

ABSTRACT: The aim of the present paper is to discuss the role of rapid prototyping in a seamless, lean process from the concept design to the construction of a building. The role of 3D CAD models and rapid prototyping in the design process are reviewed. Next, the state of the art in the fields of rapid manufacturing and automated construction techniques based on such models are presented. Finally, the insertion of rapid prototyping within the design and building process is discussed.

1 INTRODUCTION

When CAD systems were still rudimentary compared to nowadays packages, Charles Eastman (1975) demonstrated his concerns about the "sequential translations between the various design descriptions" involved in the design process, and envisioned an integrated Computer Aided Building Design system (CABD). In such system, the designer would work directly on a 3D model of a building, from which all 2D drawings would be automatically generated. The idea was innovative and is present in most CAD packages nowadays, eliminating all possible inconsistencies between different plans and sections of the same model. However, the problem in this type of approach is that it is based on the assumption that 2D drawings, an intermediate representation, are inherent to the process.

This fact raises an interesting challenge based on lean thinking philosophy, a determined pursuit of eliminating waste in a given process i.e., any unnecessary actions that do not create value for customers (Womack & Jones, 1996). If we think about the design/building process as a sequence of information transfers one can infer that it is possible to make it leaner by reducing waste in the information flow. In this sense any efforts to shorten the distance between product development processes and the final building are welcome. According to this view, the driving forces for lean production of buildings could be digital fabrication enabling automation, customer responsiveness and certainty of outcome in terms of cost, time and quality (Pasquire et al. 2006).

The present paper aims at conceiving a theoretical framework for a digital design and building process that evolves seamlessly from the conceptual design to the construction site, challenging traditional methods. The research methodology includes a literature review in the fields of computer-aided design, rapid prototyping, rapid manufacturing, automated building systems and lean thinking related to product development and construction.

2 3D CAD MODELS

3D CAD models were first used for visualization purposes. In the past years, however, not only 3D but also BIM (building information models) and 4D models have been used to integrate the architecture, engineering and construction practices. BIMs are extended 3D CAD models that include databases with information such as a building components' properties and quantities, as well as manufacturers' contact information. 4D models are 3D CAD models with the added dimension of time. They allow to predict the evolution of a building during construction time, making it possible to evaluate different conjectures and their consequences. More than allowing vizualization, BIMs and 4D models can help resolve ambiguities and avoid design conflicts and inconsistencies early in the process, which results in economy.

They allow for first run studies, a method for pre-testing construction processes, involving the representatives of the building team, intermediate evaluations, and precise planning of the whole operation. According to Reffat (2002), the cost of repairing design and construction mistakes at the conceptual phase can be one thousand times less costly than when construction has started, which makes 3D models indispensable nowadays. Similarly, Dell'Isola (1997) asserts that the potential for savings is much greater the earlier a value engineering technique is applied.

3D CAD models are also seen by many authors as having a key role as a connection between design and automated construction, allowing for a seamless (i.e., without intermediate 2D representations) translation between design and production. Ballard et al. (2002) assert that:

"A key support for simultaneous product and process design ... will be integrated product and process models, i.e., complex databases capable of representing product design in 3D and also capable of modeling the manufacturing, logistics, assembly, commissioning (start-up), operations, maintenance, alteration and decommissioning of that product or its components." (p.242).

3 RAPID PROTOTYPING IN THE DESIGN PROCESS

According to Modeen (2005) the use of computer-aided manufacturing processes "is still a relatively recent phenomenon in the design related fields" and hasn´t been used "as the inceptive catalyst for conceiving a design" (p.216). Rapid prototyped architectural models are still relatively expensive and only justifiable in the case of extremely complex and costly projects. Digital fabrication techniques are still rarely used in the production of final parts of the building. Among the few exceptions are buildings designed by world-famous architects such as Frank Gehry and Norman Foster.

Buswell et al. (2007), on the other hand, assert that digital fabrication is already having an impact on design, especially in the case of freeform conceptual structures that need to be turned into buildable constructions. They cite many examples that confirm the presence of Rapid Prototyping in the design process:

"Foster and Partners (London, UK) have a suite of modeling equipment that includes CNC laser cutting tools and a 3D printing process; 3D model production bureau's such as Slovinova (Hampshire, UK), specialize in producing 3D architectural models; there have been exhibitions of architecture and digital fabrication; and academic publications on the topic."

In fact, many architecture schools throughout the world are improving their traditional model shops with rapid prototyping equipment. Such is the case, for example, of MIT´s School of Architecture and Planning and Harvard´s Graduate School of Design. Although this type of technology is still not very common in South America, in Brazil, the School of Civil Engineering, Architecture and Urban Design at the State University of Campinas (UNICAMP) has recently created a digital fabrication laboratory, with a 3D printer and a laser cutter. The purpose of these labs is not only to produce sophisticated architectural models, but also to introduce this new technique in the design process.

4 RAPID MANUFACTURING AND AUTOMATED BUILDING SYSTEMS

Theoretically, rapid prototyping could be used to produce an actual building directly from a computer-generated 3D model. Koshnevis (2004), for example, has proposed to produce conventional buildings using contour crafting, an automated process of pouring concrete in layers.

However, while this type of automated construction device is still under development, other forms of digital fabrication - also known as rapid manufacturing - can be used to produce building components. According to Buswell et al. (2007), "Rapid Manufacturing is a family of digitally controlled additive processes that have the potential to impact on construction processes" (p.225). It allows, for example, to produce formwork (molds) on site using automated milling devices. Multi-axis milling is connected on site to a dedicated computer system that directly transfers its data to production controlling functions over the movement of a machine, as in the construction of Gehry´s office buildings, in Düsseldorf. Cutting with plasma and water-jet is the most commonly used fabrication technique. It is also possible to automatically bend metal sheets to form complex surfaces that are used as façade elements or even for the production of laminated glass panels with complex curvilinear surfaces as in Gehry´s The DG Bank Berlin atrium roof project. Buswell et al. (2007) presents examples of the use of large scale digital fabrication in the industry, such as the production of building structural components and façades.

Another approach to automated construction is the automated assembly of pre-fabricated parts. According to Lauge-Kristensen and Best (2002),
"Innovations in the area of computing and robotics are improving building quality and productivity. Computer-aided design in conjunction with computer-aided manufacture can improve the precision of fitting of pre-fabricated building components and modules on site by ensuring good dimensional accuracy" (p.432).

De Valence (2002) points out that robots can be used in different parts of the construction process, such as excavations, foundation work, concrete work, steel frame placing and welding, pre-fabricated concrete parts positioning, and even finishing, among other tasks. Such procedures are more commonly used in Japan, France, Sweden, the UK and the USA.

What the rapid fabrication of parts and automated building systems have in common is the fact that they all depend on 3D digital models of the building. In other words, the use of such technologies implies that the design process itself has also been based on digital descriptions of the building.

5 DISCUSSION

According to Thomson (2006) in a traditional design process the cost and difficulty of implementing changes in a project increases from the initial (briefing) to the final (construction site) phases, while the possibility of adding value to the final product decreases (Fig.1). This can be explained in part by the fact that changes in intermediate descriptions of the building (such as 2D drawings and cost spreadsheets) imply in extra costs. Because of this, contractors are likely to avoid any changes, even if a design mistake is perceived just before the construction. Such mistakes are often repeated in further instances of the building, especially in housing developments. This situation could be reversed with the use of automated processes that would allow for dynamic improvement of the design as mistakes and malfunctioning are revealed, and at the same time ensuring conformity of outcome in terms of time, cost and quality.

In medicine and dentistry, 3D virtual and physical (rapid-prototyped) models are already becoming fundamental in the planning of surgeries. Authors such as Silva (2003) and Foggiatto (2006), describe a process in which a patient's bone structure is virtually modeled from MRI images. Bone or dental replacements can be designed based on such models. Next, both the patient's original bone structure and the replacements are rapid-prototyped for performing surgery planning, rehearsals and adjustments. It is possible to envision a similar process in which rapid prototyping can be used for planning a building process, thus avoiding surprises in the construction site and reducing costs.

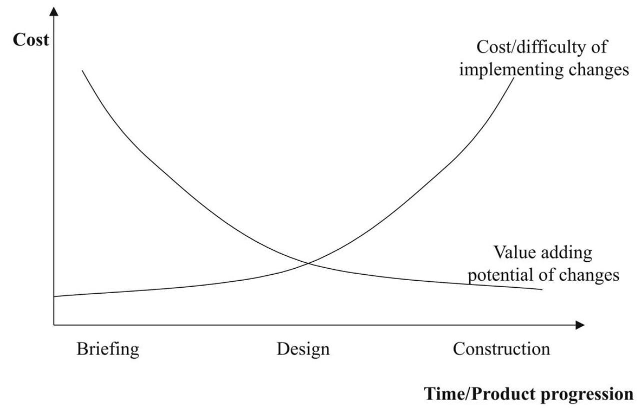

Figure 1. Evolution of cost/difficulty of implementing changes versus value adding potential of changes, after a diagram developed by Thomson (2006).

In the construction industry, however, there is the problem of scale. An architectural model is much smaller than the final building part, which makes the process less direct than in medicine. Sass (2007) has discussed the "dilemmas ... found in the translation of a description that drives rapid prototyping tools and descriptions that drive CAD/CAM machinery for full-scale component manufacturing." The author proposes a production method for facilitating this translation. According to him, "this new production method, with virtual and physical models throughout design and construction, diminishes the need for architectural drawings as the catalyst for design production".

Based on the literature review herein presented, it is possible to deduce that the introduction of RP processes in the design process cannot be restricted to the production of beautiful, well-finished architectural models for presentation. It is only justifiable in an integrated process that starts with the concept design and ends with the production of building parts or with fully automated construction. This seamless process can result in a truly lean production system, in which errors can be previewed and intermediate representations are eliminated (Fig. 2).

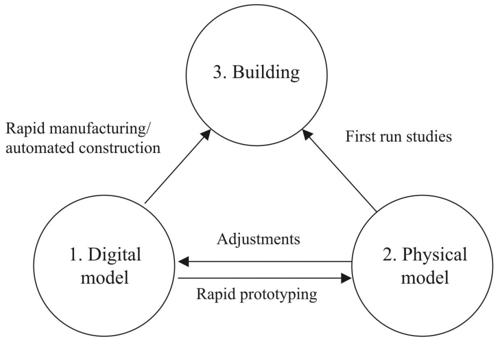

Figure 2. A model of a design/building process based on digital representations (adapted from Mitchell, 1994).

6 CONCLUSION

Although this paper only presents a literature overview of rapid prototyping and related automated construction techniques, and speculates on their potential to create a leaner process from product inception to the delivery of buildings, it is clear that rapid prototyping has more to offer than making models for visualization. The radical challenge for rapid prototyping technology in construction will be the creation of full-scale buildings. The potential for innovation is huge, as product buildability should be no longer confined to the limits of existing construction processes.

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