DIGITAL FABRICATION IN THE ARCHITECTURAL DESIGN PROCESS

by

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Bachelor of Architecture
University of Arizona
May 2000

Submitted to the Department of Architecture in partial fulfillment of the requirements for the degree of

Master of Science in Architecture Studies
at the
Massachusetts Institute of Technology

June 2004

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ABSTRACT

Digital fabrication is affecting the architectural design process due to the increasingly important role it has in the fabrication of architectural models. Many design professionals, professors, and students have experienced the benefits and challenges of using digital fabrication in their design processes, but many others in the field are not yet aware of the possibilities and drawbacks afforded by these technologies. The research presented here unveiled key issues on the matter through a series of interviews with twenty-five individuals, focusing on digital fabrication in their practices and schools, and through three experiments utilizing eight digital fabrication methods, such as three-dimensional printing, laser cutting, and desktop milling. The interviews and experiments form a basis for suggesting better ways to utilize current digital fabrication methods in design and for proposing future methods better suited for the architectural design process.

Thesis Supervisor: Lawrence Sass
Title: Assistant Professor of Architecture

ACKNOWLEDGMENTS

I wish to express my most sincere gratitude and appreciate to the many people who have played a significant role in my education and work.

My advisor, Larry Sass, for his continuous guidance and support. This thesis would not have been possible without him.

My reader, Bill Porter, for his wisdom and trusted counseling.

Tim Eliassen, also my reader, for his enthusiasm and for keeping me grounded.

The Center for Bits and Atoms, for funding my research position with Larry Sass and providing me with access to the Fabrication Lab.

I am indebted to all those I interviewed, for their time and assistance. I learned the most from them in this thesis. It could not have been possible without them. My deepest thanks to Charles Blomberg, Joshua Katz, Paul Kempton, Kurt Komraus (especially Kurt, for the many hours he spent with me), Paul Koontz (and Grace Nugroho, my friend, for getting me in touch with Paul), Jim Maitland, Rolando Mendoza, Julian Palacio, Caroline Smogorzewski, Kirk Alcond, Fernando Domeyko, Mark Goulthorpe, Earl Mark, John Nastasi, Daniel Schodek, Jan Wampler, Charles Austin, Josh Barandon, Carlos Barrios, Joseph Dahmen, Talia Dorsey, Han Hoang, Jelena Pejkovic, Alexandra Sinisterra, and Alexandros Tsamis.

John Difrancesco, Tom Lutz, Thom Allwood, and Tom Berezansky, for their help and patience in the Fab Lab.

Sarah Hudson, for months of hard work, help, and fun with the experiments.

Michael Mulhern, for trusting me and teaching me.

Renée Cheng, for her mentorship and assistance. All of my professional and scholastic work stems back to her.

Michael Samra, for his friendship, support, and trust.

John Rappa, "Duke" Duchnowski, Big Bob, Little Bob, Keith, Dave, and Bill, for their friendship and for teaching me how the manufacturing process really works.

Dave Dow and Pat McAtamney, for their guidance in 2.008 and helping me understand more about CNC processes.

(continued...)

Thalia Rubio at the MIT Writing Center, for her advice on my writing.

My SMArchS classmates, especially Alexandra, Rita, and Keru, for their consistent support and friendship.

My grandparents, Nana & Pa and Grandma & Grandpa, for their support and love.

Laurie, my sister, for keeping in touch with me these last two years and simply for being my sister.

My Dad, for believing in me and loving me.

My Mom, for helping me tremendously with my writing and for her love and support. I enjoyed having her be a part of this.

Most of all, I thank my husband, Jason, for all the years of love, encouragement, friendship, and advice he has have given me. It is a privilege to have him in my life and a pleasure to share this with him.

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PREFACE

My understanding of the tectonics of architecture grew during my undergraduate education with the help of my professor and mentor, Renée Cheng. By graduation I was very interested in the designing and manufacturing of architectural details, and how the details relate to an overall architectural design. In July 2000 I began working for Tim Eliassen and Michael Mulhern at TriPyramid Structures, an architectural component design and fabrication company.

I was directly involved in the designing, manufacturing, and assembly of architectural details during my time there. I learned the concepts of many different types of manufacturing methods, such as creating digital files which were used by waterjet and laser cutting manufacturers. I sat adjacent to the shop where parts that I drew were being manufactured. It was an entirely different level of design than I had been taught in school.

I worked there for a little over two years before I went back to school. My interests in tectonics and my recent experience at TriPyramid influenced what I chose to do at MIT. I took Larry Sass's Design Fabrication workshop, where I was introduced to various digital manufacturing machines, and John Fernandez's Emergent Materials workshop, which introduced me to various types of materials. I participated in an undergraduate Mechanical Engineering course, Design & Manufacturing II, where I gained hands-on experience with full-size CNC milling machines, CNC lathes, injection molders, and vacuum formers. I also taught an undergraduate class where I trained students how to prepare digital files for the laser cutter and three-dimensional (3D) printer. In addition to these classes, I was fortunate enough to work as a Center for Bits and Atoms research assistant in Larry's Digital Design Fabrication Group. Through the work I did for the group I gained an extensive amount of hands-on experience with a range of digital fabrication machines, which allowed me to teach students how to use these machines in two more of Larry's workshops.

As time went on I saw that there was a growing interest in digital fabrication among students, both in and out of studios. It appeared to me that each of these machines embodies different qualities and fits into schools and offices in different ways, some having more relevancy than others in the design process. Equipped with my professional and research experience, I felt I was in a good position to evaluate the state of digital fabrication in the architectural design process.

CHAPTER 1: INTRODUCTION

Various types of digital fabrication machines are working their way into architecture schools and offices, slowly being integrated into the array of tools architects utilize to create physical representations of their designs. These fabrication technologies were developed for professions other than architecture, such as industrial design and mechanical engineering, so when architects start to use them they are forced to conform to other ways of working that may not be natural in the architectural design process. These technologies are having positive and negative effects on the design process as more architects and students integrate digital fabrication methods into their model making processes. Now is the time to step back and address what these effects are in order to understand how architects can better use the machines that are currently available. This thesis also proposes the attributes future digital fabrication machines should embody in order to be better suited for use in the design phases of architecture.

1.1 Background

Digital fabrication is defined as computer-aided processes that manipulate material through subtractive or additive methods. These processes can be broken down into two groups: computer numerical control (CNC) processes and rapid prototyping (RP) processes. The fundamental difference between these two is that the CNC processes create objects by removing material (subtractive) while RP processes create objects by building it up layer-by-layer (additive). A few examples of CNC processes are milling, waterjet cutting, and laser cutting. RP processes include three-dimensional printing, stereolithography, and fused-deposition modeling.

Researchers began contemplating the "automatic model shop"[1] thirty years ago when they became aware of the possibilities provided by

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[1] William M. Newman and Robert F. Sproull, *Principles of Interactive Computer Graphics* (USA: McGraw-Hill,1979) 298

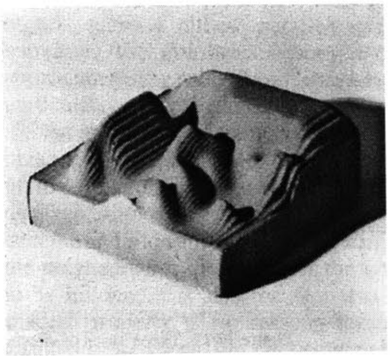

Fig. 1. Physical model of object constructed from computer model with numerically controlled machine, *Principles of Interactive Computer Graphics* (USA: McGraw-Hill, 1979) 299.

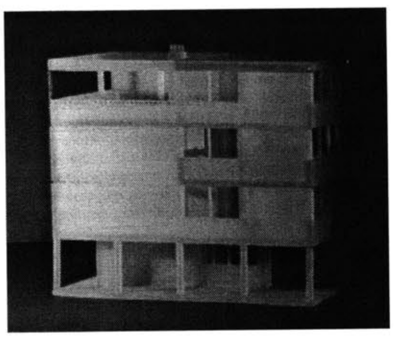

Fig. 2. Model of Le Corbusier's building in the Weissenhofsiedlung generated by stereolithography, "Creating Architecture Models by Computer-Aided Prototyping," *Proceedings of the 21st ICAAD,* 1991.

computer-aided milling machines (fig. 1). In 1977, Mitchell wrote that by "interfacing production machinery with computer graphics systems, a very sophisticated design/production facility can be developed".[2] Technology progressed, and by the 1990's there was an extensive body of research conducted by Bernd Streich at the Department of CAAD and Planning Methods at the University of Kaiserslautern in Germany. He wrote numerous papers and a book on the topic of computer-aided techniques for fabricating physical models. In 1991 he introduced the use of stereolithography, one of the only RP techniques available then, as a feasible method for building architectural models (fig. 2). In 1996 he co-authored a book titled *Computergestützter Architekturmodellbau* [*Computer-Aided Architectural Model Building*], which was the first complete work to describe the topic of digital fabrication in the architectural design process.[3] Alvise Simondetti's 1997 Master's thesis, titled *Rapid Prototyping in Early Stages of Architectural Design*[4], addressed how digital fabrication could be used to make architectural models. In his thesis, Alvise teaches the reader 25 frequent mistakes made by a designer when he or she attempts to use these technologies. In 2002, researchers in the Rapid Design and Manufacturing Group at the Glasgow School of Art published a paper discussing the applicability of RP techniques in the field of architecture.[5] Even more recently, Breen, et al. at the Delft University of Technology published an article describing how CNC milling machines, laser cutters, and three-dimensional printers can be utilized

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[2] W. J. Mitchell, *Computer-Aided Architectural Design* (New York: Wiley, John & Sons, 1977) 372.

[3] Bernd Streich, *Computergestützter Architekturmodellbau* (Basel: Birkhäuser, 1996)

[4] Alvise Simondetti, "Rapid Prototyping in Early Stages of Architectural Design", Master of Science Thesis, MIT, 1997.

[5] Gerard Ryder, et al., "Rapid Design and Manufacture Tools in Architecture," *Automation in Construction* 11 (2002)

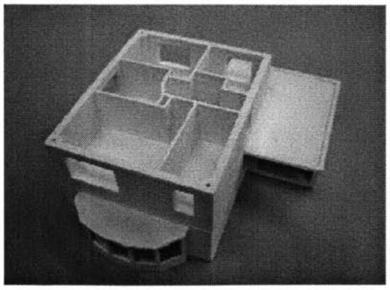

Fig. 3. 3D printed house (scale 1:100) from plaster-based powder, "Tangible virtuality—perceptions of computer-aided and physical modelling," *Automation in Construction* 12 (2003) : 651.

in the architectural model-making process (fig. 3).[6] Since then, prices have come down and these digital fabrication machines have found their way into even more schools and offices. As these machines become more common in the field, designers, professors, and researchers are exploring new methods of designing, teaching, and working with digital fabrication.[7] Now that designers have had the chance to integrate these fabrication processes into their model building techniques, I am stepping back to analyze how this new way of working is affecting the design process.

1.2 Methodology

In order to fully understand the topic of digital fabrication in the architectural design process, I needed to couple my knowledge gained through research and practice with others' observations. This research unveils key issues on the matter through a series of interviews with twenty-five individuals focusing on digital fabrication in their practices and schools and through three experiments utilizing eight digital fabrication methods. These interviews and experiments form a basis for suggesting better ways to utilize current digital fabrication methods in design and for proposing future methods better tailored to the architectural design process.

This investigation brought many important issues to the surface regarding the use of digital fabrication methods such as the designer's sensitivity to cost, time, and user-friendliness. Physically representing an architectural design can be done in many ways, but the cheapest, quickest, and easiest methods will always prevail.

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[6] Jack Breen, Robert Nottrot, and Martijn Stellingwerff, "Tangible Virtuality – Perceptions of Computer-Aided and Physical Modelling," *Automation in Construction* 12 (2003)

[7] See the Bibliography: Bechtold, et al., Broek, et al., Burry, Chaszar and Glymph, Ham, Kolarevic, Malé-Alemany and Sousa, Mark, Modeen, Pegna, Shih, and Wang and Duarte.

CHAPTER 2: CURRENT DESIGN AND FABRICATION PROCESSES

Every designer has a slightly different design process from the next, yet we all generally work in the same general-to-specific manner. Usually a professional designer or student begins with a conceptual idea, extensively refines it, and eventually arrives at a final design he or she feels solves the problem in an appropriate manner. At the same time, the design processes found in the educational world versus the professional world of architecture vary quite drastically. Ultimately, each group is designing with a different goal in mind. The architect's ultimate goal is to construct a full-scale building, while the student's goal is to construct a smaller-scale, physical representation of a building. Students have a different palette of model-making tools than professionals. This is significant because "Architects tend to draw what they can build, and build what they can draw."[8] If students are building for a RP machine and professionals are building for a steel manufacturer's machine, the designs between the two groups are going to be different. This chapter provides an overview of the most common physical representation types used in the architectural design process and the fabrication methods used to create them.

2.1 Physical Representation of Architectural Designs

Many different forms of representation in the architectural design process exist, ranging from digital to physical, and from two-dimensional to three-dimensional. Sketches, drawings, renderings, animations, and physical models all help to portray the designers' ideas to another person. Whether it is a student conveying an idea to a professor, an architect presenting a design to a client, or an architect providing building instructions to a contractor, representation is a key part of the architectural design and construction process. Among these

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[8] William Mitchell, "Roll Over Euclid: How Frank Gehry Designs and Builds," *Frank Gehry, Architect* (New York: Guggenheim Museum Publications, 2001) 354.

forms of representation I focused on physical models, which serve many different purposes in the design process. They help designers generate new ideas, represent their ideas to others, and test the behavior of full-size building components. In this section, I will present the different types of physical representations that can be found in the field and the different methods for making these models.

2.1.1 Model Types

I would like to review five different levels of architectural modeling found in schools and offices. In their paper, *Rapid Design and Manufacture Tools in Architecture*, Ryder, et al. describe three typical levels of modeling drawn from interviews and a literature survey. The three model types they found are: the feasibility model, the planning model, and the final project model. In addition to these three, I found two more levels of modeling through my survey that I would like to add to the list: the abstract model and the full-scale mockup.

Ryder, et al. describes the *feasibility model* as an object typically used to convey the concept of the building design. Not much detail is added and the size is usually small, yet it is starting to take the general shape of an architectural form.

The *planning model* is used when a little more detail needs to be conveyed at a slightly higher quality than the feasibility model. The designer can portray a more clear understanding of the building design and its relationship to its context.

The *final project model* shows what the project will look like once it is completed. In practice, this is the type of model that is shown to clients and the public. In school, this is the model shown at a final design review to portray the final design intent.

The *abstract model* is commonly used for abstract form or space studies. This type of model is often created to present the "sensibility"[9] of a design in the earliest stages of the design process.

Full-scale *mockups* are occasionally needed in practice to test the final behavior of a certain set of assembled building components. Fabricated at the full scale, these models allow the designer to verify the final form and functionality of the chosen assembly. Students are sometimes required to build small mockups in school in order to experience how real, full-sized building materials perform.

The fabrication methods that are used to create architectural models can be split into two groups: *handmade model making* and *digital fabrication*. The handmade methods are presented purely as a reference. I will elaborate more on the digital fabrication methods in order to prepare the reader for discussions in subsequent chapters.

2.1.2 Handmade Model Making

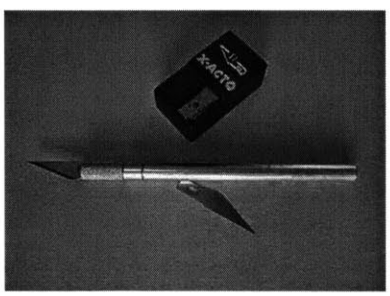

Fig. 4. X-Acto knife and blade.

When employing one of the many methods of handmade model making, the designer has immediate control of the tool's manipulation of the material. A wide range of tools can be used to create architectural models by hand and each tool typically has a limited group of materials that can be manipulated by it.

Handheld tools used for making architectural models include scissors, X-Acto knives, utility knives, hacksaws, chisels, files, and sandpaper (fig. 4). Scissors, a tool everyone is familiar with, cut thin sheet materials such as paper, acetate, foil, rubber, and foam. X-Acto and utility knives are used when highly controlled cuts are needed or when the material is thicker or slightly harder. Chipboard, cardboard, foamboard, bass and balsa woods, and thicker foils can be manipulated with these knives. They can also sculpt woods, foams, and clay. Saws are best used when even thicker, harder materials need cutting such as

[9] Mark Goulthorpe. Personal Interview. 15 April 2004.

larger wood sticks, small aluminum or copper members, or extruded plastic members. Chisels, files, and sandpaper are used for finishing the edges and surfaces of model materials.

Conventional machines can be categorized as another group of tools used in handmade model making. These machines have been around for decades and are a common part of any shop. Instead of the user guiding a handheld tool, the user guides the material through the machine. These machines include different types of saws, drill presses, milling machines, routers, lathes, grinders, and sanders. Table saws and routers are used to cut large, flat sheets of material such as woods, plastics, and foams. Band saws and chop saws are used to cut smaller, more manageable pieces of the same types of materials. Drill presses are used to drill holes in almost any material of a manageable size. Milling machines and lathes are used to subtract material from standard blocks or rods of metal, wood, plastic, plaster, or foam. Grinders and sanders are typically used to clean up the edges and surfaces of various materials.

In addition to all of these tools and machines, a person's *hands* should also be considered as tools. They are involved with all of the *hand-made* model-making methods and can manipulate materials on their own without being limited to a certain group of materials. Not only can hands bend, fold, and tear materials, but they can add materials together through sculpting clay or gluing materials together. It is the only tool I have mentioned so far that manipulates materials in an additive fashion. The only other set of tools that build objects in this fashion are the rapid prototyping machines, which will be presented in section 2.1.3.

All of these handheld tools and conventional machines have been used for decades in architectural model making. Every architecture school and many offices have their own model shops consisting of many of these tools and machines. Only within the last few years have digital fabrication machines started to join the group of well-utilized, model making tools in architecture.

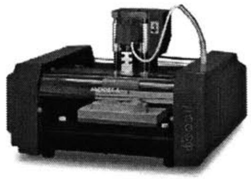

Fig. 5. Roland Modela MDX-20 desktop milling machine.

2.1.3 Digital Fabrication: Computer Numerical Control and Rapid Prototyping

When employing digital fabrication methods in the model making process, the user has almost no control of the tool at the moment it is manipulating the material. All digital methods start by the user setting up a file in the computer and end by the user sending the file to the machine. The user has varying amounts of control over the manipulation of the material during set up, but once the file has been sent, the user can do little but watch. There are rare exceptions where some machines allow the user to slow down or speed up the process of manipulation, but never the manipulation itself.

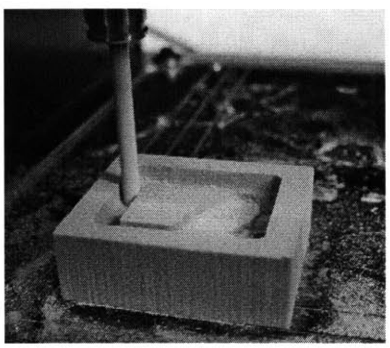

Fig. 6. Rigid foam being milled on the Modela MDX-20 milling machine.

The digital fabrication methods I will focus on throughout the rest of this thesis can be split into two groups: computer numerical control (CNC) processes and rapid prototyping (RP) processes. The fundamental difference between these two is that the CNC processes all work through subtractive methods of manipulating material to create the final object, while all RP processes utilize additive methods of building up material layer-by-layer.

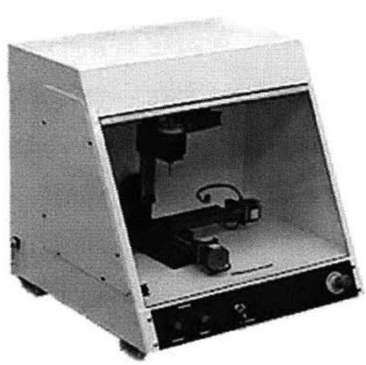

Fig. 7. Denford Micromill 2000 desktop milling machine.

One should keep in mind that all of these processes were originally developed for use in industrial design and manufacturing. Machines designed for use in industrial shops are typically difficult for an architect or student to use because there are too many factors that must be considered for a novice to efficiently operate on his or her own. However, many of these processes have been compacted into smaller, more user-friendly machines that are more suitable for architecture offices and studio environments. This has made it easier for designers to use the machines in architectural model making.

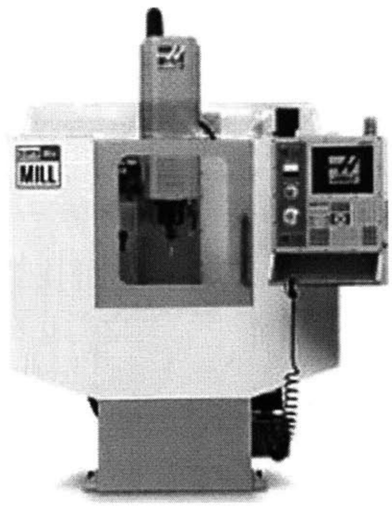

Fig. 8. HAAS Super Mini Mill.

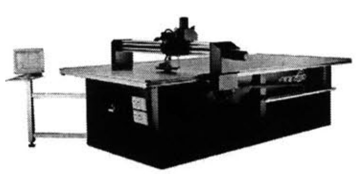

Fig. 9. Precix Industrial Series 9100 4'x8' table router.

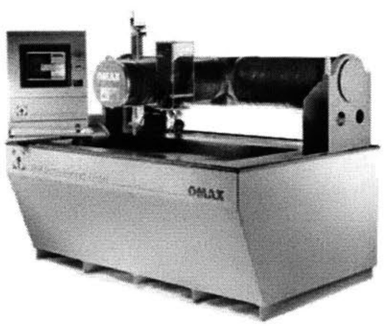

Fig. 10. OMAX Waterjet Machining Center.

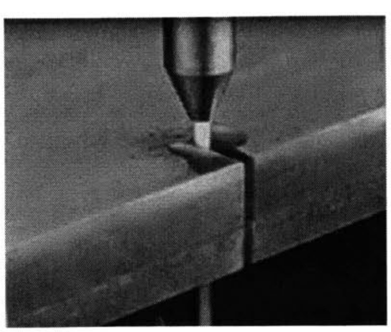

Fig. 11. Waterjet cutting example.

CNC Processes

All of the fabrication methods I am categorizing as *CNC processes* create objects by removing material from a starting block, rod, or sheet through computer controlled movements. The user starts the process by preparing a file in the computer, sets up the material in the machine, and then sends the file to the machine. The machine automatically mills or cuts the material according to the computerized directions it is given. I will briefly present the five most common CNC processes that are used in the architectural design process. More detailed information is discussed in *Manufacturing Engineering and Technology* (Kalpakjian and Schmid, 2000).

CNC milling is used to create forms from blocks of materials such as woods, metals, plastics, and foams. These machines come in a variety of sizes. The MIT Department of Architecture has two desktop CNC milling machines, the *Roland Modela MDX-20* (figs. 5 and 6) and the *Denford Micromill 2000* (fig. 7). I also had access to a larger, industrial-sized *HAAS Super Mini Mill* (fig. 8) milling machine, which I could not run without the assistance of a well-trained operator. This fabrication process is most useful for creating small, singular architectural components.

A similar digital fabrication process is *CNC Routing*, which works in a similar fashion to milling except it is meant to cut large, flat, sheet materials versus smaller, block materials (fig. 9). Many architecture schools have table routers, such as the *Precix 9100* in their shops due to the router's applicability in creating large site models or other complex forms from materials such as large plywood or foam sheets.

CNC waterjet machining is also used to cut large, flat sheets of material. An advantage the waterjet cutter has over the table router is the wide spectrum of materials it can cut. In addition to

Fig. 12. Universal Laser Systems X-660 Laser Platform.

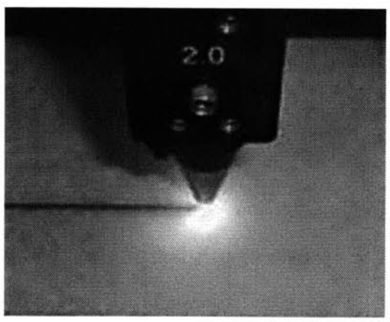

Fig. 13. Laser cutting example.

Fig. 14. Roland CAMM-1 vinyl cutter.

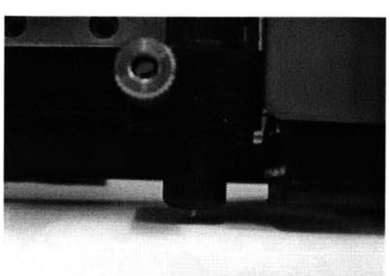

Fig. 15. Roland CAMM-1 vinyl cutter.

plywood and foam, it can cut metal, stone, glass, rubber, composite materials, and many more. As a part of the Center for Bits and Atoms, I was able to use the center's *OMAX 2652* waterjet cutter (figs. 10 and 11).

Like CNC milling machines, *laser cutters* also come in a variety of sizes, ranging from desktop to shop-sized machines. The MIT Department of Architecture has an *Universal Laser Systems X-660* laser cutter (fig. 12), which can cut sheets of material up to 18"x32". Universal Laser Systems also provides desktop laser platforms that are cheaper and more suitable for small offices. Laser cutters typically cut thin, sheet materials such as wood, paper, chipboard, museum board, cardboard, foamboard, and plastics (fig. 13).

The fifth CNC machine is the *Roland CAMM-1 vinyl cutter*, which cuts very thin sheets of vinyl, paper, acetate, and foil with a small blade (fig. 14). Creating precise, smooth cuts is its greatest advantage (fig 15).

Many other CNC processes exist; however, the five that I have mentioned are the most useful in the architectural design process. CNC plasma cutting, wire cutting, turning, and turret punching are some of the many other processes currently available. The prices of CNC machines currently run between $2,000 and $500,000.

Rapid Prototyping

All of the fabrication methods I am categorizing as *rapid prototyping* (RP) create objects by building up material layer-by-layer through computer controlled movements. The way the process is started is generally the same as it is for CNC processes. The user starts by preparing a three-dimensional file in the computer, sets up the machine, and then sends the file to be 'printed'. The machine automatically builds up the material according to the computerized directions it is given. I will briefly present the five most common rapid prototyping processes that are used in architectural design. More detailed information is discussed in *Rapid Prototyping* (Gebhardt, 2003).

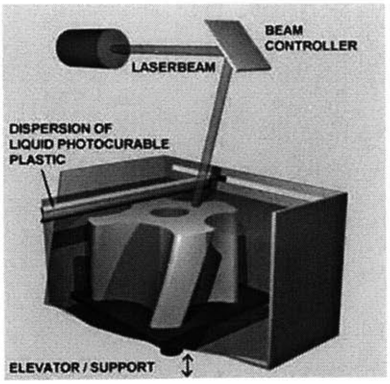

Fig. 16. Stereolithography process.

During the *stereolithography* (SL) process, a laser draws a layer of the desired object on the top surface of a photosensitive liquid resin, curing the top surface (fig. 16). Following each writing of a layer, the support surface holding the solidified resin moves down one layer's thickness at a time, recoating the top surface with liquid resin and the next layer is written on the top surface again. A light matrix of material must also be "drawn" under protruding parts of the objects in order to support them during the printing. In the end, the models are made out of a very durable, transparent resin. 3D Systems' stereolithography was the first RP process to be commercialized, starting in 1988 (fig. 17).[10]


Fig. 17. SLA system at Stevens Institute of Technology.

Fused deposition modeling (FDM) has been commercialized since 1991 (fig. 18). This processes 'draws' one layer of the desired object at a time with molten plastic. When a layer is complete the bed moves down and the next layer is drawn upon the previous one. Support material is drawn where needed throughout the process, as in stereolithography. The final models are made of a fairly strong ABS plastic. The MIT Department of Architecture currently owns a *Stratasys FDM 2000*, however the newest FDM machine on the market today is the *Dimension* 3D printer.

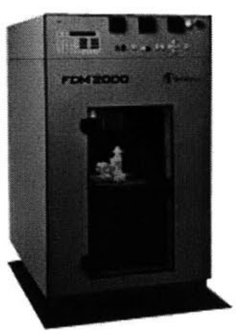
Fig. 18. Stratasys Fused Deposition Modeling machine.

Commercialized in the late 1990s, *three-dimensional printing* (3DP) is rapidly working its way into the architectural design process more so than any other RP method (fig. 19). The architecture department at MIT owns the *Z Corporation Z400* 3D

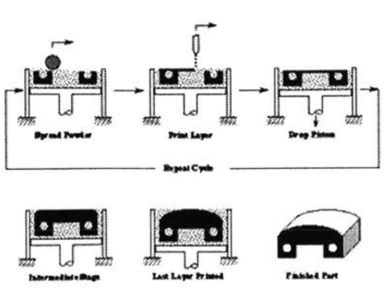
Fig. 19. 3DP process.

[10] Paul F. Jacobs, *Rapid Prototyping & Manufacturing: Fundamentals of StereoLithography* (Dearborn: Society of Manufacturing Engineers, 1992)

Fig. 20. Z Corporation ZPrinter 310

printer along with a depowdering station and wax oven. Since MIT purchased the Z400, Z Corporation has released a more compact 3D printer, the *ZPrinter 310,* that can also print color (fig. 20). An inkjet-like printing head prints an entire layer of a given object with a water-based binding fluid on the top surface of a bed of fine, starch- or plaster-based powder. When the first layer of printing is done, the bed moves down, a thin layer of the powder is spread over the freshly printed layer, and the printing head repeats the process until the object is complete. The non-printed powder in the bed acts as the support material for the print. In the end, the models are made out of a brittle, plaster-like material. Finishing requires blowing off excess powder and lightly curing the outside surface with some sort of binding fluid or hot wax.

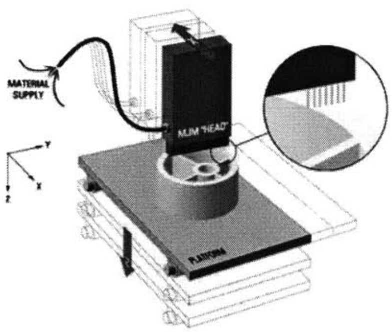

Fig. 21. MJM process.

Also similar to an inkjet printing, *multiJet modeling* (MJM) prints with a head releasing tiny drops of melted, opaque wax to create the print. Each time a layer is completed the bed moves down and the next layer is printed until the object is complete (fig. 21). MJM is found occasionally in architecture schools and was introduced to the market in 1999. MJM machines include *3D Systems InVision 3D Printer* and *Thermojet Printer.*

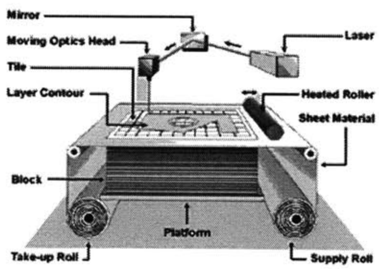

Fig. 22. LOM process.

The *laminated object modeling* (LOM) process creates objects by repeatedly laminating thin sheets of paper, plastic, or composites. Each layer has a profile cut into it by a laser or blade, and is laminated to the previous layer. The remaining material is used as support material (fig. 22). LOM has been commercialized since 1991 and currently appears to be the least utilized process compared to the SL, FDM, 3DP, and MJM processes.

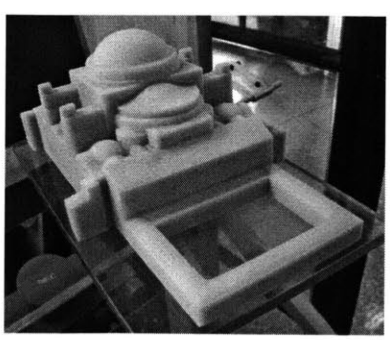

Fig. 23. Hagia Sophia model fabricated by selective laser sintering.

Many variations of these technologies and other RP processes exist, but are not used in architectural model making mainly due to high costs. Some of these other processes are laser sintering, laser generation, and selective inhibition of sintering (fig. 23). The prices of rapid prototyping machines currently run between $20,000 and $900,000.

CHAPTER 3: SURVEYING THE ARCHITECTURAL DESIGN FIELD

Chapter 2 presented the spectrum of tools available for use in the making of architectural models. This chapter focuses on a series of interviews I held with architects, professors, and students through which I learned about their differing views and uses of digital fabrication machines in their design processes. I surveyed a range of people in each of the three categories. Some people had used these machines very little while others had extensive experience. I found people that had more skeptical views about digital fabrication than others, and each person I spoke with provided me with a different perspective on these machines.

3.1 Primary Issues Unveiled

Eight primary issues arose through this survey which were very enlightening. I learned that the design process found in schools differs from the process found in offices. It appears that there are a couple of machines that are favored over other machines by the majority of the field. One fabrication process affects designs more than the rest, while others are less useful than some would hope. A particular group of machines can mislead designers about manufacturing methods, whereas another produces challenges to the academic community. Most of the people interviewed appeared to be very sensitive to the amount of time, money, and effort it takes to make a model. And finally, I found through a few of the interviews that physical models of architectural designs have more significance to them than just physically representing a building. The eight issues are discussed in detail in the following sections.

3.1.1 Differing Design Processes

Architecture students and professionals have different objectives in their design processes and this leads to some frustration among the two groups. Students are very interested in learning the latest software and


Fig. 24. Student making model in studio. (Naveem Mowlah)

rapid prototyping technologies while they have the luxury of having access to these things at little or no cost. Because of this circumstance, architectural students learn to integrate these technologies into their design processes. Students also go through extensive design explorations when developing a studio project, employing most of the types of representation along the way (fig. 24). The students are taught that extensive exploration, is the way the design process works.

Professionals, on the other hand, have to make money. Of course, most architects would love to explore design options as extensively as they did in school, but few are able to afford that luxury. Another money-driven issue is that they cannot afford to try new technologies as freely as students since it is considerably more expensive to do so outside of an academic setting. Trying new software programs is costly not just because of the price of the program, but the time it takes to learn it and incorporate it into the office's design process. RP, discussed later, is still very expensive for architects to use relative to more conventional methods of model making.

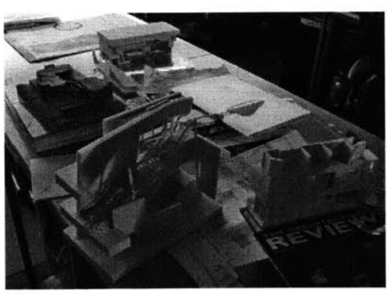
Fig. 25. 3D printed models at Morphosis.

A few rare firms exist, such as Morphosis in Santa Monica, California, that own their own laser cutter and/or 3D printer (fig. 25). Architects at Morphosis design their projects primarily in the computer through the use of 3D digital models. The 3D printer is a natural extension of such a process and they find it is cheaper than outsourcing 3D printing to outside parties. Since Morphosis' way of working is much closer to the academic design process in terms of design exploration and new technologies, a huge number of students want to work there. This causes frustration among students when there are too few firms that match what they are looking for in a job and they can't get it because everyone else is applying for the same position. This situation can also cause frustration for firms that utilize more conventional technologies when they hire freshly graduated designers with skills that are different than what the office needs.

3.1.2 Cost Issues and Evolving Technologies

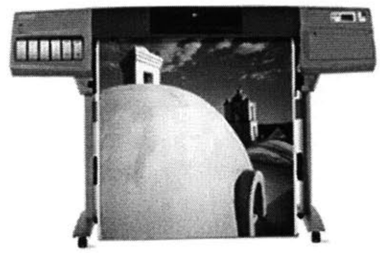

Fig. 26. HP Designjet 430

Discussed earlier is the drastic difference between the student's cost for 3DP at school versus the professional's cost to outsource 3DP. In order to understand more about the cost issues that surround these new technologies, I thought it would be useful to compare the prices of the machines to the prices of large-format color plotters (something most schools and offices own). Hewlett Packard offers a whole line of large-format color plotters with a price range starting at $1,195 for the HP Designjet 430 24" wide format and ending with the HP Designjet 5500 60" wide format at $19,995 (fig. 26).

Below are the prices of all the digital fabrication machines mentioned so far, plus a few others that are useful for the architecture community (Table 1). One should keep in mind that the most expensive color plotter is $19,995, and even that is considered to be too expensive for many smaller firms.

***Table 1.* Prices of digital fabrication machines in April, 2004.**

$2,295	Roland CAMM-1 Vinyl Cutter
$4,495	Roland Modela MDX-20 Milling Machine
$6,400	Denford Micromill 2000
$9,995	Universal Laser Systems desktop VersaLaser 200
$17,250	Universal Laser Systems M-300 Laser Platform
$24,900	Dimension 3D Printer (FDM)
$25,050	**Universal Laser Systems X-660 (25 watt) Laser Platform**
$31,800	**Z Corporation ZPrinter 310 System**
$39,900	3D Systems InVision 3D Printer
$39,999	HAAS Super Mini Mill
$49,900	3D Systems Thermojet Printer
$119,000	OMAX 2652 Jet Machining Center (up to $180,000)
$169,000	3D Systems Viper SLA System

The two most popular machines (shown in bold above) among the architectural community both exceed the price of the most expensive large-format color plotter. This is a part of the reason why most architecture firms outsource rather than purchase their own machines. In addition to the initial cost, most of these machines require annual

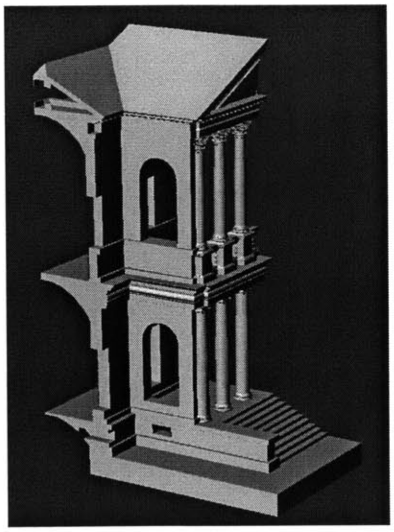

Fig. 28. Palladio STL model by Larry Sass.

maintenance, which can also be quite costly. Another factor is the continually evolving technologies which are costly and time-consuming. The laser cutter and 3D printer, as well as the 3D Systems Thermojet Printer (an MJM machine), are found in architecture schools frequently where there is more budgetary room for exploring new technologies.

Companies such as Xpress3D provide outsourcing of RP and CNC processes through the internet (fig. 27). In order to learn how much companies such as Xpress3D charge, I submitted an STL file a model (fig. 28). The Palladio model's dimensions are 2.94"x4.84"x7.78" and the prices ranged from $281 for a 3DP to $814 for an SLA print. Since RP technologies change frequently and the machines are expensive and difficult to maintain, it makes sense for architecture offices to outsource rather than own their own machine.

Fig. 27. Xpress3D online RP quotes.

3.1.3 Favored Machines

Among professionals and students, the laser cutter and 3D printer proved to be the most favored digital fabrication machines. Each group responded differently, however. Professionals utilize the laser cutter more so than any other machine in the digital fabrication group. The 3D printer appeared to be the second most used, although it is still not well integrated into the design process by most architects. Meanwhile, students responded overwhelmingly that the 3D printer was their machine of choice, with the laser cutter coming in as a close second.

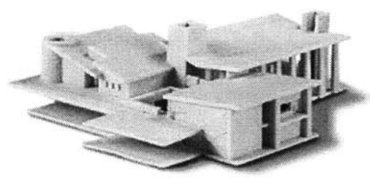

Fig. 29. 3D print of typical architectural model by Service Point.

There are a few reasons why I think these machines were chosen as the favorites and why professionals and students view them differently. The reason 3D printing is used more by students than professionals starts with cost, as mentioned previously. MIT Architecture students only pay $3.50 per cubic inch of material, which adds up to $10-$70 for a completed 3D print. The key factor influencing the low price is that students are not being charged for the printing time and post-processing. Except for a rare handful, all professionals must outsource 3D printing, which can be expensive. Service Point, a reproductions company in Boston, Massachusetts, offers 3D printing as one of their services (fig. 29). Service Point includes the printing time and post-processing (dusting and sealing the model) in their fees, which ultimately forces the prices up to $300-$1,000 per print.

Another explanation as to why 3D printing is more popular in schools than in businesses is that students tend to three-dimensionally design within the computer more than professionals. Most architecture offices mainly work in 2D in the computer, sometimes incorporating a partial 3D model used to render specific views of the project.[11] The 3D printer must have a complete 3D digital model to work from or no print can be made. Altering the design process to accommodate 3D printing needs can cost companies even more time and money. Architects would need to teach their designers a new design process, which is not a small task.

[11] Joshua Katz. Phone Interview. 20 April 2004.

Service Point has noticed that there is a high level of interest in the 3D printing service they provide, yet very few architects are actually taking advantage of the service. Service Point's original target audience was architects, but when they experienced this hesitation they started targeting industrial designers as well, which has helped bring in more business. At the moment, Service Point makes about two to three prints each month, only one of which is usually ordered by an architect. Jim Maitland, Service Point's manager of 3D operations, stated that a part of the problem is that most architects are simply not working with 3D digital models yet, which means they cannot take advantage of his 3D printing service.

Joshua Katz, in Washington, DC, provides many architectural design services, including 2D drafting, 3D modeling, conventional model building, and 3D printing. Since Joshua has included 3D modeling as one of his services, he has been much more successful with his 3D printing service than Service Point. Architects can give him whatever they have, whether it's a partial 3D digital model or even a set of 2D drawings, and he will create the 3D digital file needed to make a print. By providing this extra service and complete model finishing, including sanding and painting, he produces up to ten prints per week.

Fig. 30. Students building a model with laser cut parts; laser cutter in the background. (Christine Gaspar and Marlene Kuhn)

The laser cutter has become a standard part of the academic studio (fig. 30). It has proven to be a faster, more precise method of making cuts one would otherwise make by hand. Unlike the 3D printer, the laser cutter has been demystified, helping it remain the better utilized of the two in spite of the popularity of the 3D printer. Some of this is attributed to the cost of 3D printing, while the rest could be blamed on its inestimable qualities.

3.1.4 Most Influential Machine

Although the 3D printer (fig. 31) is not as well utilized as the laser cutter, it is currently having the greatest impact on the design process in schools. Students are the primary users of this fabrication method,

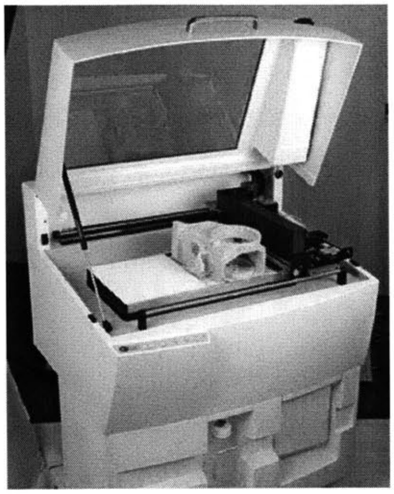

Fig. 31. Z Corporation
ZPrinter 310

which explains why changes would happen here first. Closely involved in the academic studio, professors have been witnessing the changes that have occurred in students' design processes as these new technologies become available. The laser cutter has not had as much of an impact on the design process because its capabilities directly correspond to the designer's handmade model making methods. The 3D printer, however, requires an entirely different method of working due to how the digital file must be set up and how the object is produced.

The effects on the design process are both positive and negative. Through my survey, I found four positive and three negative effects on the design process when designers use 3D printing as one of their methods for model making.

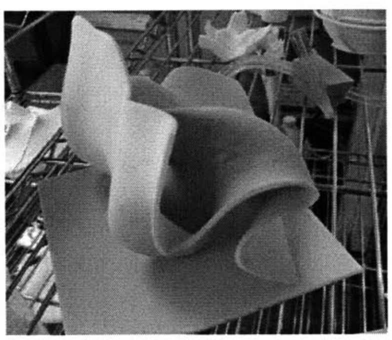

Fig. 32. 3D printed physical representation of digital model. (Nicolas Rader)

Positive effects of using 3D printing are:

1. *Designers are physically exploring different designs than they would otherwise be able to with a physical model* (fig. 32). If the 3D printer was not available, the designs would remain in the computer as digital models or be physically represented in a much more rough, imprecise manner.
2. *Designers are now using this technology to confirm the quality of their digital models.* 3D printing provides an honest representation of a digital model, revealing detrimental imperfections that would otherwise go unnoticed.
3. *Designers are exploring more designs in a shorter amount of time.* Although not quantified, a few regular users of 3D printing noted this as one of the reasons they prefer using the technology as one of their primary methods of creating physical models.
4. *Designers are evaluating their designs in a range of scales from a single model* (fig. 33). Since 3D printing requires the designer to create a 3D digital model, that single model can be

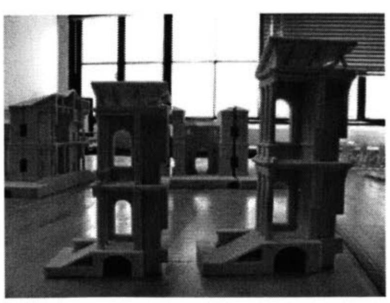

Fig. 33. 3D prints of Palladio building by Larry Sass presenting different scales derived from the same digital file.

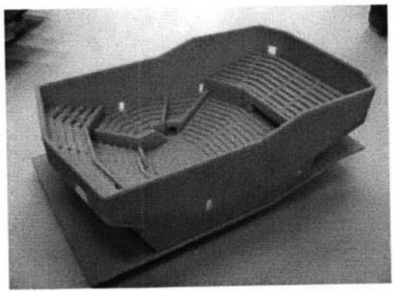
Fig. 34. Anonymous student model of auditorium.

printed at a variety of scales, ranging from details to urban sites.

Negative effects of using 3D printing are:

1. *Designers are designing for the 3D printer rather than for construction processes used to construct buildings.* Therefore, designers are creating buildings with more surfaces and less slender elements (Fig. 34). 3D prints are made of a brittle, plaster-based material that tends to break very easily. Designers who use this machine to create physical representations of their designs tend to design for the machine's output, which ultimately forces them to shy away from slender elements.
2. *Students are further removed from the building process.* A concern to many professors and professionals is that students become somewhat removed from the building process of architecture when they use the 3D printer as a model building technique. The machine creates the physical object, not the designer.
3. *Students are designing homogeneous buildings.* The danger here is that students begin to see buildings as monolithic objects and not as an assembly of a wide variety of components. Buildings consist of many different types of materials assembled together in many different ways, yet a 3D print consists of one material printed in a monolithic fashion.

3.1.5 Misleading Fabrication Processes

The 3D printer is not the only rapid prototyping method to provide inaccurate representation of real construction processes. 3DP, FDM, SL, MJM and LOM all manufacture parts through a homogeneous, additive, layer-by-layer process, which is far removed from any real construction process. Concrete or rammed earth construction are close, but elements such as windows, reinforcing bars, and plumbing must still be placed in the walls during the construction process.

3.1.6 CNC Milling Challenges

CNC milling machines are becoming more common around architecture schools, yet are appearing to be less useful than some would hope. Many of these machines are desktop milling machines, such as the Modela or Denford that MIT owns; however, a few schools have acquired large-scale machines similar to the HAAS described earlier.

Before conducting my interviews and experiments, I thought the milling machine would undoubtedly be a great resource to have in any architecture school. However, I realized after interviewing students who have had hands-on experience with these machines, that their experiences are not meeting the expectations of the professors who introduced the machines to the school. Only when this knowledge is coupled with class lectures and tours, can these machines become a significant teaching tool. Even so, a few students commented that using the machines did not help them at all and that it was solely what they learned in class and on tours of offices and shops that helped them grasp manufacturing concepts.

3.1.7 Importance of User-Friendliness

Architects and students are very sensitive to the amount of time and money it takes to represent a design. The other major factor is user-friendliness. If a fabrication method is too tedious to learn and use, people will find another method that is more straightforward. I think this is another reason why the vinyl cutter, FDM, and especially the milling machines are not exploited like the laser cutter and 3D printer.

Sending prints to the 3D printer is analogous to sending a print to a standard laserjet printer. The reason architects can look past the tedious post-processing is that the overall concept of 3D printing is simple to grasp.

Operating the laser cutter is analogous to the slightly more complex process of large-format, color printing. Fortunately, this is something most architects are familiar with, which is why laser cutting appears user-friendly. Plotting from AutoCAD is a standard part of the architectural design process for most architectural designers, and that is exactly how they send files to the laser cutter. Making changes to the file is also comfortable because it is simply altering 2D drawings in AutoCAD.

3.1.8 Significance of Physical Representation

The physical representation of a digital file has a significance of its own for two reasons. One reason has to do with the spirit and sensibility of the design it is representing. The other has to do with the reality it brings to the 3D digital model.

Physical models do not just represent the reality of an architectural design, but capture the spirit and sensibility of the design as well. Some people prefer handmade models over laser cut ones because the laser cut models tend to feel sterile. 3D prints of architectural projects run the risk of losing the sensibility of the design, yet they can sometimes introduce a new kind of spirit as well. 3D printed models typically emerge as homogeneous, precise, unfinished models that tend to have little or no spirit, such as a 3D print of a typical house. However, some objects that are fabricated with the 3D printer cannot be fabricated in any other way, and these models tend to have a liberating spirit to them because they bring the digital to life.

Another significant aspect of physical representation is the reality the physical model brings to the digital model. One could argue that physically representing a digital design is necessary for the architectural design process. During one of my interviews, a comparison was made between the architectural design process and the graphic designer's design process. When designing a book cover, a graphic artist starts by creating the image in the computer, visually interacting with it through a screen. In order to evaluate the image accurately, the artist must repeatedly print the design out on paper and adjust it in the computer. The computer image is not a reliable representation of the final design.[12]

This seems synonymous to an architect designing a building in the computer, repeatedly stopping to create 3D prints of the building in order to evaluate how the 3D space actually works. The designer knows what adjustments are needed on the digital model by physically experiencing the design, both spatially and contextually. One main difference I see between the graphic design process and the architectural process is the homogeneous character of 3D prints. Materials in architecture are the same as colors to the graphic designer. Today's 3D prints do not allow architects to evaluate how materials will interact in their designs. Maybe this is where developments in 3D printing can help in the future.

[12] Joseph Dahmen. Personal Interview. 12 April 2004

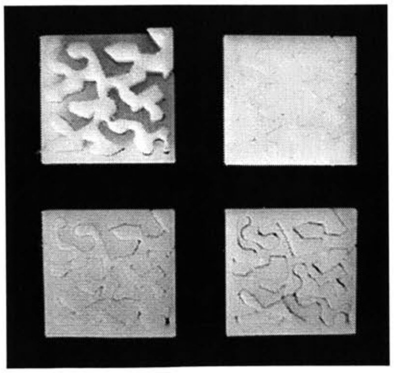

Fig. 35. FDM tolerance testing.

CHAPTER 4: EXPERIMENTING WITH DIGITAL FABRICATION

I am in the fortunate position of having access to eight digital fabrication machines and took advantage of the opportunity. I conducted three experiments on these machines in order to gain a better understanding of each process. In all of my explorations I utilized one or more of the machines to which I have access in the MIT Department of Architecture and at the Center for Bits and Atoms Fab Lab.

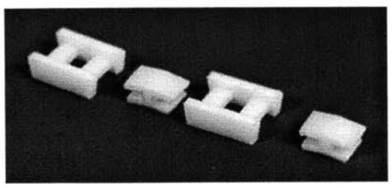

Fig. 36. FDM components of one-way arch.

4.1 Experiment 1: Fused Deposition Modeling of Self-Assembled Domes

The only machine used for this experiment was the Stratasys FDM 2000 which prints objects with a robust, white ABS plastic. I worked on this project with Larry Sass and Sarah Hudson for the Center for Bits and Atoms during the summer of 2003. (In this section, whenever I say "we" I am referring to Larry, Sarah, and me.) The ultimate goal of this project was to digitally fabricate complicated dome structures based on designs developed in eifForm, a performance-based computer program, developed by Kristina Shea, that generates structural forms.[13]

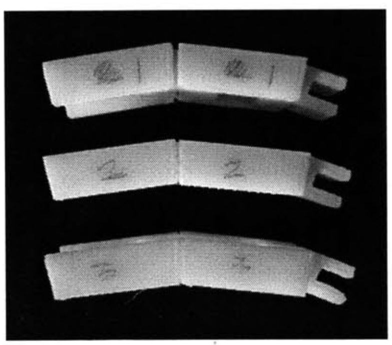

Fig. 37. Tolerancing of FDM parts.

We started studying the machine by documenting tolerances, material usage, and print times (fig. 35). We learned that one needed to design for the FDM process in order to create the parts we were intending to print. Once we felt we understood the Stratasys, we began designing and building simple, self-assembling arches and domes. In this case, "self-assembling" refers to a structure whose components dictate the order in which they should be assembled (fig. 36). The first few assemblies were self-supporting, one-way arches consisting of many interlocking parts that dictated the method with which they must be assembled. Before moving on to the next step, we went through the

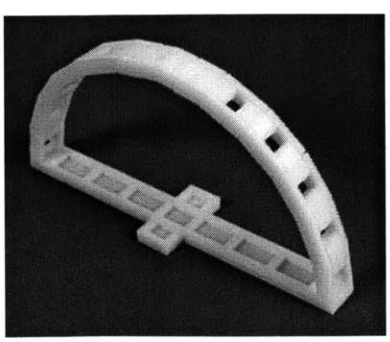

Fig. 38. FDM one-way arch .

[13] Shea, Kristina. "Digital canopy: high-end computation/low-tech construction" *arq*, 6.2 (2002) 230-245

tedious process of tolerancing the interlocking parts so they would fit together tightly (fig. 37).

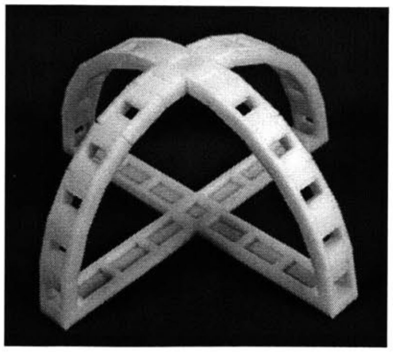

Fig. 39. FDM two-way arch.

The one-way arches (fig. 38) were followed by two-way arches, which forced us to start thinking of more unique parts (fig. 39). The two-way arches were followed by an elaborate half-dome made of many repetitious, interlocking components, some of which were unique (fig. 40). The regular half-dome was followed by an irregular half-dome (fig. 41). We explored two different types of connections on the irregular dome, one of which was chosen as the connection for the next project. We worked toward the conclusion of a very complicated partial-dome assembly consisting of many unique components where there was only one way to assemble them (fig. 42).

Fig. 40. Regular half-dome.

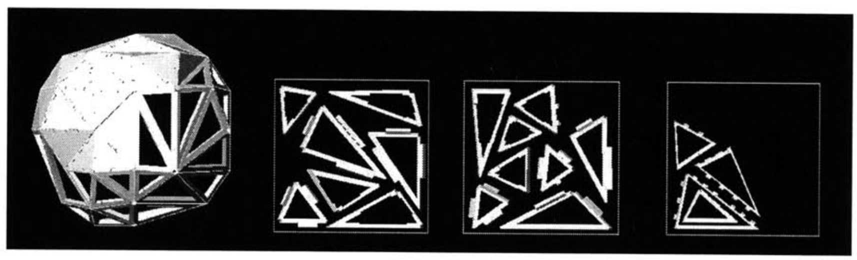

Fig. 41. Irregular half-dome digital file showing parts arranged for FDM.

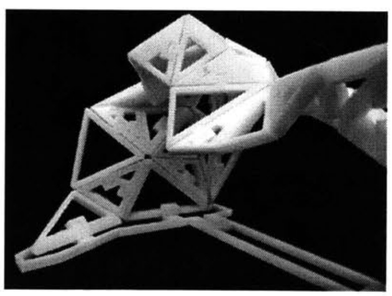

Fig. 42. FDM irregular partial dome.

We learned to like the FDM process because the ABS printed parts were robust. Once we figured out the tolerancing, we were able to design parts that friction-fit together, which was very helpful in creating self-supporting assemblies. Learning how to operate the machine was not too difficult; however, it was tedious enough that Sarah and I had to be assisted for the first few times we sent prints to it. Occasionally the machine would encounter errors, which we had to learn to fix (fig. 43).

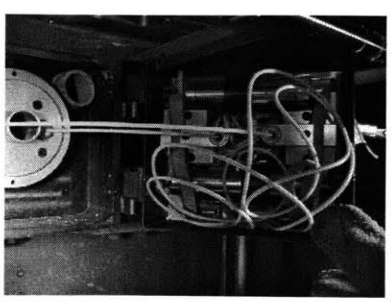

Fig. 43. FDM offline.

Through this experiment, I realized that in order to make the FDM parts work together the way I intended them to work, I had to design for the machine. I had to have a decent understanding of the tolerances the machine worked within, how the output would appear if the objects were oriented in different positions, and where the support material would be located. If I didn't keep these things in mind as a I prepared the parts to be manufactured, I would have difficulties getting the parts to work the way I intended.

4.2 Experiment 2: Digital Fabrication of Self-Assembled Joints

After the first experiment, Sarah, Larry, and I continued to work on the complicated partial-dome assembly utilizing four digital fabrication machines. (I will refer to the three of us as "we" again in this chapter.) We continued to use the FDM, in addition to using the CAMM-1 vinyl cutter, the laser cutter, and the Roland MDX-20 milling machine. We worked in a general-to-specific manner, starting with the overall dome design and worked toward detailing the joints. We originally intended to complete the experiment by milling the components out of aluminum; however, the more we learned about the manufacturing process, the more we realized that our design was not very conducive for milling.

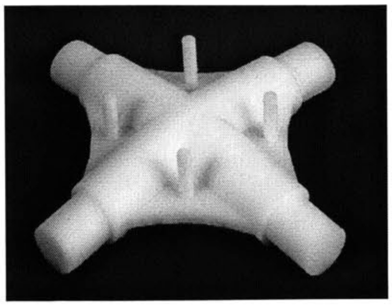

Fig. 44. FDM typical joint.

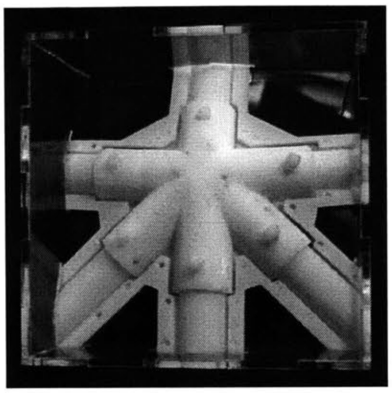

Fig. 45. FDM typical joint with laser cut plexiglass.

We started by creating a monolithic representation of a typical joint on the FDM (fig. 44), followed by another typical joint fabricated piece-by-piece on the FDM (fig. 45). Then we moved to cutting all of the dome's tessellated faces out of acetate on the Modela CAMM-1 desktop vinyl cutter. Sarah created a cut sheet of each triangular face and "printed" it on the CAMM-1. Once all of the faces were cut, she taped them together to create a small physical representation of the structure (fig. 46).

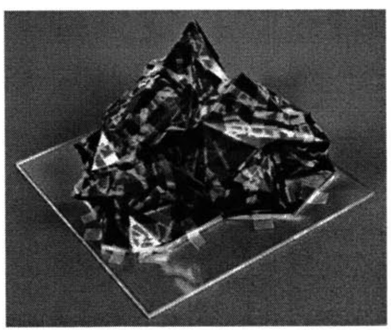

Fig. 46. Triangulated surfaces of irregular dome, cut with CNC vinyl cutter.

Then we chose which joints of the triangulated structure we were going to model and cut those panels on the CAMM-1 as well. The thin acetate panels were taped together as before and overlaid on an abstract FDM model of the triangulated structure (fig. 47). The seams of the two models, fabricated by different machines, lined up with each other perfectly. This verified that we were able to convey information accurately to multiple machines.

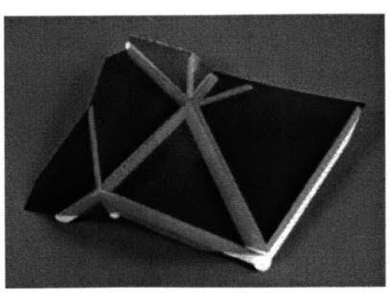

Fig. 47. Selected section of dome. Structure modeled with FDM and surfaces cut on CNC vinyl cutter.

We chose one of the joints to design in detail and used the FDM and laser cutter to create a prototype (fig. 48). The fused deposition modeled joint and struts fit together well with the laser cut panels. The next test was to mill the components in rigid foam on the Modela and, if that went well, ultimately mill out of aluminum on the HAAS.

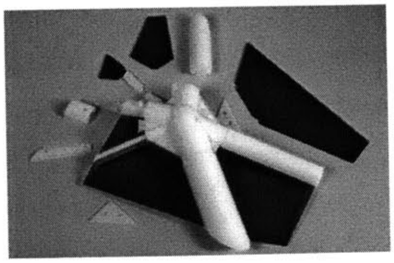

Fig. 48. Disassembled FDM parts and laser cut panels.

Milling on the Modela was generally a good experience (fig. 49). I milled the three-joint structure out of rigid foam which ended up being twenty-three parts in all (fig. 50). The assembly called for nine glass panels which I laser cut out of acrylic. Ultimately, the entire assembly took weeks to manufacture. Milling those twenty-three parts taught me that we had not designed the parts very well for milling, even though when we started we thought we had designed the parts well. The assembly still went together well, but comparing the physical output to the digital model revealed areas that could have been better designed.

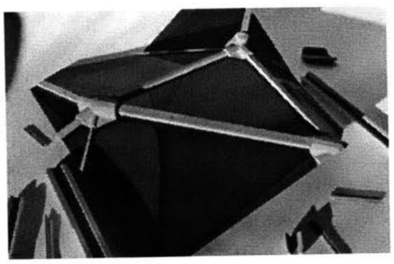

Fig. 49. Rigid foam assembly milled on the Modela MDX-20 with laser cut panels.

When we saw that the components we had designed did not work as well as we had hoped, we decided to redesign them before proceeding to mill them out of aluminum. After a few days of digitally modeling these complicated joints, we came to the conclusion that it was not practical to manufacture this joint by milling. Casting turned out to be the most appropriate manufacturing method for such a joint, and since we wanted to stay focused on digital fabrication, we decided to end this experiment with the milled foam assembly.

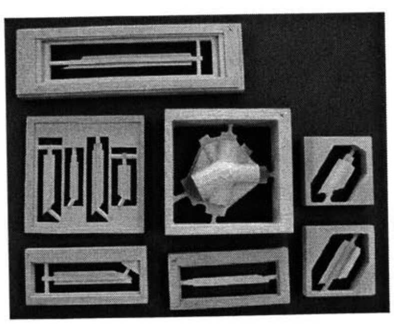

Fig. 50. Milled rigid foam parts, milled on the Modela.

What we learned was that there are appropriate and inappropriate methods of manufacturing for different parts. When we tried to mill parts that were not meant to be milled, they come out looking worse than desired, they take a long time, and in the end, they did not work properly. A designer must fully understand what the fabrication process will be when he or she designs a building or component for a building in order to design for that process in the digital model. Otherwise, the designer and fabricator will both be very frustrated.

4.3 Experiment 3: Digital Fabrication of an Architectural Component

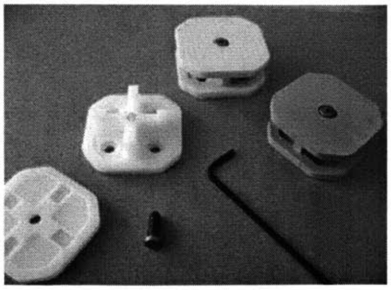

Fig. 51. Glass clamp prototypes.

The 3D printer, FDM, Modela, Denford, and HAAS were all used to create a series of identical prototypes of a typical glass clamp (fig. 51). This was a valuable experiment because I was able to compare how much time and effort each machine required to create the same parts. The waterjet cutter was also used to cut out small glass panels for the prototypes (fig. 52). The same digital model was used to set up the master files which drove each of the five digital fabrication machines. One should keep in mind that the (*) next to the HAAS Super Mini Mill in Table 2 denotes that only one half of the clamp assembly was milled in the stated time, while the other four processes are the timed fabrication of both halves of the clamp assembly (fig. 53).

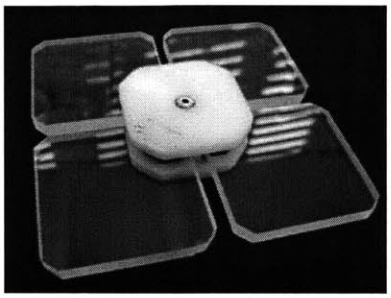

Fig. 52. FDM clamp assembly with waterjet cut glass.

Table 2. **Comparison of Glass Clamp Assembly Manufacturing**

Machine	Total Processing Time	Total User Time
Stratasys FDM 2000	2.5 hours	15 minutes
Modela MDX-20	2 hours	20 minutes
Z Corp. Z400	3 hours	1 hour
Denford Micromill	6.25 hours	5.5 hours
HAAS Super Mini Mill*	15 minutes	7 hours

Fig. 53. Aluminum HAAS milled part showing many errors.

Table 2 makes it pretty obvious why the additive machines are commonly known as *rapid prototyping*. I think, in spite of the subtractive fabrication process, that the Roland Modela can be considered a rapid prototyping machine as well. The Denford, however, is a manufacturing machine at a desktop size. A great amount of skill is required to operate this machine and it took me quite a few weeks of constant use to really understand how to run the Denford and what to expect.

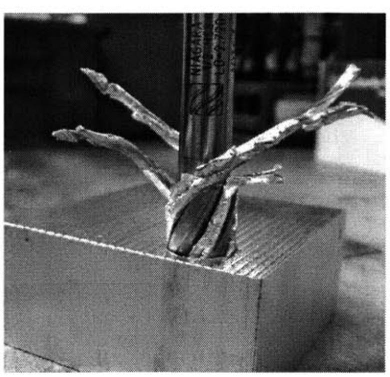

Fig. 54. HAAS milling accident.

The HAAS is an incredibly complicated machine to use and I do not recommend it to anyone unless a trained operator is available for assistance (fig. 54). The actual milling time took only 15 minutes, which was very quick. Even the setup time took only an hour, including the development of the toolpaths and machine preparation for the fabrication process. The factor that made the process take so long was that one number in the operating code wasn't correct and that kept us hung up for the rest of the seven hours I have counted as user time. This occurrence helps illustrate how having a large amount of details to keep track of increases the chance for mishaps.

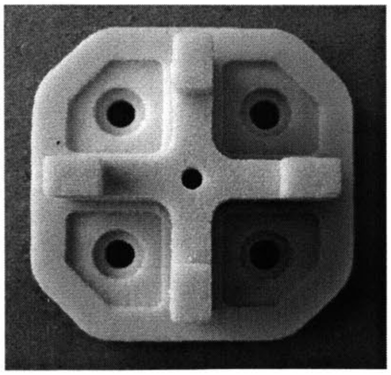

Fig. 55. 3D printed glass clamp.

If one compares the 3D printer to the HAAS, we will find that there is very little room for errors with the 3D printer (fig. 55), but an extensive amount of room with the HAAS. On the other hand, currently the user has no control over how the part gets 3D printed, while the HAAS allows full control of the toolpaths, end mill type, and material type.

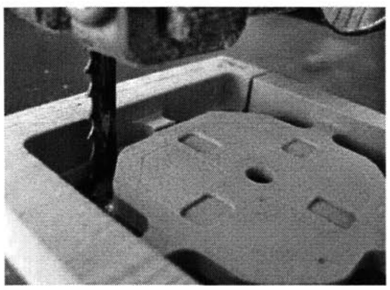

Fig. 56. Cutting component from stock with conventional band saw.

Each manufacturing method required different types of post-processing. The milled parts required the object to be cut from the stock (fig. 56). 3D prints required excavation, cleaning, sealing, and setting up the machine. The FDM prints required the support material to be moved. And the waterjet cut parts required drying and the machine required clearing. No matter which method, they all required hands-on work at some point. The FDM print was much less labor intensive than the rest, while the 3D printer required the most post-processing. The milling required more hands-on work in the beginning because the stock needed to be prepared for milling.

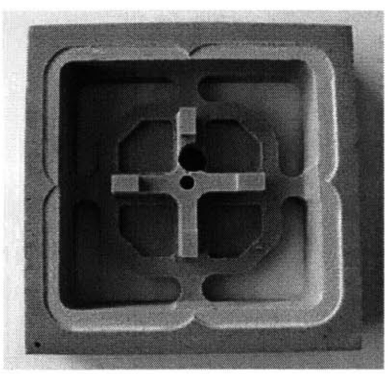

Fig. 57. Rigid foam part milled on the Denford.

I only damaged the part and had trouble controlling the machine when I was using the Denford and the HAAS milling machines (fig. 57). All the other fabrication methods are relatively simple to use and rarely damage the part through accidents.

CHAPTER 5: COMPARATIVE ANALYSIS

Numerous pros and cons stem from the use of digital fabrication in the architectural design process. Digital fabrication affects professionals differently than students due to the various objectives to which each group aims. We have to ask the question: Is it worth it? I believe it is, but one must understand when it is the appropriate time and place to utilize each of these technologies.

That time and place occurs in different parts of the design process for professionals and students. As mentioned in Chapter 3, professionals' ultimate goal is to see a project get built, while students' ultimate goal is to learn. Professionals must design for the construction of the final building, unlike students who have the freedom to explore designs independently from the construction process. The professional's use of digital fabrication cannot be entirely separate from manufacturing and construction processes.

In this chapter, an overview of the benefits and challenges that arise when architectural designers incorporate digital fabrication into their design processes will be provided.[14] Two common misconceptions found among some architectural professionals, professors, and students will also be presented in section 5.2. The chapter ends with a description of the positive and negative effects caused by the architectural field's adoption of digital fabrication into the design process.

5.1 Benefits and Challenges

Before the effects of digital fabrication on the architectural design process can be discussed, one must understand the benefits and challenges that arise from the use of different types of fabrication machines. Due to these pros and cons, issues have developed that

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[14] See Appendix B for a more extensive list of the eight machines' positive and negative attributes.


Fig. 58. Acetate cut on CAMM-1 cutter.

effect how designers in the architectural field design, both positively and negatively. Below is a description of the benefits and challenges of the eight machines I used throughout my experimenting. Interviewees' responses are also taken into account for the following descriptions.

The cheapest of the eight machines I am focusing on in this thesis is the *Roland CAMM-1 vinyl cutter.* The CAMM-1 is fairly easy to use and requires very little space. It is capable of precisely cutting a broad palette of thin, sheet materials (fig. 58). Since thicker materials are often required in architectural models, the acceptable material thickness can be limiting for the designer. Maintaining the sharpness of the blade and applying backing material to each "print" hinders the designer as well.

Another Roland desktop machine, the *Modela MDX-20*, is fairly easy to use relative to other milling machines. The MDX-20 is cheap, requires very little space, and is capable of producing high-quality milled surfaces. It is a good teaching tool because it engages the user during the set up and post processing phases, yet requires very little monitoring which keeps it from consuming too much of the user's time. However, its material palette and size of output is very limited. The MDX-20 requires a fair amount of maintenance and has special environmental needs. Although its milling process is analogous to large scale milling, the lack of operator assistance and material limitations can mislead students into thinking milling requires very little time or skill.

The *Denford Micromill 2000* is the other desktop milling machine I was able to use for the experiments. The Denford is a much better teaching tool than the Modela MDX-20 because it requires the user to create the toolpaths and monitor the machine while it is running. Since the Denford is more powerful it can mill a wider range of materials, yet it still cannot mill many of the harder materials the industry often requires (such as stainless steel or titanium). Because of this, a student may assume that all manufacturing is as easy as milling foam or aluminum. The user's time is often consumed by setting up the machine, preparing the material, creating the toolpaths, and monitoring the machine while it is running. So many variables exist among all these steps that there is a lot of room for error and tends to intimidate inexperienced users. Like the Roland milling machine, the Denford also requires a clean environment.

Like other rapid prototyping machines, the *Stratasys FDM 2000* makes seemingly impossible digital models physically possible. The ABS prints provide robust models that require very little user time to create. The size of the machine is no larger than a large-format plotter; therefore, it can fit in offices and schools fairly easily. The print time is long, and the surface quality of the output is often lower than what is desired by most architects. Orientation of the object on the printing bed makes a big difference on the surface quality and precision of the part, as well. The Stratasys is also fairly expensive, which can be a deterrent for many architects.

The *Universal Laser Systems X-660 laser cutter* offers a high level of user control, yet is very user-friendly. The laser cutter can cut a broad palette of materials very precisely and rapidly, which makes it possible to shorten the model building time while creating more finished models. The laser cutting process is scalable to shop-scale laser cutting, which can help students understand more about manufacturing. The machine is expensive, however, and requires a special setup in a clean environment. Users must be trained to use the machine because there are many small details to know and forgetting some of them can cause big problems. Also, students can become too involved in the details due to the machine's precision.

Creating 3D prints with the *Z Corporation ZPrinter 310* is easy and relatively fast. Precise models with nice surfaces are common for prints fabricated by this machine. The overall process of creating objects in the ZPrinter is very user-friendly. Although the models are typically brittle, they can be strengthened by using different powders and sealing epoxies. Even with these stronger materials, this fabrication process is not suitable for slender objects. The biggest disadvantage of 3D printer is that the post-processing can be extremely tedious and messy. Because of the mess and the size of the set up, special environments are needed.

Milling with a "real" milling machine has some very strong pros and cons. Using the *HAAS Micro Milling Center* allows a wide range of materials to be milled very quickly. The HAAS is similar to the manufacturing machines found in fabrication shops, so it allows the architectural student to personally experience the manufacturer's milling process. Because of the complexity of the process, designers who use this machine are instilled with an appreciation for the machinists who specialize in CNC milling. Although the milling process is fast, there is so much room for error throughout the process that one minor mistake can severely hinder the operation. The HAAS requires special facilities and maintenance, as well. Once the machine is running, it must be monitored the entire time. Ultimately, the HAAS can prove to be extremely time-consuming, tiring, and "unpredictable"[15] experience for a designer, yet still provide a very good learning experience.

The *OMAX 2652 Waterjet Cutter* can cut almost any material and is relatively easy to use. The OMAX is synonymous with waterjet cutters found in manufacturing shops, which allows the architectural student to witness how waterjet cutting works in a professional shop. At the same time, it is very expensive and requires special facilities. Those facilities are rarely provided by an architecture department or office, which makes accessing a waterjet cutter difficult.

[15] Jelena Pejkovic. Personal Interview. 3 April 2004.

The eight machines described in this section embody positive and negative attributes that cannot be fully understood by an architectural designer until he or she has had hands-on experience with each machine. Since some of these machines, such as the Denford milling machine, are comparable to manufacturing shop machines, one will still lack the understanding of how these fabrication processes fit into the production of final building components unless he or she is exposed to actual shop settings where these machines are used. Many professionals, professors, and students lack hands-on experience with digital fabrication machines and exposure to professional manufacturing processes, which can lead to misconceptions about digital fabrication in architecture. The following section describes two common misconceptions found through the survey and experiments.

5.2 Common Misconceptions

Now that I have described the pros and cons that surround each of these machines, I would like to draw attention to two misconceptions I have run into throughout my research.

The first, and most troublesome, misconception in the architecture community is "...that uniqueness is now as economic and easy to achieve as repetition..." [16] due to the computer controlled manufacturing methods we now have. Although today's manufacturing methods are more economically feasible than they used to be, I can say from firsthand experience that uniqueness is definitely not as easy to achieve as repetition. If we look at this simply from the machine's point of view, it does not care what numbers the user gives it. Nevertheless, for one to design many unique parts, prepare the digital files for manufacturing, organize them in preparation for assembly, and keep track of all the different parts while assembling takes much more time and effort than it takes to go through the process of designing and manufacturing many repetitious elements. Ultimately,

[16] Slessor, Catherine, "Atlantic Star," *Architectural Review* Dec. 1997: 34

time costs money, which means that this is not as economical as repetition.

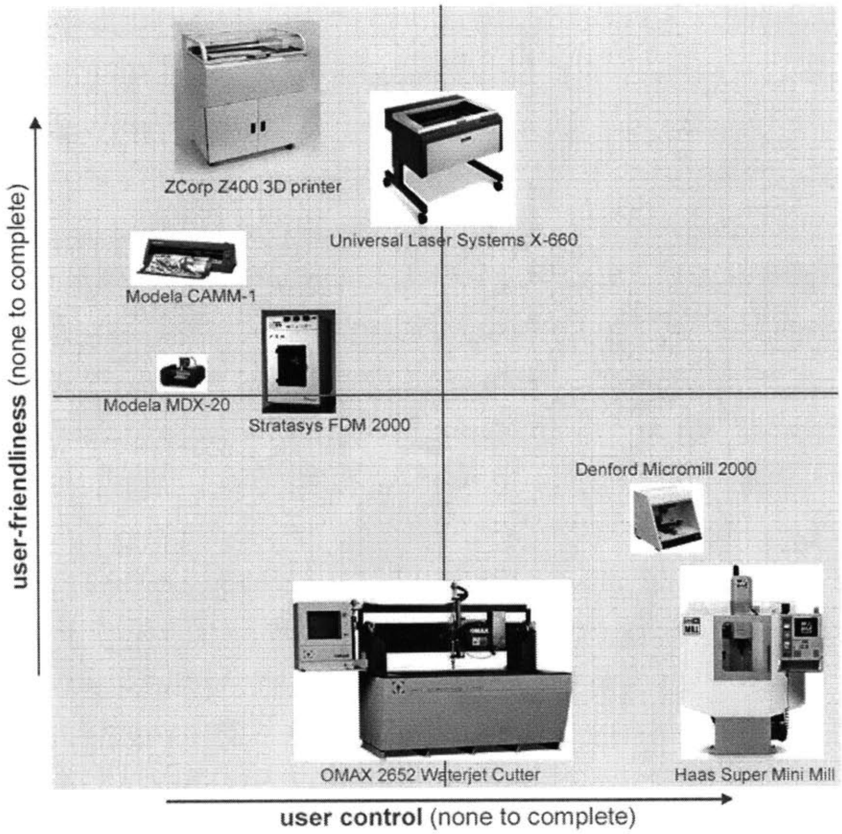

Fig. 59. Comparison of machines' user-friendliness to user control.

The other misconception about digital fabrication machines is that more user-control is better than less user-control. I certainly thought this before I began working with these eight machines. If a user has more control over the machine's method of manipulating material, he or she will be able to experiment with the machine's capabilities more freely than if he or she had very little control. However, if architects are the operators of these machines, especially the more complicated machines like the HAAS, increased user-control can be a bad thing. The more control one has, the more room there is for things to go wrong. This can make the whole process a very frustrating experience. For architects, I have found that user-friendliness is the most important attribute when using a machine, and if a machine can still be considered "user-friendly" yet allow more user-control, then that is a great machine. Unfortunately, there is no such machine yet (fig. 59).

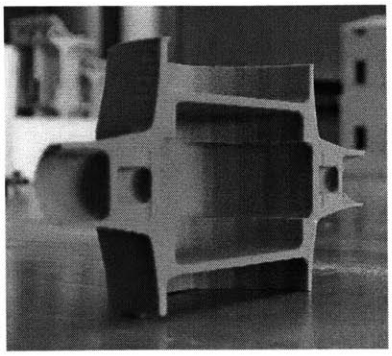

Fig. 60. Milled rigid foam building component. Model by Jelena Pejkovic.

5.3 Effects on the Design Process

The misconceptions, benefits, and challenges found through the research in this thesis are what cause the positive and negative effects of digital fabrication on the architectural design process. Through my own experience and learning from the experience of others, I found that some machines have more of an impact on the design process than others. These impacts will be presented in this section.

As described in section 3.1.4, the *Z Corporation ZPrinter 310* appears to be the most influential machine of the eight machines used in the experiments. The positive effects of using 3D printing during the architectural design process are: (1) Designers are physically exploring different designs than they would otherwise be able to with a physical model. (2) Designers are now using this technology to confirm the quality of their digital models. (3) Designers are exploring more designs in a shorter amount of time. (4) Designers are evaluating their designs in a range of scales from a single digital model. The negative effects of using 3D printing are: (1) Designers are designing for the 3D printer rather than for construction processes used to construct buildings. (2) Students are further removed from the building process. (3) Students are designing homogeneous buildings. The positive effects are influenced by the user-friendliness of the 3D printer and the nice surface quality of the 3D printed models architects produce on the ZPrinter. The negative effects are influenced by the brittle, homogeneous material used by the machine to create 3D printed models.

The Roland desktop milling machine, the *Modela MDX-20*, is cheap, small, and relatively user-friendly, which explains why students feel more comfortable using it over all other milling machines. As students' use of the MDX-20 rises, their knowledge of architectural component manufacturing rises, which influences what and how they design in studio (fig. 60). Although this fact can be seen as a positive effect because students are thinking more about how building elements join, one can also see it as a negative effect. Especially concerning architecture students in their first or second year of studio, the use of the MDX-20 can cause students to become too focused on the details of a building design, leading them to forget about the overall design concept. Students can also be misled into thinking that the rigid foam they are milling an object out of is synonymous to the stainless steel being milled by a manufacturer for "real" building components, causing the students to suggest milled components that may be unrealistic.

The *Denford Micromill 2000* has similar effects on the design process to the Modela MDX-20. Students may begin to design the details of a building before understanding the overall building design. They may also suggest unrealistic milled parts because they do not know enough about how milling is used in the manufacturing of building components. Instead of milling foam, students may mill aluminum in this machine, which is still not synonymous to stainless steel. Since the Denford is not conducive for creating building models, the Denford may hinder inexperienced students by drawing their attention away from the overall design concept.

The third CNC milling machine discussed in this research is the *HAAS Micro Mill*, which is very similar to the types of milling machines used in manufacturing shops. Like the MDX-20 and the Denford, it also has the tendency to lure students into thinking more about the details of a building than the overall building design. Due to the large range of materials that can be milled at high speeds with this machine, not only can students mill full-scale details, but professionals can create models and mockups with the HAAS. Closely related to the HAAS are table routers, which allow students and professionals to create large objects such as site models and molds for vacuum forming. The design

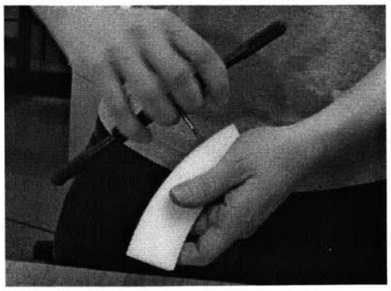

Fig. 61. Tapping an FDM print. Model by Michael Powell.

process is changed because the designer must to design for whichever machine he or she will be using in order to make the process run more smoothly.

Similar to a table router, the *OMAX 2652* waterjet cutter cuts large sheets of a many different types of materials. It also allows architects and students to create large objects, facilitating the fabrication of full-scale mockups. Using the waterjet cutter often forces designers to confront issues that arise when building an actual building. Waterjet cut assemblies, as well as table-routed assemblies, are often mockups, which forces one to be aware of how connections, material thickness, and gravity all have an effect on the final design. Typical small-scale physical representations often do not provide this type of learning experience.

The *Universal Laser Systems X-660* laser cutter cuts material in a similar manner to the waterjet cutter. There are also shop-scale laser cutters that can cut large sheets of materials such as stainless steel. Therefore, the 18"x 24" bed laser cutter found in many architecture schools is useful as a scaled down version of fabrication processes used by manufacturers to create building components. This influences the design process because the parts designed by students for the studio-sized laser cutter can easily be fabricated by waterjet cutters and larger laser cutters.

Creating parts with the *Stratasys FDM 2000* effects the design process in a similar way to the 3D printer because it can build a wide variety of forms. Not only does using the Stratasys influence designers to create objects that can only be built in an additive layer-by-layer process, the machine produces very robust models that allow designers to manipulate the objects more easily (fig. 61). Since support material is needed during the creation of an FDM print, one must design the object in such a way that the support material is can be removed. The orientation of the object makes a difference in the surface quality as well, so careful attention must be paid to the orientation of the object on the print bed.

The *Roland CAMM-1 vinyl cutter* seems to be the least influential machine compared to the other seven digital fabrication machines discussed in this thesis. Although it is cheap, easy to use, and can cut a wide range of materials, its limitation of only being able to cut very thin sheets of material keeps it from being used very much by architects and students. In order to create complex forms with this machine, one must use a software program that can create complex surfaces and flatten them in order to define where the CAMM-1 needs to cut. This is a small effect on the design process for many architectural designers.

In general, the ability to create objects with digital fabrication machines has a huge effect on the design process. Instead of creating drawings and models by hand, architects and students create drawings and models in the computer. Different types of software programs and digital fabrication machines are used in the architectural design process, replacing tools such as the pencil, straightedge, and X-Acto knife. These machines, especially coupled with the software programs used to produce the digital models, cause new classes to be taught in schools and new positions in architecture offices.[17] Mixed feelings exist about whether or not students' and architects' heavy use of digital fabrication in the architectural design process is a positive occurrence. There are positive and negative effects on the field, but it does seem that the positive effects are outweighing the negative effects. If it were the other way around, the industry would not be seeing such wide use of these technologies. Most importantly, the architect, professor, and student must understand when and how each machine is most appropriately used in the architectural design process.

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[17] Examples are Larry Sass' *Design Fabrication Workshop* at MIT and Earl Mark's *Computer Numerical Control Fabrication* class at University of Virginia, as well as Kurt Komraus' title as *3D Coordination Manager* at Gehry Partners, LLP.

CHAPTER 6: CONCLUSIONS

Effects on the architectural design process arise from the architect's use of digital fabrication to make physical representations of architectural designs. The processes used when one utilizes these machines were originally developed for professions other than architecture, which is why using digital fabrication machines changes how architects work. Now that the effects have been presented, suggestions and cautions will be made concerning the use of machines currently available. An outlook on the attributes tomorrow's machines should embody will also be presented in section 6.2. To close, I will make some speculative remarks as to what the architectural community could expect in the decades to come.

6.1 Suggestions and Cautions for Today's Machines

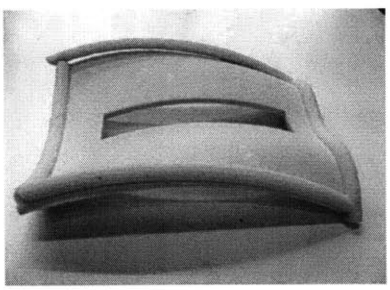

Fig. 62. 3D printed model used to display imperfections in a digital model. Model by Daniel Schodek.

Although architects, professors, and students are beginning to incorporate today's commercialized digital fabrication technologies into their design processes, it is not always in the best way. Through my survey and experiments, I learned how we can better utilize the tools we have at the moment.

The Z Corporation 3D printer is the most popular rapid prototyping machine among the architectural community. This is the first time that architects are faced with "printing" physical representations of their designs. Because architects are not accustomed to this process, yet are starting to use it quite heavily, they need to learn better ways of utilizing the technology (fig. 62). At MIT, students usually print their model and finish it with wax, even though there is more room for finishing and altering the model. One can seal 3D prints with different types of epoxies, which adds strength to the models, as well as sand and lacquer the surfaces to produce a more finished product. Because of the different finishing options available for 3D prints, the prints can work well for study models or final presentation models. One can also use the machine more strategically by printing an overall model in

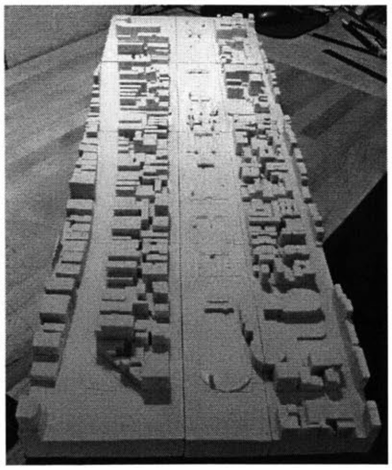

Fig. 63. 3D printed site model constructed in modules. Model by Josh Barandon.

sections to allow the replacement of updated sections of the design (fig. 63). This strategy is particularly useful for urban design and site models where much of the context will not change during the design process. One can also manipulate a 3D print by drilling or tapping holes into it. Manipulations must be done very carefully, however, due to the brittleness of the material, but some of the epoxies and powders now on the market strengthen the material significantly.

Milling models out of rigid foam on the Modela milling machine has advantages because it does not need to be monitored while milling. By utilizing this technology, one can create complex 3D forms without sinking too much time into it. However, there are a few cautions for designers I would like to address. Since this machine is relatively easy to use, students are particularly drawn to it when they want to mill an architectural component. Using the Modela can distract students, however, causing them to pay too much attention to the details too early on in the design process. Professors can become frustrated when a student with little architectural design education gets too caught up in the details. The user-friendliness of this machine can also lead an unaware student to believe that real manufacturing has the same qualities. The Modela doesn't mind if the part it is milling comes loose or the endmill runs into something it cannot mill; upon the slightest resistance, the machine will stop without causing damage to itself or the endmill. Manufacturing-scale machines, such as the HAAS, cannot be left alone because the machines can cause serious damage if they run awry. Also, using a material like foam to represent stainless steel parts is very misleading and non-machinists need to be aware that the material differences are great.[18]

The Denford desktop milling machine is best used for short assignments as a part of a design and fabrication class. In this setting,

[18] During a tour of TriPyramid Structures, students in the Design Fabrication Workshop realized the vast difference that exists between the stainless steel or titanium parts TriPyramid mills and the rigid foam or aluminum parts they were milling in class. Spring 2004.

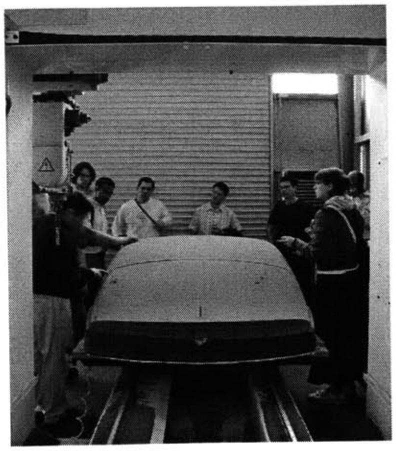

Fig. 64. *Design Fabrication Workshop* tour of TransFX, standing near a large multi-axis milling machine.
MIT, 2004.

a student is exposed to real manufacturing techniques that can be coupled with class lectures and tours of architecture offices and shops. A student should learn how the manufacturing process works through hands-on experience, but the concept is more successfully ingrained in the student if he or she has been exposed to professionals using these processes every day (fig. 64). If the student is assigned to use the Denford as a part of a short assignment, he or she will learn the basics of milling, yet will not feel too pressured about how much time it takes to complete the project. If students are left with the option of milling something on the Denford or the Modela, they will undoubtedly pick the Modela because it requires very little of the user's time.

I think the HAAS is best used for the same types of educational assignments as I suggested for the Denford. The benefits the HAAS has over the Denford are that the manufacturing process is more realistic and the milling operation is much faster. Since the process is complicated and tedious, it is essential for the student to be assisted by a professional machinist. This can be true for the Denford as well. Unfortunately not many architecture schools have a machinist as a part of the staff.

I focused on these four machines because I find they are having more influence, for better or worse, on the student's architectural design process than the other machines. My final suggestion of how these machines can be better used in architectural education is to create a class that incorporates the machines throughout all parts of the design process. If digital fabrication techniques are going to continue to be used in architecture, students need to learn when and how to use the machines appropriately during different stages of the design process.

The suggestions in this section are suggestions for how we can better utilize what we currently have. Through my research, I became aware of the possibilities that lie ahead for digital fabrication machines in architecture. I feel it is important to take that next step into the future to suggest the types of machines architects should be utilizing.

6.2 Outlook on Tomorrow's Machines

A problem with today's machines is that they are all developed for a professional field other than architecture and, therefore, embody many attributes that are not ideal for the architect. Through many of the interviews, as well as through my experience, I realized what attributes a future machine should have in order to be suitable for the architectural design process. Seven attributes of an ideal machine repeatedly surfaced throughout this investigation.

Price

The ideal price would be cheap enough that the one-person architecture firm could afford it. Many interviewees compared this ideal price to the price of a laser printer, digital camera, laptop, or color plotter. In 2004, the price range is $200 to $20,000; however, it appears that anything more than $10,000 is above the one-person firm's budget.

Speed

The ideal time it would take to produce a 3D object would be no more than five to thirty minutes. Many interviewees compared this time period to be equivalent to the time it takes to produce a large format color print today.

Size

The size of the ideal machine versus the ideal size of the output is a tough issue to tackle. Many people commented that they wanted the prints to be larger, around the size of a table for instance. There were even a few comments on how nice it would be to create house-sized prints. At the same time it seemed equally important for the machines to be smaller, around the size of a typical laser jet printer meant for the desktop. Of course a desktop machine is not going to print a house-sized object, but I found that there needs to be a happy medium between the two. I felt comfortable using the desktop machines, yet was frustrated by the size limitations of the output.

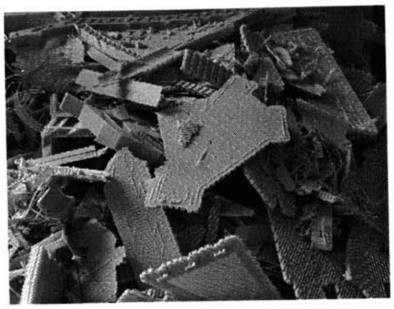

Fig. 65. Pile of support material waste accumulated over three months of constant FDM printing.

Materials

A majority of the interviewees commented on the need for a greater diversity of materials. Designers appear tired of the materially homogeneous 3D printed objects produced by rapid prototyping machines. The furthest we have gotten away from that in today's technologies is adding different colors to a print, but color variation cannot replace material variation. Many commented on the need for structural and manipulatable materials, as well. Quite frequently, the issue of environmentally-friendly materials was addressed. Currently there is no way to recycle 3D prints, yet technology makes it easy to create many of them very quickly. In the end, this cycle tends to produce large amounts of waste (fig. 65).

Build Process

The ideal build process for these 3D objects is a topic that is wide open for discussion and invention. Many people commented that the 3D printing process Z Corporation uses is very close to an ideal object-creation process, with the added suggestion of crisper, cleaner surface quality. Professors and students alike commented that they would like to see an RP building process developed that emulates the actual full-scale building process. The homogenous material that builds up in layers is far removed from standard construction processes in which many different elements come together to form a whole. Many interviewees also felt that there is a need to develop a method where one does not need to remove any support material. In all rapid prototyping processes, there is some sort of support material which must be removed from the completed object, which is usually a tedious process. Others commented on their desire to see a machine that allowed control of the material grains and tool paths which form the 3D objects. Quite a few people also mentioned their interest in being able to use a combination of media, even handmade materials, with the machine. In this case, the machine's fabrication process would be more integrated with the user's design process.

Interaction

The ideal machine should be able to interact with a wide range of media. In this system it would be possible for everything in the design process to talk to each other. The machine should have the capability to convert models into drawings and sketches into models. A designer should be able to manipulate a physical model and count on the machine to automatically update the digital model. The human and the machines would work together throughout the whole process. Architects typically work with all types of media and scales while designing and much of the movement between each step requires a lot of repetition. It would be incredibly useful to have a machine that would help cut down on the repetition and expedite the design process.

User-friendliness

Above all, the entire process of using this ideal machine must be completely user-friendly. Complex 3D digital models would not cause software programs to crash and no file conversion process would be needed to prepare for 3D printing. One could send a "print" to the machine from the software program that was used to create the digital model. The concept of using the machine would be easy to learn and there would be minimal setting up and post-processing needed during the process.

If all seven of these attributes were realized, architects would have their ideal machine. It would be an incredibly useful assistant to the design process. Even for the designers who still prefer to create sketches, drawings, and models by hand could benefit from such a device. I believe this machine would become as commonly used as the laser printer is today. Imagine sending a print of a materially diverse digital object, hearing the machine start processing the file, and picking up the "print" shortly thereafter without any post-processing or cleaning up. In section 6.3 I will speculate more about what we could expect of digital fabrication methods in the decades to come.

6.3 Speculative Remarks

These attributes help describe the bare minimum a machine for architects should be able to perform. However, there is still room for speculate even further into the future. If I make the analogy that it would be just as simple and common for us to print 3D objects as it is to print black and white laser jet prints, why not take it one step further and suggest that there could be the capability to print different quality models. If the print was meant to be a quick study model, one could print a quick, cheap "draft" print, using less material and printing at higher speeds. If one needed a high quality presentation model, one could print with the high quality setting that would take slightly longer to complete.

Take another step into the future and we can talk seriously about stereoscopic modeling. When I spoke to Mark Goulthorpe, he mentioned in passing that making models in the design process is all about modeling quickly and that physical modeling may not always be the best. Virtual screen representations are very quick and can still tell a lot about the design. Upon hearing this, I thought about bringing this idea together with the stereoscopic system John Nastasi has at the Stevens Institute of Technology. What if we could bring a quickly rendered 3D model which can be viewed in real-time together with EON Studio's stereoscopic system? We could be working on a model that, to the human eye, appears three-dimensional on a 2D screen. Not only could this be used in the design process, but for presentations as well. Instead of physically representing designs, architects could stereoscopically represent designs.

Prodding even deeper into the future reveals even more fantastic ideas. Alex Tsamis, a fellow SMArchS student, introduced me to the idea of a machine that can assign properties (materiality, transparency, conductivity, etc.) to individual 3D pixels, or voxels, in a voxelized cloud (fig. 66). The assignments could be made by programming each voxel rather than physically printing it. In a fabricating technique such as this, the door is wide open to possibilities. The architecture, engineering, and construction industry would be forced to reevaluate how we make buildings. A digital fabrication system like the one Alex suggests would also add another dimension to the architect's role in building design. By forcing a part of the architectural field to be more closely related to material science, designers would be able to assign material properties in order to create architectural objects.

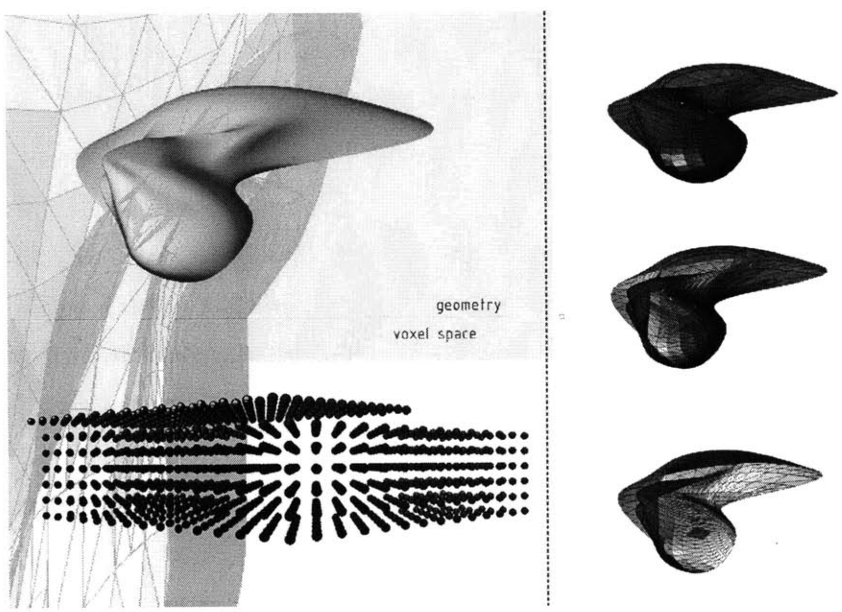

Fig. 66. Variable material definition of form, through voxel space, provided by Alexandros Tsamis.

Not only would materials start to change in buildings, but change in construction techniques as well. Many comments were made in the survey about the desire to see an RP machine that builds in a way that

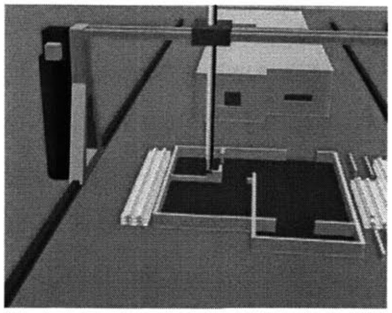

Fig. 67. Contour crafting of a concrete building.

suggests the real construction process. However, construction processes might start to emulate current rapid prototyping processes instead, constructing buildings in an additive layer-on-layer process. One example that is already on its way to becoming commercialized is Contour Crafting. [19] Developed by Behrokh Khoshnevis, this fabrication process constructs concrete buildings in a layer-by-layer fashion (fig. 67).

Digital fabrication has an increasingly important role in the architectural design process. We are just now witnessing how the use of these machines can alter designers' thought processes and the resulting designs. Architects, professors, and students must be aware of the benefits and challenges of each digital fabrication method and decide when it is most appropriate to utilize a given method. Designers must fully understand all aspects of the use of these machines in order to not fall victim to their misconceptions.

[19] Behrokh Khoshnevis, "Automated Construction by Contour Crafting – Related Robotics and Information Technologies," *Automation in Construction* 13 (2004) : 5-19.

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APPENDIX

Appendix A:
People Interviewed in Survey

A.1 Professionals

Blomberg, Charles. Personal Interview. 26 March 2004
(Director, Rafael Viñoly Architects)

Katz, Joshua. Phone Interview. 20 April 2004
(Provides 2D and 3D services for architects, EZ Track Solutions)

Kempton, Paul A. E-mail Interview. 1 April 2004
(Architect, Sasaki Associates, Inc.)

Komraus, Kurt. Personal Interview. 10 March 2004
(3D Coordination Manager, Gehry Partners, LLP)

Koontz, Paul. Phone Interview. 27 February 2004
(President, Denford Inc.)

Maitland, Jim. Phone Interview. 16 April 2004
(Manager of 3D printing operations, Service Point)

Mendoza, Rolando. Personal Interview. 12 March 2004
(Architect, Morphosis)

Palacio, Julian. E-mail Interview. 21 April 2004
(Architect, Office dA)

Smogorzewski, Caroline. E-mail Interview. 1 April 2004
(Architect, Ann Beha Architects, Inc.)

A.2 Professors and Supervisors

Alcond, Kirk. Phone Interview. 19 March 2004
(Shop Supervisor, UCLA Department of Architecture and Urban Design)

Domeyko, Fernando. Personal Interview. 19 April 2004
(Senior Lecturer, MIT Department of Architecture)

Goulthorpe, Mark. Personal Interview. 15 April 2004
(Associate Professor, MIT Department of Architecture)

Mark, Earl. Phone Interview. 16 April 2004
(Director of Computer Technologies and Associate Professor of Architecture, University of Virginia School of Architecture)

Nastasi, John. Personal Interview. 25 March 2004
(Program Director, Product-Architecture Lab, Stevens Institute of Technology)

Schodek, Daniel. Personal Interview. 6 April 2004
(Kumagai Professor of Architectural Technology, Harvard University Graduate School of Design)

Wampler, Jan. Personal Interview. 13 April 2004
(Professor, MIT Department of Architecture)

A.3 Students

Austin, Charles. Personal Interview. 14 April 2004
(MArch student, MIT Department of Architecture)

Barandon, Josh. Personal Interview. 8 April 2004
(MArch student, MIT Department of Architecture)

Barrios, Carlos. Personal Interview. 16 April 2004
(PhD student, MIT Department of Architecture)

Dahmen, Joseph. Personal Interview. 12 April 2004
(MArch student, MIT Department of Architecture)

Dorsey, Talia. Personal Interview. 15 April 2004
(MArch student, MIT Department of Architecture)

Hoang, Han. Personal Interview. 3 April 2004
(SMArchS student, MIT Department of Architecture)

Pejkovic, Jelena. Personal Interview. 3 April 2004
(MArch student, MIT Department of Architecture)

Sinisterra, Alexandra. Personal Interview. 2 April 2004
(SMArchS student, MIT Department of Architecture)

Tsamis, Alexandros. Personal Interview. 19 April 2004
(SMArchS student, MIT Department of Architecture)

Appendix B:
Benefits and Challenges of Digital Fabrication Machines

B.1 Roland CAMM-1 Vinyl Cutter

Benefits:

- Cheap: Base price per machine is $2,295.
- Easy to use: The user sends prints through Adobe Illustrator, a program many architects are comfortable with already. The machine is relatively simple to operate and not too many parameters to remember.
- Broad material palette: One has the choice of almost any thin, sheet material. Choices include papers, vinyls, acetates, copper or aluminum foils.
- Speedy cutting: An 18" x 24" sheet with many lines only takes about five minutes to cut.
- Precise cutting: Very precise, smooth cuts are made compared to cutting sheet material by hand, especially when the cuts are curved lines.
- Compact size: This machine easily fits on a desktop and consumes no more space than a laser printer.

Challenges:

- Limited material thickness: The CAMM-1 can only cut very thin, sheet material. The blade cannot cut through anything thicker than approximately 0.020". Majority of materials used in architectural models require some stiffness to support other elements and join with other materials. Very thin, flimsy materials are not needed very often in models which makes the demand for such a cutter lower than the laser cutter.
- Backing material required: Because this machine was developed to cut vinyl with an adhesive backing, any material an architect would cut on this, such as paper, needs to be adhered to a secondary sheet of paper with something like spraymount. This causes a sticky mess on the back of the

material that is being cut and either damages the quality of the material or is difficult to remove.

- Maintenance: One must pay attention to the sharpness of the blade which needs to be changed quite frequently, especially if thicker or tougher materials are cut.

B.2 Roland Modela MDX-20 Milling Machine

Benefits:

- Cheap: Base price per machine is *$4,495.*
- Easy to use: The MDX-20 is not quite as easy to use as the CAMM-1, but after one use students feel free to use it on their own. It is simple enough that with decent step-by-step instructions a first time user does not need any assistance at all. This machine also does not require the user to define any toolpaths or settings crucial settings. All one has to prepare is a digital model of what they want milled, the block of material, and insert whichever endmill they think is best to use.
- No babysitting required: This machine could be included in the rapid prototyping group because it does not require a person for any of the manufacturing – only the setup and clean up process.
- Compact size: The machine easily fits on a desktop and consumes no more space than a laser printer.
- Precise cutting: Compared to the 3D printer or FDM, this machine creates parts within 0.010" of their intended dimensions.
- Surface quality: Compared to the Denford, this machine can create 3D milling with a decent surface quality rather quickly.
- Good teaching tool: Students are exposed to the basics of milling through the use of this machine without having to go through the time consuming process of setting up all the parameters themselves. It gives an actual representation of milling as an industrial manufacturing process.
- Not time-consuming for the user: Although it may take a few hours to mill an object in this machine, very little of that time

requires the user to be involved. This helps give the student an appreciation for the time involved in using milling as a manufacturing method without making them be involved in every minute of the process.

Challenges:

- Limited materials: Because of the low power and speed of this machine, there is a limited range of materials that can be milled by it. Softer materials such as rigid foam, wood products, and acrylic are best. Rigid foam takes the least amount of time so it tends to be the most preferable material to use.
- Maintenance: The machine does not require too much maintenance, but it does need to be cleaned thoroughly after each use and during milling if larger parts are being milled. If too much dust gathers it can clog the motor or hinder the machine's movements. The rod, upon which the head moves back and forth, must also be oiled occasionally.
- Wrong assumptions: A challenge to professors of architecture trying to teach students the realities of manufacturing is that this machine tends to present milling as something which does not take too much time or effort. Milling rigid foam on a machine that the operator can walk away from is not directly correlated to milling stainless steel on a machine which requires constant monitoring. One must remain aware of these differences.
- Special environment needs: This machine creates a very loud, high-pitched noise when milling and requires a shop-vac for vacuuming shavings. These two issues require this machine to exist in a shop-like setting versus a studio or office setting. However, the shop must be a "clean" setting due to the computer that is required to run the MDX-20.
- Limited object types: This machine appears more conducive to making components of architectural details than building models. Since the milling process takes so long and building models usually have detailed components, openings, multiple

materials, etc., it does not make sense to use this machine to create models of buildings.

B.3 Denford Micromill 2000

Benefits:

- Relatively cheap: Base price per machine is $6,400.
- Good teaching tool: Using this machine helps the student appreciate the amount of time and coordination that goes into milling a part out of aluminum. The user has to setup the toolpaths and create the code that runs the machine. The user must also stay with the machine to monitor it while it is operating and periodically clean off the metal shavings so they do not get in the way of the end mill.
- Broad material palette: In addition to aluminum, the Denford can mill many other materials such as rigid foam, woods, acrylics, and if one were patient enough, harder metals such as steel.
- Material reality: Some architectural components are made from aluminum, which can help the student understand actual material properties.

Challenges

- Wrong assumptions: Although the Denford gets a student closer to the actual manufacturing process and materials, it still does not represent that process accurately and causes students to idealize that process.
- Short runs only: The Denford Micromill 2000 was originally intended as an educational tool for machinists and engineers, not as a manufacturing tool. The motor on the milling machine was set up to endure a low amount of heat, and the longer the machine runs, the more heat is generated. Therefore, longer milling operations cause the machine to shut down after the first hour of operation, and once the machine is running again, it continues to shut down every 30 minutes thereafter. This is

frustrating for someone giving up so much time already to mill an object.

- Time-consumption: The Denford is a more powerful machine than the Modela and cannot be left alone during a milling operation. This requires the user to monitor the machine for the entire time it is running. This either forces people to design smaller parts or use a significant amount of their time monitoring the machine, which is not acceptable for busy professionals and students.
- Scariness: Many people think this machine is "scary" because of its high speed and relative unpredictability. Architects are not machinists which means they are not trained to know every detail of machining. The typical architect does not know what to watch out for during the course of milling an object.
- Special environment requirements: Like the Modela, the Denford requires a shop-vac and space where noise and mess is not an issue. Thus, it cannot exist in an office or studio, but should be in a shop.
- Material preparation: Aluminum is the material of choice to mill on the Denford yet most architecture schools and offices only have easy access to cut wood, not metal. Many schools have a metal shop, but the metal cutting machines are often not as accessible as the wood cutting machines. Extra time and effort is required of the student in order to get a block of material prepared for milling.
- Too many variables: For someone that is not a trained machinist, the Denford embodies too many variables, which leaves a lot of room for errors to occur. The variables include endmill diameter and length, feedrate, spindle speed, depth of cut, stepover distance, material, cleaning and oiling all moving parts of the machine, and tightening screws on moving parts of machine.

B.4 Stratasys FDM 2000

Benefits:

- Relatively cheap: Base price per machine is $24,900, which is cheap compared to other rapid prototyping machines.
- Makes the impossible possible: A benefit of the FDM that is common to all rapid prototyping methods is that forms generated in the computer can become physical realities, even if there is not a way to fabricate them at a larger scale with a different material.
- Robust models: Unlike the ZCorp, FDM models are very strong. The robust, ABS material is conducive for designers to simulate the connections of architectural details.
- Small size: The machine takes up relatively little room.
- Minimal post-processing: If the machine is set up correctly, there is minimal post-processing. The support material must be removed, which is usually a quick process.
- Little user time required: Although the printing process takes longer than the ZCorp's, the overall process requires very little of the user's time.

Challenges:

- Training required: Although the Stratasys is not too difficult to use, there are many steps to remember in preparation for printing. A new user needs to go through a few times of using the machine before he or she can remember all of the steps.
- Poor surface quality: Some of the students I interviewed commented that they did not like the surface quality of the FDM prints. I think it is especially apparent when curved surfaces are printed. This causes the machine to not be well suited for surface verification studies.
- Lack of precision: The thickness of the material determines how thick a print will actually be. With some testing, however, one can get a "grasp" of the tolerances and design for them.

- Not much manipulating: FDM prints do not appear to be conducive for a high level of finishing, such as sanding and painting.
- Long printing time: The Stratasys prints one line at a time so it takes longer for this method to create the 3D object than the ZCorp takes time to print. At the same time, there is almost no post-processing and very little human interaction which makes the overall process take less time. Something about the instant gratification of seeing the object, even if not complete, tends to make people not appreciate this machine as much.
- Orientation of print: The orientation of the print in the machine makes a big difference in surface quality.

B.5 Universal Laser Systems X-660 Laser Platform

Benefits:

- Broad material palette: A large array of materials can be cut on the laser cutter with thicknesses up to about 0.250". The materials include paper, chipboard, museum board, wood, and acrylic.
- Shorter model building time: The laser cutter requires less time to cut parts, especially if there are many parts or parts that are repetitious, curved, small and delicate, or scored.
- Precise cuts: Cuts made on the laser cutter are very precise, clean cuts. They make for nicely finished, precise models. Many people appreciate the precision for larger models where flaws are more noticeable. Laser cutting also makes is possible to score and cut very fine details on a model, helping it convey more information.
- User-control: The user has control over the speed of the cut and the intensity of the laser beam. Depending on the combination of these two aspects, the beam will either cut or score the material. The intensity of the scored line can then be altered to be lighter or darker.

- User-friendly: Since most architects know AutoCAD and how to plot from the program, the laser cutter can be considered user-friendly. The process of sending a "print" to the laser cutter is synonymous with sending a color plot with varying line weights to a large format color plotter.
- Alteration-friendly: Since the files that are created for the laser cutter are AutoCAD drawings, it is very easy for one to alter the file and resend the file to the laser cutter. "Prints" are sent directly from the AutoCAD program to the laser cutter so it is possible to make a quick change to the file immediately before sending the file.
- Scalable to shop manufacturing: The laser cutter found in many architecture schools and offices is very close to being directly scalable to the actual laser cutting process. By using this machine for making architectural models, one will have a conceptual idea of how laser cutting a large sheet of stainless steel works.

Challenges:

- Training required: Although the laser cutter is rather simple to use, it is ill-advised to use the laser cutter before going through proper training. The machine is expensive and significant damage can be done if the user is not aware of all issues. The laser cutter can even become dangerous if someone tries to cut a material that they aren't supposed to. Some materials are flammable, while others are reflective which can redirect the laser beam out of the machine, causing damage to surrounding surfaces or even the user.
- Expensive: The 18" x 24" bed laser cutter is the minimum size to be most useful for architects and is expensive ($25,050). As described earlier, the laser cutter's price falls outside of the usual range architects spend on peripherals; thus, they are not found very often in offices, but outsourced frequently.

- Too precise: Some think that laser cut models tend to be too perfect which kills the spirit of a model.
- Carried away with details: Since the laser cutter allows such fine cuts and scoring, it is easy for someone to get carried away with details that are unnecessary at a particular phase of design. There is no need for doorknobs in a schematic model.
- Special environment requirements: The laser cutter creates fumes and smoke which must be vented out of the room. This requires some sort of ventilation system to be installed and at the same time pollutes the space with smell and noise.

B.6 Z Corporation ZPrinter 310 System bundled with the ZD4i Depowdering Station

Benefits:

- Makes the impossible possible: This machine is capable of printing objects that are either impossible to accurately make in any other fashion or would be very time consuming.
- Nice surface quality: Prints made in this machine have a smooth, crisp surface quality.
- Precision: Prints are typically within 0.010" of desired dimensions in all directions.
- Wide range of post-processing techniques: The typical method for sealing a ZCorp print is to dip it in the hot wax and let the was soak in and harden. Other finishing possibilities include embedding the model with different types of epoxies, or sanding and painting.
- Fast printing: Although the post-processing can be time-consuming, 3D printing an object takes very little time. Especially if a sketch model is needed, one does not even need to finish the model.
- Very user-friendly: I think one of the reasons this machine is more popular than others is that the ZCorp is extremely user-friendly. Sending a print is very similar to sending a print to a laser printer. There are only a few steps one needs to remember.

- Strength can be found: 3D prints are known to be extremely brittle; however, as one embeds epoxy the model becomes quite strong.
- Physical check of digital model: The danger with three-dimensionally modeling architectural models in the computer is that sometimes flaws appear in the model that can easily go unnoticed. 3D printing is a quick way to conduct physical checks of the digital model to be sure everything is modeled appropriately.
- More models in less time: Many models can be printed at the same time in this machine by organizing the models to "float" above each other.

Challenges:

- Expensive: At $31,800 per machine, this machine is considered too expensive by most architects.
- Very brittle models: The 3D printed objects are very brittle when first extracted from the machine. It is very easy to break the print during this extraction process, during the post-processing, and during transporting even after the object has been cured with wax or epoxy.
- Tedious post-processing: Although printing an object on this machine is easy and fast, the process of removing the object from the machine, curing it with melted wax or epoxy, resetting up the machine and cleaning the mess that has accrued through all of this is a very long and tedious process.
- Special environment requirements: Working with the powder and wax or epoxy for the ZCorp generates dust, fumes, and noise, which requires a shop-like environment. The 3D printer also needs space since it comes with a depowdering machine. I see it as synonymous to having a diazo machine in architecture offices, which create unpleasant fumes, yet can be placed in a nearby room in an office.

- No fragile designs: Because the prints are so brittle, slender elements such as columns and rods will not work on these prints. Slender elements will surely break at some point during post-processing.

B.7 HAAS Micro Milling Center

Benefits:

- Wide range of materials: This powerful machine is capable of milling many different types of materials, from foam and woods to stainless steel and titanium. The only difference is that the harder materials will take longer to mill.
- Fast manufacturing: Of course, this means that everything should working smoothly, which in my case usually did not. But if one has a machine in good condition, being operated on by a well-trained machinist, making an object on this machine is very fast compared to other milling machines.
- Real manufacturing: This machine is synonymous with the milling machines used in fabrication shops. Real prototypes of components can be made in the HAAS, so there is no mistaking the qualities of the material.
- Helps appreciation: When a non-machinist goes through the process of preparing a file to be milled on this machine and mills an object, he or she learns to appreciate what a machinist does. A high level of attention must be paid to the details and it is not easy for someone that is not fully trained on this machine.

Challenges:

- Price: Too expensive for most architects with a price of $39,999 per machine.
- Difficult access: More so than the OMAX, it is difficult to obtain access to this machine. Architecture schools typically do not own manufacturing scale milling machines. That means the use of this machine must be coordinated with another person in

another department. I have access to one and needed assistance every time I needed to use the HAAS.

- Constant monitoring: There are many dangers that go along with this machine and therefore the HAAS must be monitored the entire time it is running. Even though the process may be quicker than a machine like the Denford, the process is still time consuming.
- More to manufacturing: Like the OMAX, this process of manufacturing is close to the real thing, but it still fails to shed light on other parts of the manufacturing process.
- Too many variables: There are an incredible amount of variables to keep track of to use this machine which means a huge amount of room for things to go wrong. Unless the user is someone who knows this machine well, chances for something to go wrong are high.
- Scary: Generally, this machine is described as "scary" because of the chance for things to go wrong and the high speed at which the spindle spins. Serious damage can be caused to the machine, the stock, and the operator if the machine isn't operated correctly.
- Time consuming: All of the steps required for the user to take to prepare the G-code for the machine, prepare the stock, and get the machine set up take a lot of time for someone that is just learning this machine. Most architects fall into this category and with so many things to learn and all the variables that go wrong, using the HAAS frequently takes longer than if another fabrication machine were used.

B.8 OMAX Waterjet Cutter

Benefits:

- Wide range of materials: Not only can one cut almost any material in this machine, but one can also cut a wide range of thicknesses and sizes. The only materials one should stay away from are materials that cannot be subjected to water.

- Real manufacturing: The OMAX's manufacturing process is synonymous to the processes used in manufacturing shops, so there cannot be any wrong assumptions made from using this machine. Because of this, full-scale mockups are possible.
- Relatively easy to use: The concept of how to use this machine and monitoring it are fairly simple. What keeps it away from being very easy to use is that the user must decide what toolpaths are needed and settings must be taken into account. Since the machine is working at a very high pressure, it can be dangerous and the user needs to know what those dangers are.

Challenges:

- Price: As the most expensive machine out of the eight, it is definitely out of the architect's price range ($119,000).
- Not studio based: For a few different reasons this machine is usually not practical for the typical architecture studio. In school, models are usually kept to more manageable materials and sizes which usually do not require such a robust machine. In practice, the use of waterjet cutters is usually rare enough that it makes sense to outsource versus owning and maintaining one.
- Not accessible: Since this machine is not as needed in the architectural studio as other machines, one must go out of his or her way to use the machine when it is needed. I have access at MIT to two waterjet cutters, but they are both outside of the architecture department. Also, most architects are not trained well enough in using the waterjet cutter to do it on their own which means there is the added difficulty of scheduling a time with someone who can assist.
- More to manufacturing: Although this process of manufacturing is close to the manufacturing processes used for buildings, it still fails to shed light on other parts of the manufacturing process.