Digital Desires, Material Realities
Perceiving the technological gap

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Abstract. *Digital design and manufacturing technologies are progressively employed in building construction and architects interest in this field has grown widely, as many recent works, publications and scientific meetings demonstrate. By identifying some of the main reasons and expectations that were at the basis of the integration of CAD/CAM processes in the discipline, this paper examines the real success of these technological developments in contemporary architecture. By analyzing current work and literature the authors argue that there is often a discrepancy between the discourse on emerging new conditions for the practice, and the practical reality itself.*
To investigate this technological gap, the paper discusses in depth one of the most advocated promises of these new technologies: the feasible mass production of differentiation. Considering design intent, available CNC fabrication processes and material properties, it describes and critically analyses different strategies for building architectural surfaces, presenting specific examples from contemporary architecture. Realizing that there are technological limitations in the fulfillment of conceptual aspirations, this paper identifies possible innovative directions in building construction, based on the idea of structural performative surfaces.
Finally, the authors reflect on the specific nature of architecture, distinguishing it from other areas that also employ digital technologies, to frame, from within the discipline, the technological expectations and its potential further developments.

Keywords. *CAD/CAM, Digital Fabrication, CNC Technologies, Rationalization, Mass-Customization.*

1. Introduction

1.1 The Integration of CADCAM in Architecture

Over the last 30 years, the dissemination of the computer has affected the practice of architecture in many ways: from drawing automation and virtual representation, to the contemporary digital techniques that assist design conception. For architects, the increasing fascination with computational tools generated a renewed interest in the exploration of complex geometries by means, for instance, of animation, parametric, generative or evolutionary techniques. However, this tendency soon revealed the limitations of existing construction technology, ruled by standardization, pre-fabrication and mass-production principles. Despite using flexible tools for the generation and control of intricate shapes, architects still faced extreme difficulties to translate them into the physical realm. This situation drew a clear gap between digitally conceived ideas and their material constructed realities, which often fed conservative discourses against the introduction of new technologies in architecture, both in practice and academia.

In this context, architects turned to other design-related fields in search for technological help. Possible answers came from automotive, aerospace, shipbuilding or product design industries, where computer-aided design and manufacturing technologies (CAD-CAM) were employed to produce geometrically diverse and complex components. This exchange revealed that a wide range of computer numerically controlled (CNC) fabrication processes were available to work with different materials, using data from digital design models. Thus, this digital continuity from design to fabrication promised to bridge the previous gap, while suggesting new opportunities for architectural practice.

1.2 Digital Desires, Material Realties

Today, CAD/CAM technologies are increasingly employed in the building industry and explored in most leading academic environments. The disciplinary interest in this field has grown widely over the past few years. Since 2001, several authors have written and edited concise publications on the theme (i.e. Callicott, 2001; Bechthold et al, 2001 and 2003; Kolarevic, et al., 2003 and 2005; Leach, et al., 2004; Schodeck, et al, 2005), and digital fabrication has become a major theme in architectural scientific meetings (i.e. the past AIA/ACADIA conference that was fully dedicated to Fabrication). Together, all these references have provided insight into the taxonomy of CAD/CAM technologies and its techniques, reviewed the history of its implementation in the discipline, presented and illustrated innovative case-studies, and outlined the emergence of new design and building construction paradigms. Moreover, these technologies have stimulated the optimistic view “that design vocabularies can be expanded and that these same designs can be made with a quality and precision previously difficult to achieve” (Shodeck, et al., 2005), while their impact on architecture has defined new conditions for the development of architectural projects, based on digital convergence, non-linear methodologies, trans-disciplinary collaboration or mass customization paradigms.

However, when architects try to materialize their ideas, the creative and innovative efforts dedicated to the exploration of digital techniques face recurrent difficulties and limitations distancing them from the announced technological promises. Even if we’ve reached a moment where one could state that everything we generate in the computer can be built with digital technology, the design process often must include adjustment procedures to make production feasible. As a result, the built artifact is not a precise translation of the designer’s ideas but, instead, a compromised material interpretation. There is still a separation between the reality of applications and what is seen as ‘ideal’ technological promises.

1.3 Paper’s Intentions

By investigating contemporary works and literature, it becomes clear that architects tend to generalize the contribution of digital technologies as a boost for new modes of practice without fully considering the degree of complexity that they involve. The result is a certain discrepancy between discourse and practical reality.

In this context, this paper selects one of the most widely admitted technological promises made to architecture, to reflect on the underlying factors that interfere in its partial or full achievement. By investigating the possibility of the viability of “mass production of differentiated shapes independent of their complexity” this paper will argue that there is an ambiguity lying behind this appreciation, which characterizes the instability between technological-aided desires and material realities. Understanding the relevance of CAD/CAM technologies is directly dependent on its capacity to affect the discipline, this paper will contribute to facilitate the perception of this technological gap which is a crucial step towards the future formulation of digital strategies to successfully drive architectural ideas into physical realities.

2. The Mass-Production of Differentiation

2.1 The need for rationalization

When dealing with the fabrication of complex shapes, architects face the necessity of developing design rationalization processes to make it viable in terms of production cost, time, transportation or assembly efficiency. When explaining the work of Frank Gehry, Shelden (2001: 78) describes these procedures as "the resolution of rules of constructability into project geometry". This necessity leads to the development of methods of surface subdivision into a set of discrete components and to the simplification of the overall design geometry at the component level. Physical form becomes an interpreted representation of the digital construction that results from feasibility concerns rather than aesthetic or conceptual ones. Rationalization efforts can thus be taken as index signs to perceive the distance between formal aspirations and their actual manifestations.

As it has been mentioned, the integration of CAD/CAM technologies in architecture promised to change this limiting condition. Inspired by what is occurring in other industries, architects have been seduced by the possibility to fabricate differentiated shapes independently of their complexity without additional difficulties or costs. However, this affirmation is not totally true because 'digital' architects still embrace rationalization processes that directly interfere with the visual and tectonic quality of the physically built objects.

2.2 Building architectural surfaces

The diagrams on FIGURE 1 summarize three current strategies to develop and build curved surfaces, which imply different levels of rationalization. In the first strategy (1.A), the built shape doesn't share the same geometric properties of the original design. Its curvilinear information is lost in the process by means of using rigid and planar sheet materials like glass or wood. In the second option (1.B), the resulting construction is much closer to the computer-defined curved surface by using bendable sheet materials like metals, which can work well with single curved surfaces. However, in the presence of complex ruled or double-curved geometries, physical constructions become approximate actualizations of virtual curvatures. Computational techniques for optimizing the subdivision into pieces by varying their sizes according to the degree of curvature -like the algorithmic subdivision process developed in the Frank Gehry's Experience Music Project-, or the

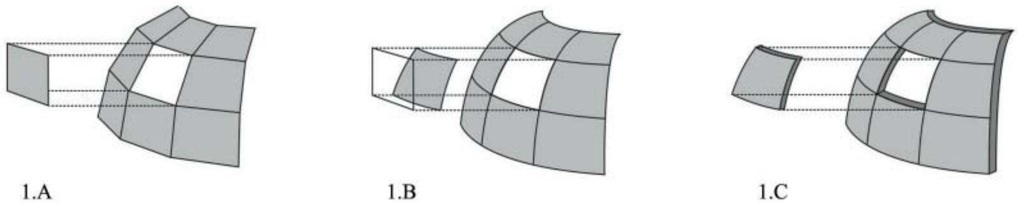

FIGURE 1: Strategies for the physical construction of curved surfaces. The option 1.A shows a strategy of approximation through flat sheet components that, once assembled, create a faceted surface. In 1.B, the component is also a flat sheet one but it has the capacity to bend during assemblage, thereby acquiring the desired curvature. Finally, in 1.C, the result is also a curved surface but it is made out of curved thick components.

use of elastic or flexible materials like fabrics are strategies that can improve the accuracy of material representations. Finally, the third strategy (1.C) shows a construction that is composed of three dimensional solid components that can be fabricated with the necessary curved geometry in materials like concrete, stone or foam.

The reading of Figure 1 reveals that the potential need for rationalization decreases from 1.A to 1.C. However, by looking at contemporary case-studies, it is possible to verify that the most common and successful applications of CAD/CAM technologies in architecture rely on the processes illustrated in 1.A and 1.B. Many examples can be found in projects that involve glazing structures (i.e. Norman Foster's British Museum Great Court or the London City Hall), metal cladding skins (i.e. many of Frank Gehry's works in the last decade like the Guggenheim Museum in Bilbao, the Experience Music Project in Seattle or the Walt Disney Concert Hall in Los Angeles), or textile membranes (i.e. Bernard Franken's Dynaform Pavilion in Frankfurt). This observation is noteworthy because although architects use advanced manufacturing processes, cost and time constraints often force them to adopt strategies that do not yield precise actualizations of digital complex geometries. To perceive this discrepancy in the current technological context requires understanding the articulation between design intent, material properties and digital processes [FIGURE 2].

2.3 Design intent vs. materials and processes.

Successful implementations of CAD/CAM entail an efficient coupling of digital design and manufacturing techniques. While CNC technologies permit the fabrication of complex shapes, recent explorations in advanced computation are providing architects with powerful tools for design development. Parametric, generative and evolutionary techniques for optimization and evaluation offer flexible ways to assist subdivision processes.

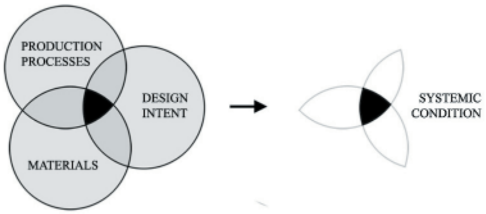

FIGURE 2: The systemic adjustment and articulation of the variable factors concerning production processes, material properties and design intent qualities is a decisive contribution for successful implementations of CAD/CAM in architecture.

Triangulation, flattening or unfolding are becoming common routines to link design to CNC cutting processes, which tend to lead architects towards rationalization processes, like the ones represented in 1.A and 1.B. Among all existent categories of digital fabrication technologies, as defined by Volker (1997: 69), the particular case of cutting, within subtractive fabrication, seems to be the only one that, in fact, can really achieve feasible mass production of differentiated shapes. By involving simple machining planning procedures, a single operation of contouring, and the use of thin materials, two-dimensional CNC cutting processes are fast and permit the production of differentiated shapes as easy as if they were all identical. Kas Oosterhuis' Web of North Holland project is an example of the use of digital technology to design and build an entire architectural construction totally made out of flat components. The office used laser-cutting processes to manufacture both the structural and the cladding system. Given that accommodating repetitive parts is usually easier to plan, the critical aspect of differentiated fabrication lies in optimizing the raw sheet material for the production of multiple components, and in assuring an efficient system of individual identification to allow and orient their future assemblage. In Oosterhuis' project, customized scripted procedures were developed to analyze the geometry and flatten the resulting components for later CNC cutting. Thus, significant time and economic advantages in design and fabrication explain the common preference for these two strategies.

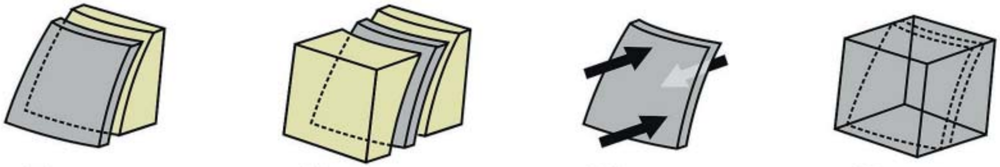

FIGURE 3: Fabrication processes that can be used to generate 3D curved components with thickness by means of computer numerical control techniques. In formative processes, materials can be deformed (3A) or cast (3B) using molds and formwork, while others can be reshaped by mechanical intervention (3C). Subtractive processes can sculpt a desired 3D part from a raw block of material.

On the other hand, the exploration of building curved surfaces out of three dimensional materials (1.C) imposes totally different constraints. The diagrams on FIGURE 3 represent different processes to produce solid curved components using digital formative and subtractive technologies. In contrast with CNC cutting, all of them imply intricate fabrication planning procedures, longer periods of manufacturing and sustainable concerns regarding the wasted material that is left in subtractive fabrication. Given that the scale of architecture implies a construction with several components, it is easy to realize how this complexity gets multiplied by a large factor. For instance, when working with structural materials like wood, stone or metal, subtractive processes are hard time-consuming because the tools cannot run fast on rigid thick surfaces, which requires long machining periods to remove the essential layers of material. Furthermore, in order to obtain the desired geometry in all the faces of a given part, one has to plan the position and fixation systems to orient and support the raw material in the machine. Facing this complexity, architects tend to avoid applying these systems to design large scale structures. Thus, employing CNC milled stones, the extension of the Sagrada Familia in Barcelona is one of the few examples that can be found of the application of subtractive technologies application to directly produce building components. Indeed, most of the applications involving 3D components in architecture are explorations of formative processes derived from formwork and molds previously produced by subtractive processes. In this fashion, architects select economic and light materials that can be high speed machined through subtractive fabrication. Given that a significant amount of material is usually wasted, its recyclable quality is also a crucial factor for keeping the whole manufacturing process both economically and ecologically feasible. Considering that formworks and molds only need to be machined from one side, the planning and assistance procedures for fabrication are significantly simplified. At the end of the process, formworks are used to cast liquid materials while molds are used to reshape solid ones under heating, steam or pressure conditions. Using these techniques, Frank Gehry explored recyclable Styrofoam blocks to cast concrete elements in the Zollhof Complex in Düsseldorf, and CNC milled molds for subsequent thermal deformation of glazed panels in the Conde Nasté Cafeteria in New York. A similar strategy was used by Bernard Franken in the BMW "Bubble" Pavilion in Frankfurt and by Peter Cook and Colin Fournier in the Kunsthaus in Graz.

2.4 Directions and Opportunities

The various strategies for building architectural surfaces described in subchapter 2.2 carry the old problematic relationship between skin and structure.

Following the classification proposed by Yun (2001: 8), it is possible to conclude that most common applications of CAD/CAM in architecture -the ones that also involve higher dimensions of rationalization- are curiously connected to the modernist paradigm of separation between skin and structure. Still following this concept, an advanced development consists in the exploration of CAD/CAM technologies to move beyond the use of independent straight structures to support curved envelope surfaces, to design and fabricate structures that actually share and follow the curvature of the skins. The exploration of the geometric inter-relation between structure and skin seems to be a possible path towards innovation in building construction.

An alternative to this approach relies in the exploration of "stiff shaped surface that serves both as primary load-bearing structure and enclosure" (Yun, 2001: 8), which falls into the 1.C strategy. Therefore, it is precisely in this less explored constructive option that seems to reside the most convincing opportunity for the emergence of a new paradigm in building construction. In the history of architecture, there are plenty of examples in which buildings were made out of structural surfaces (i.e. in stone or concrete). However, the ability to design and fabricate using CAD/CAM allows one to extend the implicit geometric challenge into a higher degree of complexity. But, to really achieve a new stage in building design and construction, the recent contribution of computer aided engineering technologies (CAE) in the process should also be integrated and further explored. In fact, by using three dimensional components, the thickness property introduces a dimension where digitally controlled performance can be introduced. In this context, innovative structural surfaces can emerge by relating complex geometries with the adaptive play of diverse and measured functional roles (i.e. structural, thermal and acoustic insulation, waterproof, ornamentation, etc). This condition of convergence between geometry and performance can only be designed, analyzed, evaluated and fabricated with the help of digital technology.

3. Final Remarks

The analysis developed in chapter 2, illustrates the problem identified in the first chapter. It evidences that there are ambiguous promises associated with the integration of new technologies in architecture, as their real application in practice is not so straightforward or innovative as sometimes it is presented. One possible explanation is that the expectations behind the exploration of CAD/CAM processes in architecture migrate from other design-related areas during technological transference processes. However, the specific nature of architecture introduces certain factors that constrain the real effectiveness of these approaches and early optimism. In other words, architecture's capacity to engage these technological possibilities is naturally different from other disciplines. For instance, although the exploration of formal complexity implied in the design of an airplane and in the design of a building can be compared, the product of the aerospace industry, once it is developed, it becomes a standard model ready to be reproduced, while buildings usually consist in unique products. This condition implies clear differences in the economic supports involved in the research and development efforts in these industries. On a different level, the scale associated with product design industries permits the feasible exploration of mass-customization procedures as many of its products are composed of few, small components. In an extreme case, in this industry there are products that consist in a unique part fabricated with a single machine. Given that architecture is a large scale and complex assemblage of components, the mass production of variation reaches a higher degree of complexity. Thus, it might be wise to recognize that architecture cannot engage in all the theoretical challenges proposed by new technologies in the same ways as other industries, otherwise there is the risk of generating a misleading discourse on this subject.

To move beyond some of the existent limitations and challenge conventional building paradigms with new technologies, architects may need to go beyond the role of "importers" and "users". The strategic combination of available fabrication processes is interesting and can be adjusted to the specificities of the discipline but, at the end, it defines a limited horizon of progression, constrained by developments that take place in other industries. The stepping forward that has already happened in the level of CAD, with architects exploring advanced modeling techniques and programming customized applications, should now happen at the level of fabrication. This does not mean that all practitioners should engage in this effort but that it is necessary to guide research on this level towards specific interest of architecture. Some initiatives are already in progress like the contour crafting technology developed by Behrokh Khoshnevis at the University of Southern California, or the huge CNC milling machine involving molds made by earth envisioned by William Massie. It is time for academic research resources and architect's creative minds to play a more decisive role in the development of digital technologies. The answer for more efficient and flexible processes of translating architectural ideas into physical constructions can possibly come from the discipline of architecture itself.

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