MATERIALIZING DESIGN: CONTEMPORARY ISSUES IN THE USE OF CAD/CAM TECHNOLOGY IN THE ARCHITECTURAL DESIGN AND FABRICATION PROCESS

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Abstract. While the ability to produce and quantify design and fabrication information has been greatly enhanced by advances in CAD/CAM technology over the last several decades, a practical link between what can be modelled virtually and what can be built physically has yet to be realized. The process of parsing complex design information and translating it into a format that can be utilized by those responsible for its fabrication is a many-stepped process, in some cases made increasingly difficult by the same technology intended to simplify the process.

The use of CAD/CAM technology in the architectural design process requires ongoing consideration as its use becomes increasingly pervasive in the design process. Within the context of contemporary architectural practice and discourse, what is the degree of fidelity between design information and fabrication information? How are advances in accessibility to, and the capability of CAD/CAM technologies affecting the role of the architect in the overall building process? Does CAD/CAM offer unique and undiscovered possibilities to re-associate the designer with the builder, or simply a process of more efficiently automating the design and construction process?

Our work builds upon issues of the fundamental differences that CAD/CAM technologies introduce to design practices; issues that were raised at the very outset of CAD/CAM's introduction to architectural design. Employing parametric design software, we design and construct a speculative façade system for a high-rise tower which is then fabricated at a reduced-scale with various two-axis CAM technology. We use relational and constraint-based logics in order to create models of parametric assemblies of discrete components which are translated into machine-ready formats, fabricated and re-assembled, in a process modelled on that typically followed in the construction of a real building project.

1. Introduction

While CAD/CAM technology provides a closer integration of information between the digital and physical realms, it has not yet matured beyond methods of basic automation. Understanding the key aspects of the current relationship between design and fabrication technology will allow us to begin moving beyond the restrictions brought by automation to discover the unique capabilities CAD/CAM may offer.

Our research involved the design and fabrication of a speculative façade system for a generic high-rise tower. The goal was to explore methods for creating scaled models of the system using two-axis CAM technology for fabrication, and to determine whether or not the scaled-system could simulate and provide information about full-scale behaviors such as structure, assembly, and appearance. Using various parametric modeling and drafting software, we built a digital 'master' model intended as the sole source of information for fabrication. The work was achieved using relational and constraint-based logics for the creation of reconfigurable parametric assemblies. Our research investigates the relationship between design and fabrication information and distinguishes the degree of fidelity between the information generated in design models and that used for fabrication and construction of actual building elements. It is a process that is also revelatory of design parameters influenced by the conventions and particularities of CAD/CAM machines themselves.

2. Uses of digital technology in the design process

In a 1989 article entitled "Design and Computers", Muriel Cooper of the MIT Media Lab wrote, "In each period of our history, design and communication have evolved synchronously with the technology of the time. Each new medium has extended our sense of reality and each has looked to its predecessor for language and conventions [referencing and adapting its characteristics until its unique capabilities can be explored and codified]. "The restrictions of the page, the frame…and the manufacturing tools also defined the degree to which the audience or user could interact with the medium." Because architects always deal with abstract representations of their final product (the actual building), the "medium" Cooper refers to may be a key problem limiting the ability of architectural designers to discover and codify the unique capabilities of CAD/CAM technologies. Designers are apt to consider the physical manifestations of their work as the actual constructs and construction components they represent instead of design artifacts composed of particular physical materials, focusing their attention on the study of the process over the product (Loukissas).

The shaping of the design process and product by the design tools is a hallmark of contemporary architectural design practice. Contemporary CAD/CAM technology requires the 'operator' to be versed in the processes and procedures necessary to operate each particular tool (both software and hardware). This immediately introduces a new role in the design process whereby the designer, who would typically be responsible for creating the design documentation, must now do so through the intermediary of the 'operator'. In many contemporary practices, this role is still fulfilled by one individual, with CAD/CAM expertise now being a requirement that firms look for in their job applicants. However, firms engaged in large and complex problems are beginning to see these roles become distinct. An example is Gehry Partners and the recently formed Gehry Technologies. It is now common practice for a 'technologist' from Gehry Technologies to be embedded in the design team for each project at Gehry Partners or other consulting services to facilitate the creation of the project's digital information.

With regard to fabrication, design information in the form of digital 2D or 3D models must be prepared according to specific, machine dependent guidelines. The role of the "interpreter" in this case is no longer a human model builder who acts to translate the design information into a physical form, but a software routine which takes geometric point and vector data and converts it into the necessary tool paths for machine fabrication. Each machine typically has its own proprietary user interface, further mediating and controlling the way a designer or operator must think about the design elements they wish to create. If one assumes that the degree of fidelity between design information and fabrication information is directly related to the number of translations the information must undergo before a physical artifact can be produced, then contemporary practice would seem to indicate that there is little fidelity between the two.

2.1. USES OF MODELS

The goal of translating design information into a physical manifestation, such as a study model, is not simply to arrive at one solution, but to arrive at many solutions. In Sciences of the Artificial, Herbert Simon makes the argument that solving a problem through a particular form of representation is an act of making evident that which was already inherent, albeit obscure, in the presentation of the problem; a reference to the notion of problemsetting versus problem-solving (Simon, 1997). Simon goes on to discuss the critical importance of representation in the design process as well as the importance of continued development in theories of representational methodology (Simon, 1997) [1]. Marvin Minsky refers to a similar methodology for multi-variant representation as "reformulation", or the use of varying conceptual descriptions in order to be able to differently see, and thereby consider within alternative contexts, a given entity. (Minsky, 1985)

In the article "Getting complexity organized: Using self-organization in architectural construction", Fabian Scheurer points to potential changes in the use and manifestation of digital design models in regard to communicating construction information, "When it comes to actual construction of a complex building the question arises: What is a reasonable quantity of explicit information for a specific design, and how does one communicate it in a reasonable fashion? Perhaps the biggest challenge for the 'non-standard' designer will be to accept that in order to optimize these processes, the designer will no longer detail the form of a design, but will design the process which generates the details." (Scheurer, 2007).

Each of these had discussed a similar problem during a different decade, and reached a similar conclusion that a crucial aspect of the issue regarding the relationship of various forms of information is structuring of that information. What is somewhat surprising is that this is the same issue that was put forward by Ivan Sutherland at the outset of the creation of architectural CAD/CAM technology in the 1970's:

> *To a large extent it has turned out that the usefulness of computer drawings is precisely their structured nature and that this structured nature is precisely the difficulty in making them.*
>
> *I believe that the computer-aided design community has been slow to recognize and accept this truth. An ordinary draftsman is unconcerned with the structure of his drawing material. Pen and ink or pencil and paper have no inherent structure. They only make dirty marks on paper. The draftsman is concerned principally with the drawings as a representation of the evolving design. The behavior of a computer-produced drawing, on the other hand, is critically dependent upon the topological and geometric structure built up in the computer memory as a result of drawing operations. The drawing itself has properties quite independent of the properties of the object it is describing (Sutherland, 1975).*

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[1] "But even though our classification is incomplete, we are beginning to build a theory of the properties of these representations. The growing theories of computer architectures and programming languages – for example, the work on functional languages and object-oriented languages – illustrate some of the directions that a theory of representations can take" (Simon 1996, p134).

2.2. PHYSICAL AND DIGITAL INTERFACES

The software interface moderates what the user sees on the computer screen and what the computer sees. A drawn line on the computer screen, for instance, may appear jagged, textured, and thick, but is understood as a line because of its resemblance to a smooth line drawn in the physical world (Mandelbrot, 1997). While a designer may be able to instantaneously recognize a line as a line (or anything else the “it” is chosen to be) regardless of whether it is displayed on a computer screen or a sketchbook, the computer only understands the line as a mathematical function between two or more endpoints affixed in a coordinate space.

The creation of a simple line within a CAD environment is in itself an outcome that is separated by multiple translations of information. A line drawn in a CAD program is a user input brought by peripheral devices such as the keyboard and/or mouse which translates into program instructions and data sent to the CPU (Mandelbrot, 1997). The CPU processes machine instructions which are encoded in the form of binary numbers using 1 and 0 electronic signals. “In the mid-1950s, high-level programming languages began to appear. In these languages, the programmer expresses the idea behind the task that needs to be performed, and a special computer program, called a compiler, translates the high-level description into machine instruction for a particular processor.” (Horstmann, 2006) Two distinct forms of communication are taking place when a user engages in the digital realm: the designer sees a graphical interface to input geometry, whereas the computer interprets the input as a set of instructions in machine language.

3. Process and Physical Artifacts: High-rise Enclosure System

The high-rise enclosure project consisted of the design, fabrication, and assembly of a façade/enclosure system for a small tower model, based on work previously completed by the Digital Design and Fabrication Group at MIT[2]. The goal of this process was to determine the effectiveness of using design information to fabricate a scaled-model tower and the relationship of that information to the type and amount of information that would typically be necessary for the fabrication of full-scale building components.

Our approach was to encapsulate the greatest number of design features in the fewest unique elements in order to simplify assembly and erection while allowing for the greatest possible formal variation. By creating a serialized framing structure which could provide for an interior, enclosed glazing system and an exterior open glazing system we were able to achieve

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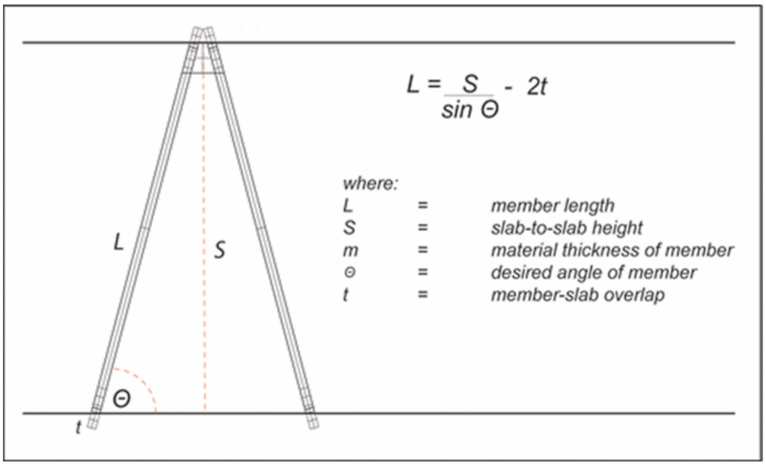
[2] See Cardoso and Michaud, 2006.

formal variation from a relatively small kit of parts. Furthermore, the enclosure system was designed in a unitized manner to allow for as much pre-fabrication as possible, and a “double-wall” system was chosen in an effort to take advantage of possibilities for passive solar and thermal loading conditions. Each mullion was parametrically defined to automatically configure its length and setback from the slab edge based on a user defined angle and the slab-to-slab height. This logic would allow for the angle of each mullion to be independently set to quickly create multiple formal variations (Figure 1).



$$L = \frac{S}{\sin \Theta} - 2t$$

where:
L = member length
S = slab-to-slab height
m = material thickness of member
Θ = desired angle of member
t = member-slab overlap

Figure 1. Parametric definition of parts.

3.1. RELATIONAL CONSTRAINTS

Since the efficacy of relational constraints is entirely dependent on the way in which the model is structured hierarchically, determining which elements drive or are driven by other elements, a robust parametric model can typically only be built once the design has been well worked out. This presents a particularly interesting situation regarding the relationship between design and fabrication information, given that during the earlier stages of a design process information is typically not rigorously structured and therefore difficult to parametrically define.

In determining the approach we would take to building the parametric model we focused on those moments of interface between the various systems and subsystems – i.e. where the façade system met the structural system (floor slabs). We began to codify the dependencies inherent to the fabrication and assembly systems we were working with; namely how the various physical elements could be fit together in press-fit assemblies, and what constituted a friction/press-fit assembly vocabulary. The two main areas we identified were: joint taxonomies, or the possible connections we could fabricate with the given tools, and assembly vectors[3]. The taxonomy of joints we gathered is by no means exhaustive, but a preliminary attempt to codify and quantify key aspects of press-fit, or snap-fit, assemblies (Figure 2).

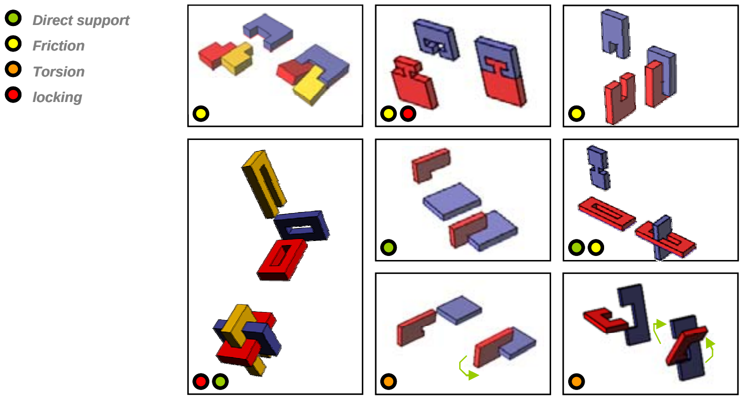


Figure 2. Taxonomy of Press-Fit Connections.

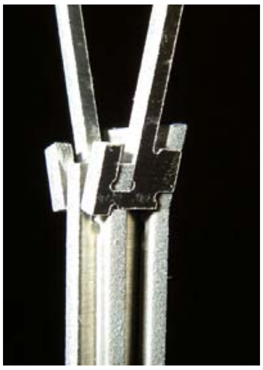


Figure 3. Waterjet cut aluminum mullion.

3.2. MATERIAL BEHAVIOR

Empirical testing reveals that press-fit assemblies rely on specific material properties and precise fabrication tolerances in order to sustain a rigid connection between elements (Cardoso and Michaud, 2006). However,

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[3] This refers to the sequence of steps that must be followed in order to assemble elements into a given connection. Typically, elements can only be assembled in one direction at a time, which we consider to be a non-obvious aspect of the construction/assembly process. By analysing the vectors or directions of an assembly process, it may be possible to design novel and innovating joining systems.

different materials displayed varying behavior at different scales, making it difficult if not impossible to predict possible changes in material behavior at different model scales and what that would mean in terms of model assembly and the efficacy of the friction joints. Ideal scenarios were achieved with cellulose-based materials (plywood and masonite) that allowed for slight material deformation during assembly. Attempts at similar assemblies with aluminum proved less successful due to the inelasticity of the material. The most successful press-fit joints that were achieved in aluminum were “slot” connections which provided an equal amount of supporting material on each of the mating pieces.

3.4. MACHINE BEHAVIOR

A two-axis laser cutter and a two-axis waterjet cutter were used in the fabrication of parts for the various models. Theoretically, each machine will result in a cut perpendicular to the surface of the material being cut that exactly matches the cut paths defined by the design information.

The laser cutter uses a high power output laser to melt, burn, or vaporize the cut material. For most applications the width of the cutting beam would be negligible, however given the precise tolerances required of press-fit assemblies, a proper friction fit could not be achieved without offsetting the desired profile, effectively creating a ‘negative’ tolerance where two mating pieces were slightly oversized with regard to one another in order to achieve the small amount of deformation necessary to establish a tight connection. Immediately this creates an inconsistency with the design information, where a digital element may typically be created based upon the size of the elements with which it is in concert. The tolerance proved difficult to calculate and had to be determined empirically through testing as a result of slight variations in the nominal thickness of each piece of material. For 1/8” thick masonite, an offset of 0.002” was used to good effect, however the design information had to be translated into fabrication-specific formats in order to make this determination.

The waterjet cutter uses a stream of highly pressurized water at high velocity in conjunction with an abrasive powder to slice through material. The cut material is typically submerged under water during fabrication, therefore limiting materials to those which will not become deformed when submerged. While the laser cutter can be operated through the built-in printing interface of most vector-based graphical programs, the waterjet cutter must be operated through proprietary, stand-alone software. This software automatically calculates the necessary offset of the cutting head during the creation of its tool paths, meaning that all profiles will be cut accurately and does not require additional tolerance offsets, potentially reducing the number of translations of the design information into fabrication-specific formats. However, all elements to be cut must be imported into the proprietary system, assigned values based on the desired speed and quality of the cut, and assigned tool paths that instruct the machine where to cut.

4. Results

The geometry necessary to fabricate a physical part is typically a special subset of all the information that is present in a digital design model. In order to isolate that information and make it accessible to a machine for fabrication however, several intermediate procedures must be followed. The steps necessary to fabricate a part include: isolating and potentially reconstructing[4] those aspects of the model the designer wishes to fabricate, arranging the elements to be cut within an envelope that corresponds to the maximal cutting surface of the given machine, and potentially having to configure the actual cutting paths and tool offsets in a separate software environment specific to a particular machine. Once the user inputs the information necessary to fabricate the part, the machine interprets vector and coordinate data and begins to cut. A particular machine contains its own information that determines the output, or product quality, in which the user must determine whether or not to adjust the product tolerances in the CAD file so as to comply with the machine’s performance for subsequent machining processes. The designer’s interaction between the digital model and physical machine bears a non-linear process where the user must adjust for unforeseen circumstances brought either by the operator or the machine itself.

5. Conclusion

CAD/CAM technology provides a closer integration of information between the digital and physical realms, yet as our research shows, it has not yet matured beyond methods of basic automation. Since we have no other frame of reference for these tools, we try to understand new technologies metaphorically, or analogically which has the reciprocal effect of limiting our likelihood of using these tools beyond the capacity of their metaphorical/analogical counterparts. In order to overcome this barrier, we must truly engage the technology as a separate and unique medium instead

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[4] Often what visually appears to be a continuous line on the computer screen is actually a series of collinear or nested lines which could cause problems during fabrication if not remade as one continuous line.

of seeing it as a simple method of task automation. In order to do this, designers and researchers need to return to a fundamental understanding of the different logic and data constructs that support both physical and digital modeling.

While our ability to produce complex digital design and fabrication information has been greatly enhanced, our ability to control and make use of that information has not kept pace, and in many ways begun to fall behind as evidenced by the need for design firms such as Gehry Partners and Zaha Hadid to seek the assistance of intermediaries such as Gehry Technologies and Design-to-Production in order to translate their design information into a fabrication-ready format.

The potential of CAD/CAM to reduce the distance between designing and making has not yet been fulfilled, due largely in part to the increasing complexity and specialization necessary to operate the technology. Such specialization further distances the designer from the production of design information.

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