

Materializing design: the implications of rapid prototyping in digital design

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Rapid prototyping (RP) today is absorbed into practice and is being recognized as a significant technology for design. This paper attempts to formulate key aspects of the design methodological framework that are coalescing with RP's capability to build artifacts as part of the creative design process. In doing so, it attempts to formulate questions and issues of RP as a design medium that supports the full spectrum of digital design as a paperless process. These issues have been the resultant of early experimental and hands-on involvement with RP technologies in research and educational environments. In this paper, a DDF method (Digital Design Fabrication) is introduced. The DDF method is a two-stage process of working that integrates generative computing and RP into one process. Together they support a process to generate diverse candidate artifacts as solutions to design problems. Through a presentation of issues, procedural observations, and research findings, a range of potential applications of the DDF model are defined and presented. It demonstrates a process of design situated between conceptual design and real-world construction.

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Physical modeling is one way through which designers realize mental concepts (Cuff, 1992). As a design representational medium, the model making process can lead to new forms beyond the original concept. Physical model making is not new to the profession of architecture. For hundreds of years model making has served as an intermediary between complex design ideas and the construction workers. When designing the Vatican, Michelangelo used physical models as an intermediary to describe construction techniques and the form of internal spaces to both clients and stonemasons (Millon, 1994). Palladio in the 16th century also used intermediate models of wood as full-scale mockups to explain buildings to masons (Burns, 1991). Today,

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computer model making affords opportunities not only to create complex shapes, but also to serve as intermediary between design and construction.

Material representation from digital files is a seminal development among the current applications of digital media in design processes. As the set of technologies known as rapid prototyping (RP) emerges and is absorbed into practice, it is being recognized as a technology of great potential significance for design. As schools of design and design professionals begin to incorporate rapid prototyping devices within the design process, issues of this mediated relationship begin to be centered less on the characteristics of the machinery and more on the nature of the design process. After the first wave of experience we are beginning to formulate approaches to methods to produce designs with these devices as part of the design environment. A characteristic of these approaches is that RP can potentially support a comprehensive and integrated environment to study form, space making and the physics of materials relative to machine processes in construction. The simultaneous conceptual manipulation of spatial—configurational, physical—behavioral and material—constructional aspects of design within RP technologies appears to present a truly unique potential for integrated design. Beyond the design-related and material-representational benefits of RP within overall design and fabrication processes, there also appear to be significant pedagogical benefits to be derived from these technologies.

1 RP as design environment

Creative fields are characterized by the generation and manufacture of objects for reflection and evaluation (Schon, 1983). Painters manufacture sketches as products of their creative process exploring the possibilities of composition in the form of pencil drawings or monochrome wash prior to a finalized painting. Architects explore many design possibilities through design sketching, hard-line drawings and physical models, manufacturing artifacts for the exploration of diverse ideas (Kroes, 2002). Currently, many architects use digital design to manufacture shape and space including advanced technologies such as generative modeling methods with parametric modeling and CAD scripting.

This paper attempts to formulate certain key aspects of the design methodological framework that are coalescing with RP's capability to build artifacts as part of the creative design process. In doing so, it attempts to

formulate questions of RP as a design methodology in support of a paperless design and construction process. These general design methodological issues have been the resultant of early experimental and hands-on involvement with these technologies in research and educational environments. Through a presentation of issues, procedural observations, and research findings we define and review a range of potential applications of RP as a medium of design process. The work described here is situated between two areas of research and design practice. The first is the exploitation of RP in the early stage design and the creation of designs as 3D shapes with attention to material detail. The second field is an emerging interest in the final building as a model of production. Here, among other approaches, *building product modeling* is a downstream method to generate models and information of building construction (Eastman, 1999). The work described in this paper attempts to synthesize these two emphases of *conceptual stage materialization* through RP and *construction information modeling*. It demonstrates a process of design situated between conceptual design and real-world construction. Research examples conceptually demonstrate a method to integrate these two fields. In the case of our research we have exploited shape grammars for form generation in conceptual stage design and building product modeling as a construction information model. However, we view the coupling and continuity of early design models with construction information models as a general problem of integrated design process beyond any particular formal models that we may have applied.

Over the past decade, there has been a rapid increase in the volume of high-profile international projects that have been designed digitally. Among this increasing proportion of digitally supported designs, many have also been characterized by shapes and spaces that are complex to build. In many cases, these visionary projects were conceived with little initial consideration for construction. Today, many designers strive to realize their concepts in construction through the use of CAD—CAM technologies applied to digital designs in the concluding stages of the design process. The most outstanding example of this phenomenon is the work of Gehry Partners whose design practice builds complex shapes as physical models made conventionally of paper, cardboard and wood. Designs are later realized for construction through the use of parametrically based software and CAD—CAM manufacturing techniques (Lindsey, 2001). In summary, in many significant examples such as that of Gehry, computing was introduced after early phase design work has been completed by conventional means.

Alternatively, for certain designers, RP may be used for finalized design representation or to study complex forms as physical artifacts. A major advantage of RP is its ability to manufacture high quality material representations for complex designs. The design process with RP also supports the creative process of designers to produce variations of a single artifact or diverse artifacts at various stages of design.

Research questions explored in this paper are the definition of processes that are needed in order to support various aspects of *RP integrated design*. Furthermore, we attempt to define the potential innovations that may be attributes of these new processes. Finally, we consider the question of the integration of RP into the design process to act as a bridge between formal methods in early stage design computing and later stage building information models including the core-model support of CAD–CAM machinery in construction.

1.1 Outline

This paper presents work and research findings on a methodology of digital design with the use of rapid prototyping in design. Theoretical points are introduced by examples from design explorations conducted as part of ongoing research projects. The paper begins with an outline of the technology and background of the use of RP for architectural design. We briefly provide a discussion of design creativity that introduces a method of working from an engineered process of artifact manufacture. A presentation of RP-based digital design and digital fabrication defines the characteristics of both fields and the advantages that come from the integration of the two areas. Issues developed from this new integrated process are demonstrated with examples. The paper concludes with a presentation of two examples illuminating possible solutions to process issues.

2 Rapid prototyping for the production of digital designs

2.1 Desktop manufacturing

Rapid prototyping (RP) is one half of a larger field identified as digital fabrication (DF), a field that spans the application of RP for design and CAD–CAM for construction (Kolarevic, 2003). Much has been written on the taxonomy of RP devices and their application to design and engineering fields (Jacobs, 1992; Cooper, 2001; Chua et al., 2003; Gebhardt, 2003). Invented in the mid-1980s, RP has been used mainly by

Figure 1 Vinyl sign cutter used to cut paper surfaces as 2D files from CAD models



product and industrial designers to demonstrate design concepts to clients through physical models. Conventional methods to produce such models start with a computer model which outputs to a file for a specific device that is manufactured typically in one or two business days. There are three common RP devices each of which is a smaller scale version of machines found in real-world manufacturing environments. First are *2D cutting devices* such as vinyl and laser cutters; they are the most common and are frequently used by designers and architects to build models of various sizes and materials (see [Figures 1 and 2](#)). Next are *subtractive devices* in the form of milling machines for desktop design; these machines tend to carve from foam or other softer

Figure 2 Laser cutting of 1/16" thick cardboard

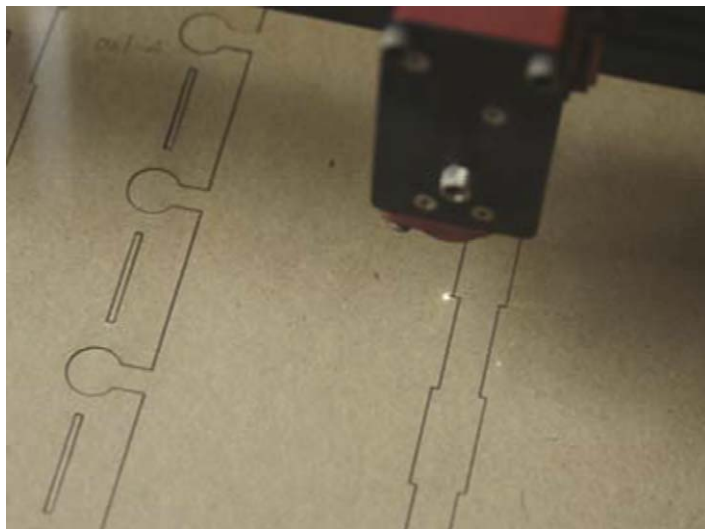




Figure 3 Micro-mill used to carve foam

materials (see Figures 3 and 4). Finally, there are *additive manufacturing devices*; these machines build solid models from loose powders or liquefied plastics (Figure 5). All three manufacturing types are intended to translate from RP devices to real-world construction and are generically known as CNC devices (computer numerical control). CNC cutting and milling has been around for a number of years. Recently, real scale manufacturing 3D printing is being developed for concrete and metal 3D printing (Khoshnevis, 2004).

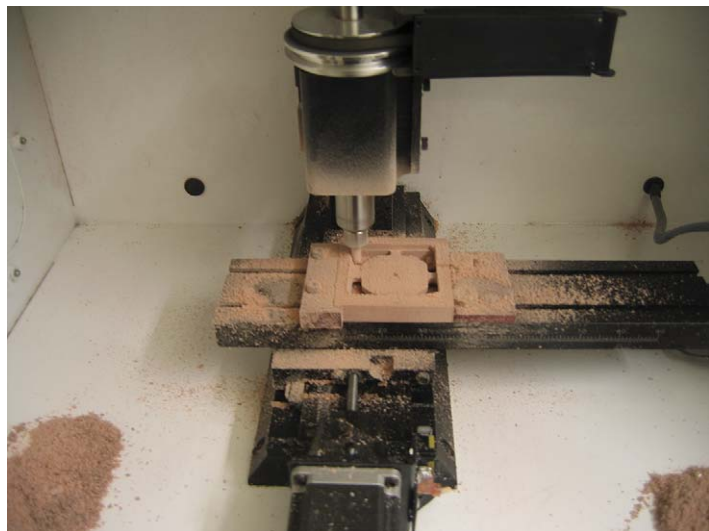


Figure 4 CNC high speed drill that carves shapes into foam and aluminum from CAD file

Figure 5 Free-form structure
built of laser cut acrylic sheets
and 3D printed parts



2.2 Traditional methods of RP in architectural design

For architects, RP was formally introduced by [Streich \(1991\)](#) as a method of translating three-dimensional models in CAD to RP models, in particular, with stereo-lithography. Later, the concept of manufacturing architectural ideas in early stages of design was described by [Ryder et al. \(2002\)](#), as a method to generate physical descriptions of design ideas. Their methods of manufacture included seven differing types of rapid building devices from stereo-lithography to selective laser sintering to 3D printing as a survey of RP processes and application methods for architecture. Simondetti presented RP and CAD—CAM methods of manufacture for small-scale 3D printed objects to full-scale design representation. He noted that full-scale models advance the cognitive processes of design by physical demonstration of structural behavior as well as visual presentation ([Simondetti, 2002](#)). These papers describe what might be considered as traditional methods to model and manufacture artifacts of varying materials using RP.

2.3 Generative models for design and their role in RP

An alternative method to model and manufacture with RP devices is to apply *generative modeling* facilitated by the use of design functions in CAD software. This method builds solid geometry for manufacture as 3D objects based on parametric constraints. One such approach to generative modeling and RP combines shape grammars as an organizing principle for shapes with solid modeling, and the resulting objects are manufactured as physical objects with stereo-lithography machines ([Heisserman and Woodbury, 1993](#)). These researchers presented

a grammar interpreter that generated robust designs for manufacturing. A second generative technique also investigated a method to apply shape grammars as an organizing principle and solid modeling to generate early design phase models (Wang and Duarte, 2002). They present a computer program that generates shapes based on design constraints. In their approach, shapes generated as solid models were manufactured with FDM 3D print techniques.

In general, generative methods to model and manufacture designs with RP are an effective basis to address issues of production speed and redesign time. Two practical shortcomings of generative methods are the technical limitations of access to solid modeling functions when programming within existing CAD programs. Also, the two generative methods presented above generated shape models without architectural features (windows, doors, etc.). This work indicates that with respect to advancing the integration of generative approaches and RP modeling in design, high-level programming skills are required for the production of sophisticated and highly detailed designs.

2.4 Generative models for construction

There are other methods to use RP models in design to generate 1:1 scale objects with CAD scripting and programming for real-world construction. Currently, there exist downstream methods to generate geometry for manufacturing of the final components or formwork for real scale manufacturing. First, professional CAD–CAM software companies such as Tekala and CATIA offer predetermined forms for steel connections and analysis. Second, there exist simpler methods to generate friction fit key joints in CAD that join sheet metal edges in any configuration (Kilian, 2003). This program creates key joinery for two or more planar sheets of heavy gauge sheet metal, the parts of which are processed by water jet cutting. A third example of a downstream process was introduced as a rule-based computer program used to fabricate lightweight sheet metal for casings for electronic devices (Soman et al., 2003). Rules within the program are based on metal material and assembly properties. The program contains rules for notching, bending and punching sheets of metal. While real-world computational methods are fast to generate, actual machine manufacturing of real-world materials for complex objects and geometries is still time consuming and complex. RP methods aid conventional modeling and manufacture methods by reduction of time wasted in the manufacturing of simulations.

2.5 Complexity, quality and time

One additional asset of digital fabrication is the quality of its output. Models printed in 3D or production with laser cutting technologies support high levels of accuracy, and there is no mistaking the high quality of the artifacts produced by current rapid prototyping devices. For example, 3D prints of Palladian villa models demonstrate many levels of detail down to leaves and scrolls on column capitols (Sass, 2003). For assemblies, the precision of digital fabrication allows for glue less/friction fit connections between parts, thus speeding up assembly time (see Figure 5).

Associated with any means of manufacturing are issues of time required to generate usable schemes in CAD and manufacture parts. For RP technologies, the construction of computer models and manufacturing time are currently far more extensive than those required in hand drawing or hand model making. The trade-off for designers is quality against time, and these technologies should therefore be selectively applied in appropriate design situations.

3 Digital design and digital fabrication

3.1 Digital design

The term, digital design, has taken on various meanings and definitions. Frequently the term has, in architecture, been associated with the representation and manipulation of complex form and space. However, the idea of unique processes of digital design, as differentiated from traditional paper-based design, most significantly implies a self-contained way of designing exclusively within a computational environment. How then does RP fit into, and integrate with, other classes of activities, operations, facilities, knowledge and reasoning that together form computational design environments?

Digital design as a method can be generically described as a constructed relationship between information and forms of representation that support design in computational environments. As we have seen this may, or may not, also include data regarding materialization and, even, construction data. Alternative methods of digital design are distinguished by their task specificity or by their comprehensiveness in a 'core-model' approach. For example, in construction-level design and representation it is common to find wire-frame renderings used to describe the components and workings of complex constructions. Parametric modeling programs such as CATIA can provide data and representations of design

projects as descriptions of the inner workings of the building's construction system.

It is clear that current definitions of digital design still differentiate between design environments and building information/construction data environments. Concepts of RP and DF tend to reduce these distinctions in digital design, to emphasize the continuities and continuousness of design, materialization and construction.

3.2 Advantages of digital fabrication

Digital fabrication for designers offers realistic opportunities for shape representation, evaluation and redesign of complex design initiatives. One asset worth noting is that digital fabrication extends learning in a digital design environment by engaging the designer with materials and machine processes similar to those used in construction. It may also be said that the use of these appliances and software extends creative design beyond the early stages of design and supports the continuity of design through its various stages. Not only is this an advantage in design, design materialization also has certain didactic advantages that support the acquisition of knowledge and the learning of design procedural structures (Oxman, 1999, 2003).

Another advantage is the development of knowledge of shape and future possibilities for real scale 1:1 fabrication (with, or without, larger CNC materials; Khoshnevis, 2004). For example, doubly curved dome structures built with curved surface modeling programs may be too complex to build by hand from a computer file (see Figure 6). Such



*Figure 6 Dome structures 3D
printed of plaster*

Figure 7 Model built of developable surfaces where each side is curved in one direction. Built in CAD manufactured using the vinyl sign cutter, flat shapes are glued together to build the object



shapes, though too complex to visualize by rendering and animation alone, are manufactured with ease using 3D build technologies. Digital fabrication also offers the possibility for study and invention of new construction systems for the support of complex design forms such as developable curves typically used by Gehry Partners (see [Figure 7](#)). Other aspects of innovative designs such as the building's assembly method can be tested and evaluated beyond dependence upon imagery. The assembly design process engages aspects of manufacturing early in the design process and supports constructive aspects of learning, as well. The illustrated examples support a design method of learning by trial and redesign. The advantage for design computing is that in such approaches knowledge can be represented in the form of parametric constraints and associative modeling that support processes of design change and remodeling.

3.3 Design learning in digital fabrication

A major characteristic of DF is the enhancement through materialization of the concept of learning by doing. An important attribute of learning in design is acquisition of processes of redescription or redesign based on acquired knowledge from a previously described artifact ([Oxman, 1999, 2003](#)). Here, DF contributes new dimensions to design learning.

Digital fabrication for RP and CAD–CAM fabrication is a relationship between modeled geometries and material properties. Critical links between CAD–CAM and RP are machine processes and materials

selection and design. Materialization as a way of designing fulfills Lesgold's presentation of *learning by doing*, which he defines as an opportunity to manage the full domain or real life experiences through activity-based learning. He argues that it is necessary to combine rules with conceptually based activity as a means to prepare people for real-world experiences (Lesgold and Nahemow, 2001).

The connection to materials for either design or construction quickly builds skill sets for rule-based design from the relationship between materials, modeled geometry and machinery. The characteristics of working with a particular material with RP machinery link cognitive design skills to modeling geometries. For example, plywood is embedded with geometric rules based on the limits of a flat sheet of stock material. Geometries are constructed in CAD as planar geometries and then translated into a model for laser cutting or CNC cutting with a flat bed wood router. If generative methods are used, rules for plywood are based on rules for the manipulation of flat sheet stock. Laser cutting cardboard flat stock material acts the same as the cutting of plywood; in essence the rules of the material are the same. For design evaluation, the only difference is that sheet material can be cut and assembled more rapidly using laser cut technology.

3.4 *Digital design fabrication*

The integration of digital design and digital fabrication extends many opportunities to design constructible solutions at many levels of complexity. Current methods to design and construct buildings using computers tend to fall into two categories depending upon the emphasis on either design visualization simulation or construction information. On one side is the production of imagery and animations to describe designed objects and their performance. On the other side is product information modeling where CAD models are generated to explain and guide physical construction. An inherent characteristic of this approach considers construction as a function in the design process and not the result. Digital Design Fabrication (DDF) is computer modeling applied to the design process from early stage design, including materialization and up to, but not generally including, detailed project information modeling. DDF represents building information as material and product models. However, these models are designed to *support constant and significant degrees of change* based on visual and performative evaluation. DDF in its ultimate sense is a materialized, parametric, and an interactive design.

4 Digital design fabrication (DDF): toward a method for integrating RP in design

The emphasis of this paper is on defining and developing methods of working with RP in continuous processes of design conceptualization, materialization, and fabrication design. This approach to a continuous integration of RP in digital design processes is seen as differentiated from discrete procedural stages of design computing, fabrication and product information modeling.

4.1 Procedural methods of product design as a model for DDF

The process of product modeling may be closer in nature to the continuous materialization methods of digital design proposed in this paper than are conventional design methods. The procedural methods of product design include the process of model making where designers manufacture many artifacts (computer and hand) for evaluation. The models are also managed for other issues beyond appearance, including production.

The product design process includes a review of many aspects of a product from design analysis to design synthesis and evaluation (Pahl and Beitz, 1988). Designs are studied to find and solve general problems as well as localized problems by isolating the product's function followed by a process of reasoning to solve product problems (Cross, 2000). For a cogent review of the product design relative to managerial methods, Smith and Morrow offer insight into the background and methods. Most important for our work, they define a clear distinction between architectural and product design. They note that engineering models are frequently designed as linear processes, while architectural process models are ill-structured leading to a process that is built mostly on cognition and perception (Smith and Morrow, 1999). Rapid prototyping is becoming a major facilitator of design production for product designers. Typically used to view products at all phases of the process, rapid prototyping can be used to demonstrate a product's functional and ergonomic makeup. In the analogy to product design, architectural exploitation of DF must include systematic ways of working that with flexibility in order to accommodate the ill-structured nature of architectural problems.

4.2 CAD—CAM and implications for DDF

Current architectural construction has seen a rise in CAD—CAM machinery for fabrication as an intermediary between design concepts

and real-world construction. Over the past decade, the design profession has witnessed many methods to construct designs using digital fabrication at the level of real manufacturing (Matsushima, 2004). Particularly common is large CAD–CAM machinery used to bend and cut metals from CAD files in the form of G-Code. The CAD–CAM building fabrication process may be considered as a way of building; it is also a way of thinking about construction through the interaction with machinery. Shortcomings of CAD–CAM as a method for teaching and learning are that the first time CAD files are materialized physically is typically the final time they are fabricated. Most materials created in this way are full scale, 1:1 models typically manufactured of nonrecyclable materials such as dense foam or fiberboards. Also CAD–CAM machinery is large and very complex requiring physical space and very skilled labor to run machines.

4.3 The potential of DDF as a design method for integrated and continuous materialization

A goal of the process is the production of effective technical artifacts with a variety of functions. A technical artifact is described as an object with a technical function of a physical structure designed and made through conscious production (Kroes, 2002). Kroes states that the nature of design must consider the method used to generate these artifacts. Within the method are also issues of design process and design product. A sketch on paper works as a technical artifact with functions such as the construct of space or 2D diagramming for orientation. Alternatively, rapid prototyping produces very technical artifacts whose functions can determine a building's form, internal spaces, construction methods and materials. Digital design as a process generates a variety of technical artifacts for visual evaluation, typically in the form of a 2D presentation (computer renderings and 3D computer models). Fabrication externalizes technical artifacts for physical as well as visual evaluation. An effective design process can use RP technology for structural models, shape and formal models, interior models, etc.

The field of DDF is attempting to achieve a synthesis of the design flexibility of conventional paper-based design, the precision and modeling capability of digital design, and the knowledge construction information models. The intention is to develop an environment to support design through the interaction with physical artifacts production that is characterized by both the flexibility of sketching and the precision and data handling capacity of product description environments. Materialization environments for design have these two poles of behavior that are

potentially contradictory: flexibility in support of the design process versus exactitude and detailing capacity characteristic of CAD–CAM modeling packages.

5 *The DDF (Digital Design Fabrication) model of design*

In this paper we introduce the DDF (Digital Design Fabrication) method. The DDF method is a two-stage process of working that integrates generative computing and RP into one process. Together they support a process to generate diverse candidate artifacts as solutions to design problems. DDF models also support physical evaluation of object form, structure, lighting, etc. versus reasoning from drawings or virtual imagery. For architectural design, model size is significant. Small-scale models support formal evaluation, while larger-scale models are needed to complete spatial evaluation, and even larger-scale models enable study of detailing. This *design scalar sequence* is also significant to computing, since different classes of data are required for each scalar level.

Our proposed DDF method combines RP production with automated generation of design variants. However, many of the findings reported here regarding the use of RP in design are valid even for conventionally generated CAD models. The DDF method integrates two automated functions (generative CAD modeling and model manufacturing) into one process. The first stage of the process exploits CAD scripting, or programming, to generate various parametric details in 3D from designated variables. The second stage manufactures the generated objects using RP. Together, these two processes produce a candidate family of models capable of being built at a high level of detail. This approach is different from the conventional design process in which a single artifact is usually produced, evaluated, modified and reconstructed. In addition to these design methodological attributes, the integration of the two processes also offers many possibilities for working with digital design forms of varying levels of complexity. DDF generates design solutions with an emphasis, even in early stages of design, upon structure and construction. The combination of the two processes supports *new opportunities for design* conceived of as a continuous integrated process of conceptualization, materialization, fabrication, and construction.

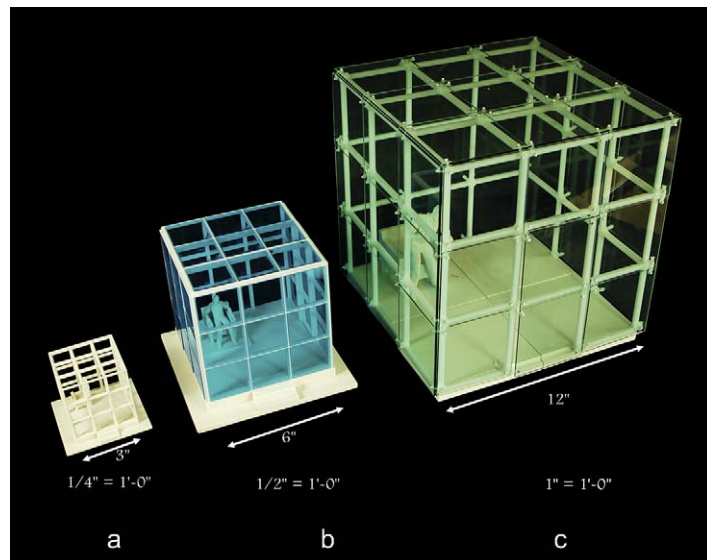
5.1 *Artifact characteristics*

The DDF process produces two model types, *design models* as a single object and *design information models* built of components constrained

by real-world construction methods. For example, early stage *design models* are generated as surfaces, or objects, in CAD manufactured with very fast RP devices. These small models (less than 10" square) are evaluated for shape, less for internal space, or assemblies (see Figure 8a). They typically do not reflect materials behavior, or construction methods. In the second type, design information models are robust assemblies containing varying levels of detailed design, or construction, information (see Figure 8b and c). In our work, we have experimented with these models as rule-based models constrained by material properties and requiring high levels of model detailing and information input.

Models of this type can be built of solid-modeled parametrically based components combined with solid objects of fixed geometries. *Design information models* are an abstract way to model building products as design products (Eastman, 1999). This may introduce certain complications in model generation and manufacturing in that models at the level of *design information models* may be physically built of two or more materials (see Figure 8b) and generally physically large in size (greater than 10" square). These models offer opportunities for design evaluation of construction processes, details, and building assemblies as well as internal spaces and form. Finally, *design information models* may require many hours of computer modeling and component manufacture time thus emphasizing the current need for computationally efficient modeling and manufacturing procedures.

Figure 8 Examples of digitally fabricated models at different scales, (a) model scale is $1/4" = 1'-0"$, (b) model scale $1/2" = 1'-0"$ and (c) model scale $1" = 1'-0"$



5.2 Generation and evaluation of designs

The use of the DDF approach in early stage design models is possible for most designers with some programming experience. As an example presented here of early stage design, 90 models were generated using the DDF method. Each model, approximately 10" square, was generated using CAD scripting and 3D printing (see Figure 9). Resulting models vary in shape from flat walls with ribs on the back for support to complex shapes and enclosed objects. Generated by CAD scripting within solid modeling software (*Rhino 3.0*), the resulting CAD models were manufactured with a 3D print device. The CAD script requests the user to draw a 2D curved line of the part geometry, to provide as additional input a desired number of structural supports, and the spacing between each support. The script generates a model approximately 10" in height and width, with the surface being approximately 1/4" thick.

The objective of the script was to generate variations of walls. The first evaluation of the models determined eight to be enclosed objects that do not represent a wall surface with structural ribs. These objects were

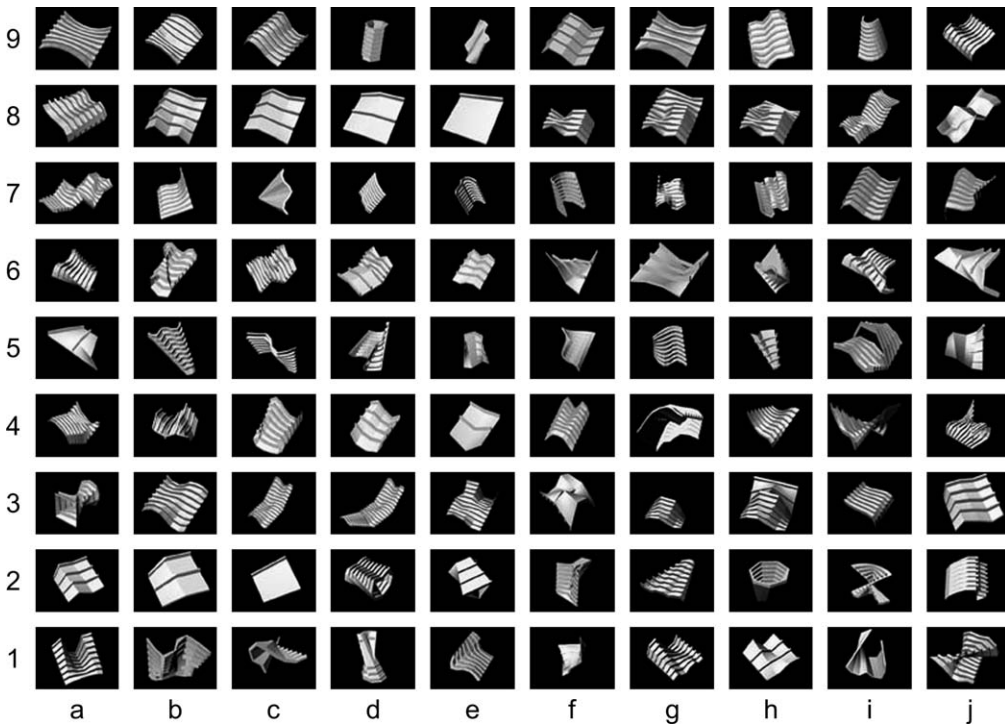


Figure 9 Ninety variations of a wall model generated with CAD scripting in an existing solid modeling program

Figure 10 3D prints of six wall surfaces selected from the 90 variations



eliminated from the corpus of candidates. Of the remaining 82 models, only 10 were printable in 3D of which only six remained in one piece when removed from the 3D print device (see Figure 10). Physical manufacture of CAD models eliminated even more designs. Thin walled structures that collapsed or design models where structural ribs intersected wall surfaces physically were also eliminated. As a result, design constraints were narrowed and altered *in the scripting process itself*. The next generation of models resulted in stronger models of diverse and interesting flat shapes.

6 *Generating information models for design*

An advantage of DDF is its ability to produce designs as intermediary artifacts between conceptual design modeling and *building information modeling* (BIM). Building information models focus on full-scale representation without supporting extensive change in model geometry. BIM models allow for some limited degree of design change. The goal of the method is to record information for construction from data to 3D modeled information. *Design information models* (DIM) are defined here as RP artifacts built of components and assemblies of many scale representations within the design process (see Figure 8a–c). These types of models are most relevant within the design process after schematics and before BIM. Design information models are the physical representation of design development including some preliminary levels of construction documentation.

These two phases begin to focus design energy on building construction as the guiding principles of representation. This phase of the design

process generates artifacts that describe the complex relationships between materials and parts assemblies at varying levels of resolution. Within this phase, designers set and solve problem at both local and global levels, including designing details and assemblies. For drawing and model making within the design development phase, problems are traditionally studied at scales from $1/4'' = 1'-0''$ to $6'' = 1'-0''$. Since architectural design produces unique solutions, management of an ill-structure process with many components at many scales over the life-time of one design project is a challenging problem of design efficiency. With respect to such problems of design process, DDF offers great potential for intermediary design. It is inspired by product modeling of building components where most components and assemblies are represented in 3D (Eastman, 1999) and these procedural characteristics are becoming most significant to the architectural design process.

6.1 Component design

An RP model of components intends to support the information relationships between architects, engineers, manufacturers and the client (see Figure 11). The objective is to build components as assemblages of parts that reflect aspects of real-world material fabrication and assembly methods. Sack (2004) presents an argument for 3D modeling in construction and design within which buildings are conceived as a composition of very large numbers of distinct component parts. The shapes of components designed and manufactured for DIM are models constrained by rules of construction. Component and assembly designs as a research challenge are a problem in management and manufacturing of geometries and manufacture of many parts at many scales. A

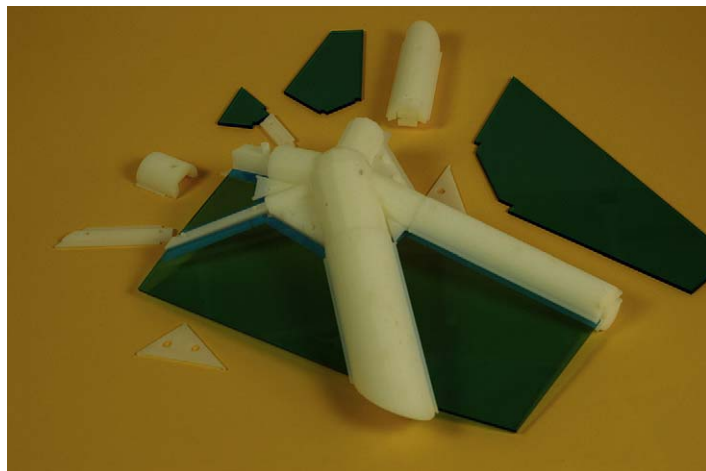


Figure 11 Rapid prototyped window frame assembly

management format for DIM looks similar to building product design in which the method manages real scale building construction as modeled objects and associated data.

Creative DDF refers to design variations *at the component level* where the component emerges as a problem of design beyond a standard building detail. Each building component has the potential to be designed and manufactured as uniquely designed parts. For example, in the case study presented, five node types were used to attach the acrylic panels to the frame in the glass room model: a total of 52 nodes were manufactured (See Figure 12). The shape of each node was based on its functional and structural attributes as a hand assembled model (see Figure 13). Since the design description in CAD has some associated properties, design changes to the surface of the glass room proved not to be simple. Change to one area of the room can lead to changes in associated geometries throughout the model. Such apparently modest changes can lead to the need for remodeling and remanufacture of new components. A major challenge for component design at the DIM level will be the

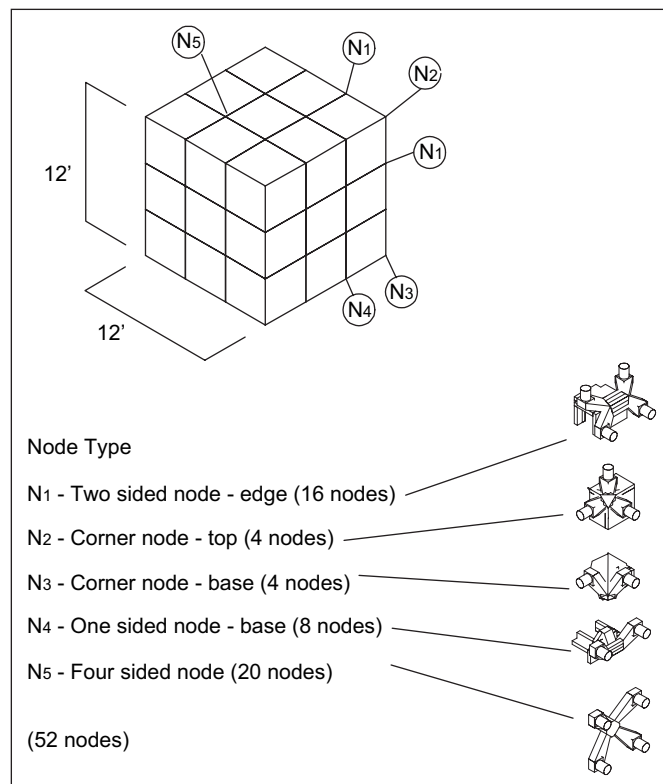
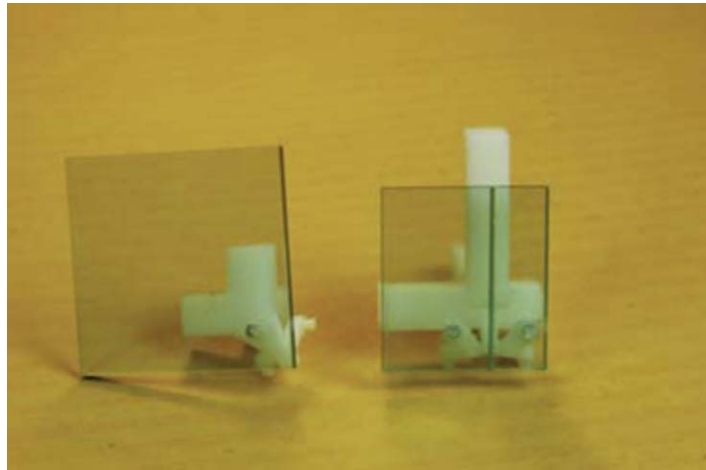


Figure 12 Nodes used to support the acrylic surface of the glass room in Figure 8c

Figure 13 Rapid prototyped node used to connect glass room model



management of assembly parts and associated parts that can lead to constructible solutions.

6.2 Assembly descriptions

A benefit of working with RP for assemblies is the emergence of new design languages at the assembly level. New assembly methods emerge from failures in testing. Assembly descriptions are parametric objects with physical and visual constraints. Although components produced here with RP are physically small, a goal for DDF has been to build assembly descriptions based on real-world construction. As with real-world descriptions an assembly description is judged for connection strength, manufacturing methods, and appearance. For DDF, components are evaluated physically by hand testing (see [Figure 14](#)).

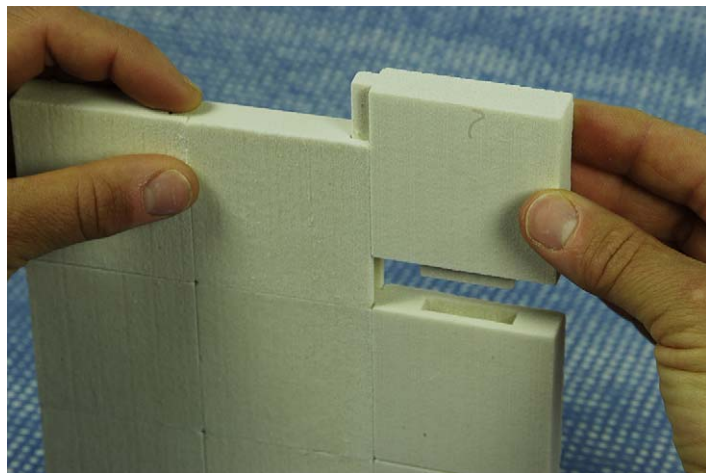


Figure 14 Assembly testing of 3D printed bricks

Assemblies are a systematic substructure of design whose emergence can lead to new design possibilities at the shape level as well as at performance and assembly levels. At the technical level assembly design for DIM gives new meaning to systematic ways of thinking for generative computer modeling. Generated components need to contain assembly features between parts. Geometries are designed and produced as conjectures, tested in relationship to building scale constraints as individually produced objects, then as a complete assembly of objects (Boothroyd and Dewhurst, 1989). For DIM models, assembly design is a bottom up approach to design engineering based on the relationship between real-world construction and abstract representation.

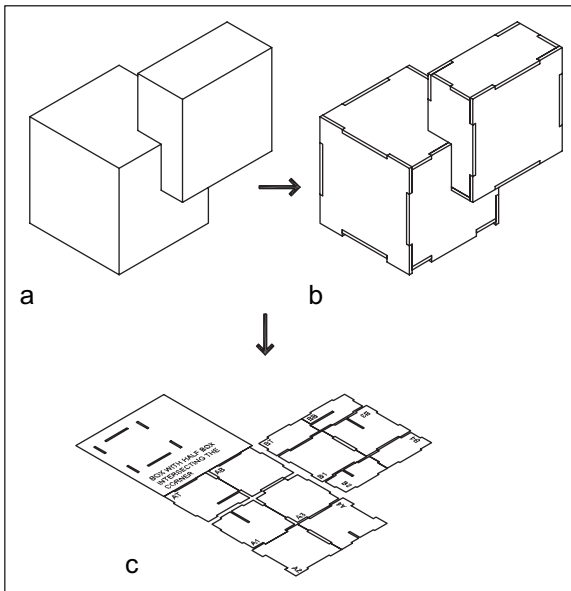
6.3 Scales of DDF

Scaling refers to measured ratios of representation between real-world construction (1:1) and DIM models of varying scales (1:2, 1:4, 1:8, etc.) (see Figure 8). Before rapid prototyping and CAD—CAM were introduced to architecture, there was little need for concern with issues of scale in computer modeling. The DDF process calls for modeling as it relates to a physical material representation and meaning that materials are modeled with specific material constraints. For the field of digital fabrication, there are two major scales of representation: CNC and rapid prototyping. Of the two types, DIM modeling relates to RP and BIM modeling relates to CNC processing. The complexity is that DIM models come in many scales of representation relative to real model making materials properties. A DIM model manufactured of 0.2 inches sheet material is not modeled in the same way as models built of 0.5 inches material. In order to reduce the need to remodel for each scale, ideally sheet material at the RP level can scale to sheet material at the CNC level. For example, 3/4" plywood sheet construction can be simulated at the rapid prototyping level with 1/16" cardboard. A geometric model built of a 4" × 8" × 1/16" rectangular sheet scales to a 4' × 8' × 3/4" sheet when scaled by a multiple of 12.

6.4 Manufacturing descriptions

Creating design for one project and the generation of many design artifacts at many scales including remodeling based on demands in design evolution are very complex problems. Effective creative design is also based on the production of artifacts and workflow. Manufacturing techniques for generating machine descriptions and machining methods can define effective workflows. New functions are needed in computer programs to generate design and fabrication descriptions in two and three dimensions. For example, laser cut models require descriptions in the form of 2D shapes from 3D models. Generation of

Figure 15 Three geometric descriptions in CAD: (a) the design shape, (b) materials descriptions (1/16" acrylic sheets) and (c) machine description (laser cutter)



a machine description from a design description is a three-stage process: (a) a design description is typically prepared as a 3D model; (b) second, a materials description is applied in order to build geometry and assemblies; and (c) finally, machine descriptions are developed (see Figures 15 and 16).

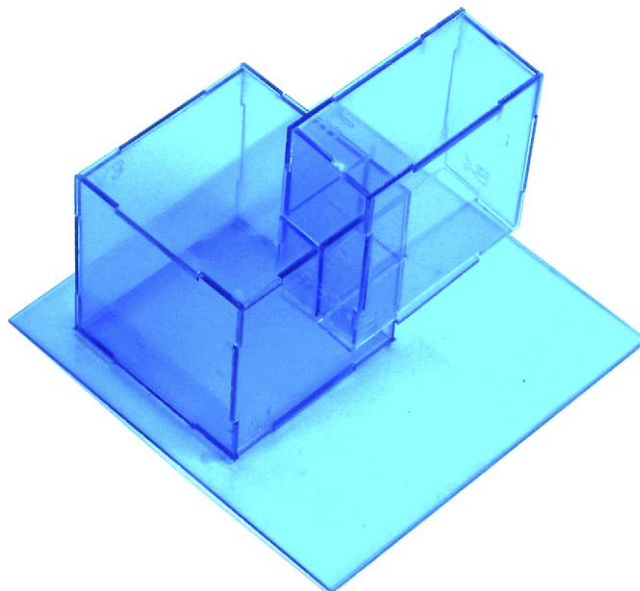


Figure 16 Final assembled model of 1/16" laser cut acrylic sheets

Success in this method of working in which files are translated from 3D solid models to 2D machine language is in the translation from a design description to a machine description.

7 *Digital design fabrication schemas*

The following two models are simplistic examples that demonstrate the technical process used to translate surface models built in CAD to manufacture descriptions and physical assembly. Both cases present schemas for design automation incorporating generative methods in CAD with RP devices. These schemas demonstrate how to manufacture one artifact at one scale as part of a design process. The generation method for shape of the original surface model is less important here, and it can be generated parametrically, or with generative software. The focus of the two schemas is on the definition of a process that collapses the space between digital information and physical objects.

The first example presents a process to build half of a dome of plastic parts by subdividing the surface into an assembly of interlocking blocks. Assembly design is based on machine and materials properties, in this case FDM 3D printing. Starting with a half dome surface model, 10" in real height, a function in CAD subdivides the surface into vertical and horizontal divisions. Second, assemblies are designed between modules as male, or female, connections (see [Figure 17](#)). The advantage of building assemblies into each module is that the logic of the components assembly is embedded within each part (see [Figure 18](#)). Once manufactured, the entire part is assembled in the real world in the same way as it

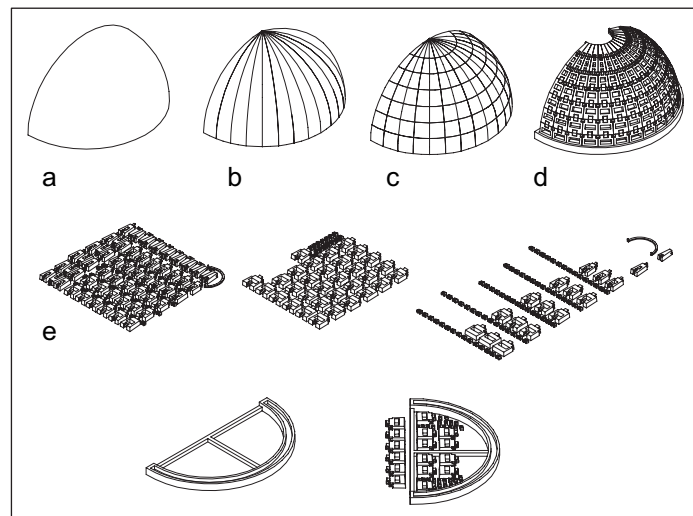


Figure 17 Fabrication schemas for a half dome

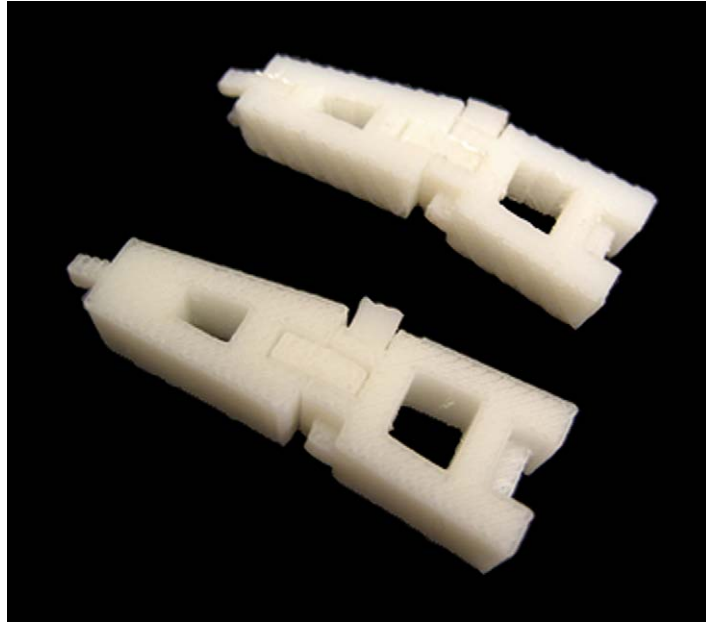


Figure 18 Component of assembly design

is in the computer model. When using FDM 3D printing, a major constraint is the removal of support material in the assembly and postprocessing phase. Support material is reduced in this case by printing parts in a flattened position; this is a method that also decreases manufacturing time (see Figure 19). Embedding logical assemblies within each module allowed the fast assembly of parts (see Figure 20).

The second schema describes a process to generate a complex surface as an arch. The arch is built of an assembly of structural triangular elements where no two triangular shapes are the same. Adding to the complexity, each triangle is connected to another triangle with specialized fittings. Surface modeling of the arch was built with a generative modeling software (Shea and Cagan, 1999) used to build structurally sound free-form truss structures. From a few input variables the program generated a surface of triangles as a dome structure (see Figure 21). In CAD surfaces were removed from the front and back of the dome to create an arch, and the final arch of triangular surfaces spans between two points. A base support was built on the ground plane to prevent the arch from collapsing under its own weight. Translation from surface to solids occurs on a local level where each triangle is given thickness (see Figure 22). To add to the complexity on each side of each triangular component, slopes are added to accommodate the angled relationship to the adjacent side. Next, the center is removed from each triangle to save on material

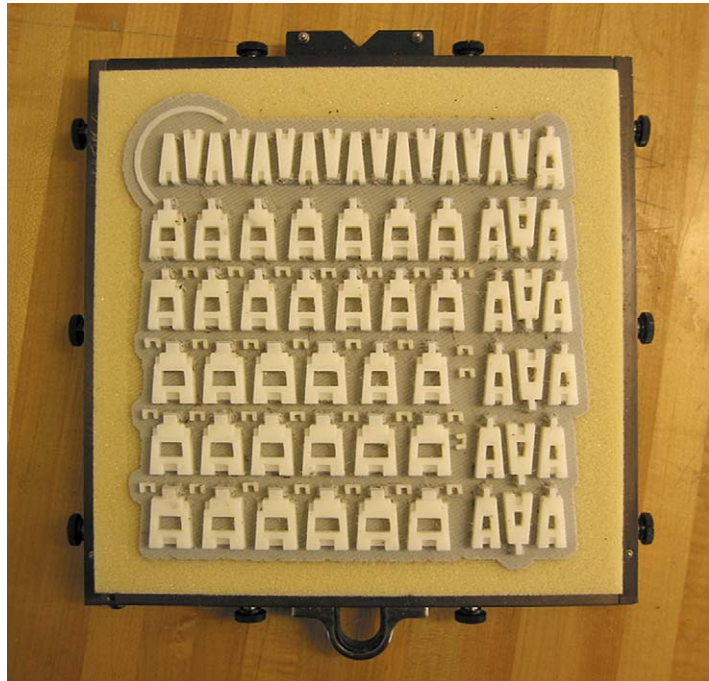


Figure 19 FDM (Fuse Deposition Modeling) 3D prints of components for dome



Figure 20 Assembled dome model

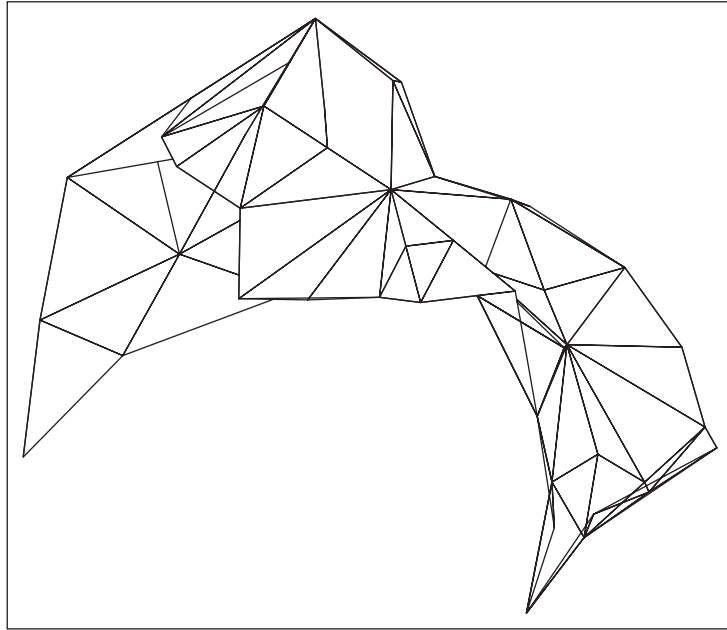


Figure 21 Design model of arch structure as surfaces

followed by an operation to create an assembly for each side of each triangle (see Figure 23). Each triangular component is a parametric object with building rules based on assembly of triangles and the geometry of the original design surface. Completion of the 3D model is preparation for real-world fabrication where each shape is a unique geometry. The assembly logic embedded in each component also means that the model only assembles in one way ensuring construction of the original designed shape (Figures 24 and 25).

8 Summary and conclusions

The first revolution in RP saw many possibilities to physically externalize designs in the form of 3D printing and laser cut projects. Curved surface modeling software and free-form modeling techniques combined with computer-based manufacturing to allow for the fabrication and evaluation of physically small models as formal studies. The first revolution also saw the use of CNC machines for full-scale realization as finished designs with designers simulating construction intent by fabricating design mockups. The next revolution will tie the two ends of the spectrum with generative technologies in both software and machinery. In support of creative methods of working, DIM modeling and RP will facilitate methods to generate high quality design representations.

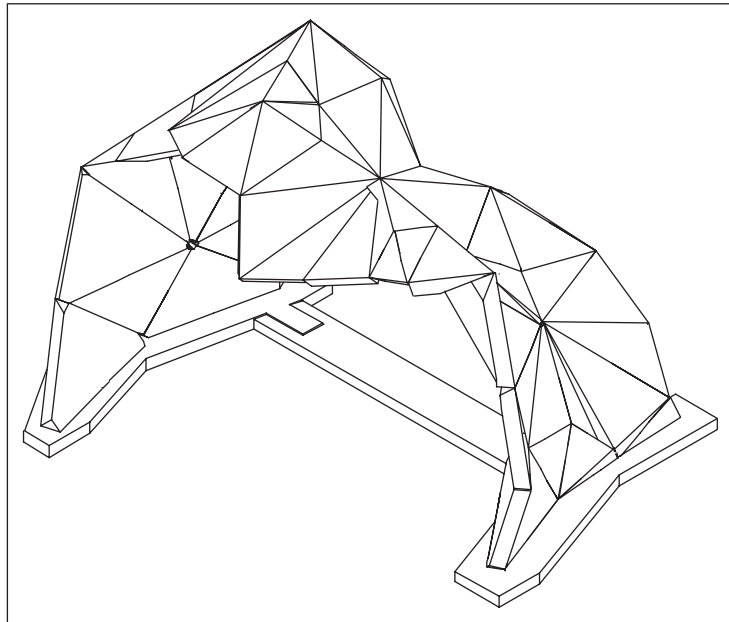


Figure 22 Solid model of arch structure from surfaces

This paper presents conceptual aspects of digital design fabrication (DDF) as an integrated, continuous design process supporting conceptualization, materialization, fabrication and construction information. For architects, the issue of scaling and ill-structured problems makes the idea of a structured method of design harder to solve. Digital design fabrication is presented as a structured means to physically externalize these complexities of architectural design within a digital design environment.

The future of digital design fabrication will integrate design models with finalized solution models (BIM) allowing a process that supports the full spectrum of digital design as a paperless process. In support of an efficient design process, both software and RP devices will need further

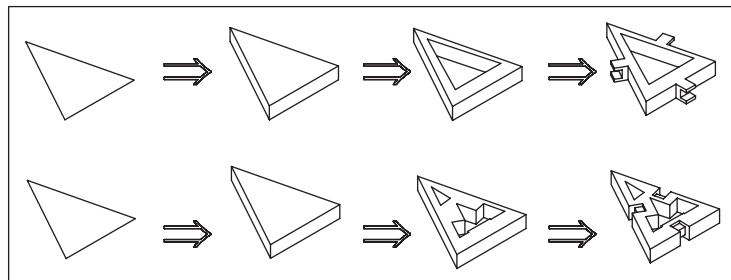


Figure 23 Schemas for surface translations for each triangle to constructible solid model with embedded assemblies

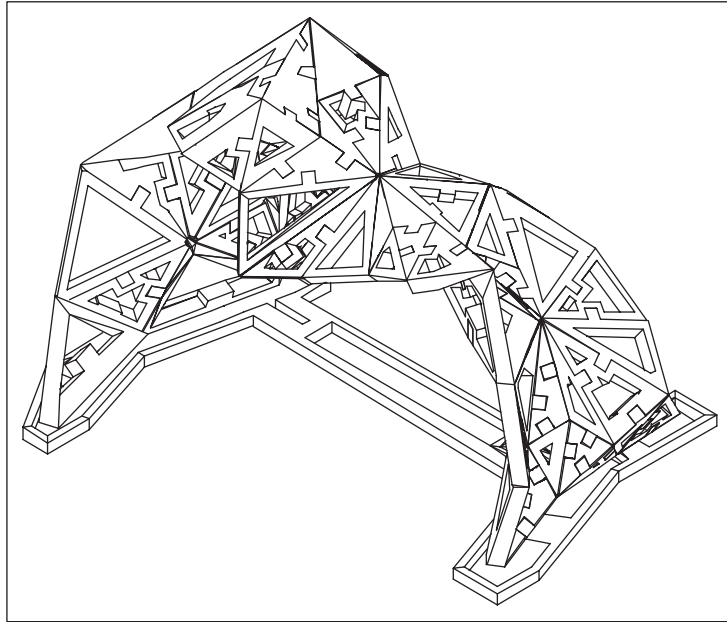


Figure 24 3D model of arch structure as solids with embedded assemblies

development. This paradigm shift in design will eventually lead to new software in support of generative methods. The shift will also lead to new methods to manufacture architectural models from RP devices in less time and with fewer machine constraints. Future research will develop new software in support of automating the design of assemblies and intelligent assignment of materials to surface geometry. These new processes will support rule-based methods to generate geometry for a particular material integrated into parametric methods for object variation.

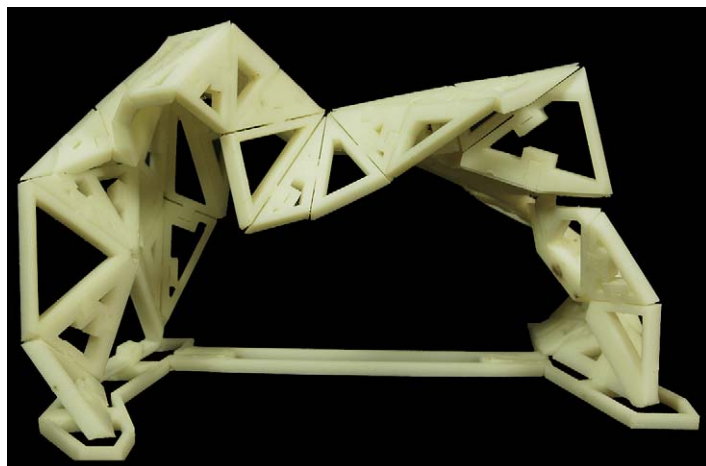


Figure 25 Model manufactured of components with FDM 3D printing

From the point of view of the design process and the vision of design as continuous and integrated processes of conceptualization, materialization, fabrication and construction this vision appears to offer great promise for a truly new definition of digital design. While much work, such as ours, is being carried on in the format of academic research, the technologies are already of such a level of applicability in industry that the distance between vision and realization appears not to be extensive. It has been our intention here to begin to both define the significance of these technologies to design methodologies and identify emerging research issues, and thereby to advance the vision of new forms of digital design.

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