Parametric Constructionist Kits: Physical Design and Delivery System for Rapid Prototyping Devices

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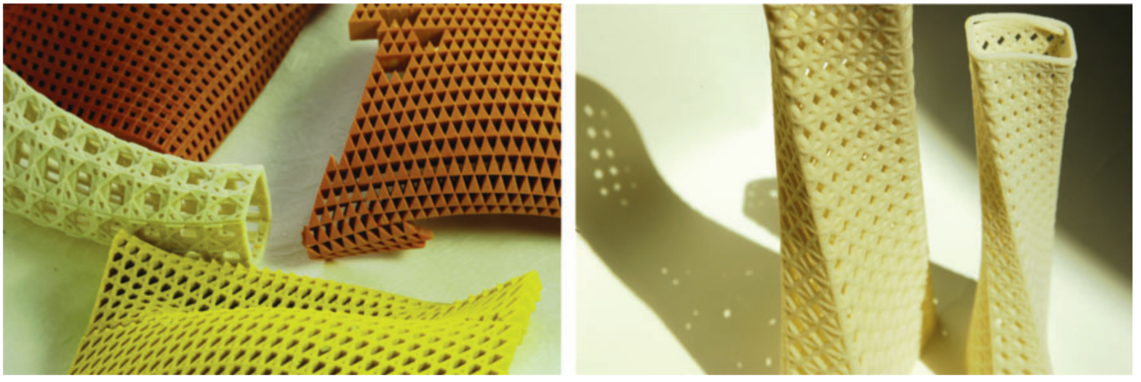
ABSTRACT

In this paper we illustrate a design methodology based on constructionist learning principles with CAD modeling and rapid prototyping. The belief is that a constructionist approach to design development extends design possibilities beyond the visual aspects of rendering and animation to building construction by way of component-based parametric modeling. This is demonstrated by way of construction kits as a proposed system of physical design production, individually and in groups. Results of the system are data sets for model manufacturing, hand assembly and design feedback. The impact of this work is to teach physical modeling as a system of production that will allow a designer hands-on learning of building structure, material mechanics and building component behavior. Also design success is newly defined as a relationship between the visual and physical evaluation; not just the visual. The paper ends with examples of complex design models generated from elements in the construction kit and a physical design grammar used to guide element assembly. Although the examples in this paper satisfy model making for building structures we believe this system can be useful for anyone who needs to construct physical artifacts beyond traditional scales found in rapid prototyping.

1. Introduction

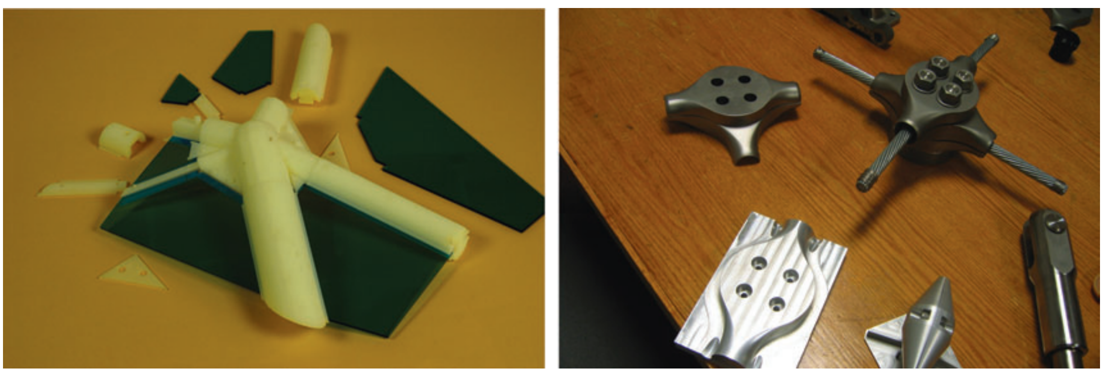
Architects are known for model making as part of the design process. They understand the need for artifacts of all types from drawings to renderings and physical models. For models that are digitally designed in CAD or with parametric modeling software, rapid prototyping devices provide efficient workflow in particular for early stage conceptual design. Purposes behind rapid prototyping, its workflow and results are well documented [1], [2], [3] for early stage architectural modeling and delivery [4], [5], [6], [7]. Early stage design models are typically solid geometries or detailed shape models produced by these machines in a single build (Figure 1). These technologies are also effective for prototyping building components (Figure 2). Questioned are???? ways to use prototyping to increase a designer's knowledge of building design as a collection of physical components with material properties, gravity, assembly methods and appearance.



▲ Figure 1. Single build 3D printed models.

This paper is a novel exploration of a new relationship between computer modeling and rapid prototyping by using construction kits as building production systems. Here rapid prototyping is use to manufacture building components for assembly by hand. Conceptual support for our way of working is common place constructionist thinking. It is a theoretical construct we used to guide learning and research methods in this paper. Constructionism is thinking on the production of artifacts based on a relationship between old and new knowledge. Thinking and methods in this area enhance social interactions in the creation of artifacts between individuals and groups by scaffolding project activities [8]. Research in Constructionism is built on cases as software that contain virtual kits of parts or software linked to physical kits of parts. Elements in the kit are assembled or built by the user with the goal of producing creative products from the elements. A core function in constructionist thinking is computer programming that works as scaffolding from which new designs are generated. Early examples included computer programs as ways to teach math to children [9]. Pioneering examples of constructionist learning matched the flexibility of programming with a desire to manipulate physical artifacts such as Lego blocks. A recent, yet very effective example of this thinking around construction kits is found in the software Scratch, a graphical kit of interactive parts that generate sounds. The user can assemble existing sounds from the program or create an array of new sounds [10].

Potential success in using construction kits to build architectural model can be found in the field of building information modeling (BIM). Here component modeling as sets of related parametric geometries is the basis for BIM. Although the field of BIM has not followed Bjork's [11] original conceptual model to link BIM with CAD/CAM manufacturing, our interest in rapid prototyping serves as a starting contribution. Commercial BIM modeling software also has yet to embody the behavioral capabilities proposed by Whitfield and De Vries [12], [13]. In many ways a physical model from BIM software can offer far more behavioral feedback than programmed software. A complete understanding of BIM is offered by Eastman et al [14]. A common form of output with rapid prototyping is modeled in Figure 2 as full scale building components generated in CAD based software. Full scale models provide an understanding of material behavior, assembly and material strength based on geometry [15].



▲ Figure 2. Plastic full scale model of joint for a complex surface and full scale finished prototypes including assembly bolts.

Few authors have discussed building models as a collection of elements with rapid prototyping. Most recently a method to generate assemblies between solid 3D prints was published. It demonstrated ways to build large artifacts as a collection of assembled models [16]. The reason may relate to the laborious nature of CAD modeling and complexities when modeling components. The need for models as components was first described by Sass/Oxman [17] in favor of physically large models for formal (exterior) and spatial (interior) evaluation (Figure 3). In order to increase our understanding of the relationship between design and construction there exists a need to build models as component kits for design similar to the way it will be fabricated in the field. We believe that models of this type capture behavioral learning that occurs at full scale. The cube in Figure 3 is an alternative delivery of a design as a large assembly of rapid prototyped components embodying behaviors discovered during construction.

Fundamentally a model built from a kit is a three step process. Here construction kits are composed of virtual (CAD models) and physical elements generated by the designer (a). Next, a grammar based production system is used to generate data for the building model (b). The final model is manufactured with rapid prototyping machinery assembled by hand (c). Construction kits will extend rapid prototyping and design thinking beyond visualization and computer modeling.

This paper starts with a theoretical framework centered on constructionist principles of making in virtual and physical environments. The core principles of our method are related to building components as parts of a kit, scaffolding for the kit and building objects to think with. We support the concept of scaffolding by using a generative modeling system in CAD to produce compliant and complex structural shapes first. A secondary generative system (a script written for CATIA) is employed to apply elements of the kit to the initial shape. We end the paper with examples of building structures as surface models are generated from a software demonstrator as designs.

► Figure 3. Physical assembly of elements manufactured with a rapid prototyping device and laser cutter

2. Constructionism

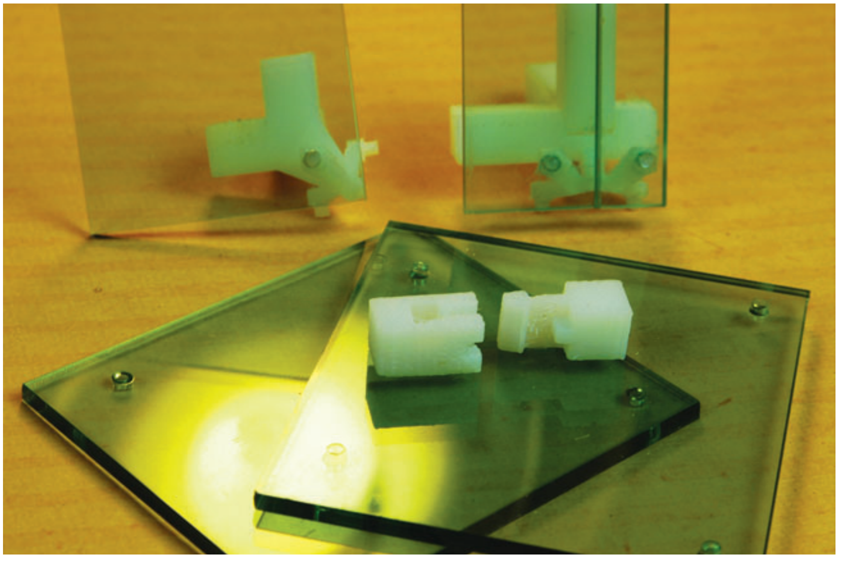
Constructionism, a term coined by Papert in the 1980's, defined educational development with emphasis on knowledge building through activity based learning. At the time Papert developed Constructionism as a technical apparatus for teaching children math as it related to computer programming. His goal was to relate mathematical skills sets when generating drawings on a computer screen with the programming language Logo [9]. It was assumed that children could build objects on the screen the way they would be built as physical objects, then program the objects in ways that generated new designs base on object rules. The elements on the screen were considered objects-to-think-with. For Papert a relationship to physical artifacts played a key role in constructing virtual artifacts on the computer [8]. Papert used construction kits such as Lego combined with Logo programming language (Logo) to develop design games, robots and software. Physical objects-to-think-with combined with software allow for new learning and sharing of thoughts in ways supported by many social scientists outside the field of Constructionism [18]. With physical objects social scientists place emphasis on learning by doing, they took advantage of physical modeling, testing and evaluation as advanced systems for learning. From physical models children take with them a complex understanding of ways to design [19]. For example, Penner et al looked at ways to teach children bio-mechanics by allowing them to build a physical mechanical arm, as opposed to drawing or computer modeling an arm [20]. In all of the cases above the emphasis was learning tool manipulation and component assembly as a way to understand design in the natural world.

2.1. Constructionist kits

Although the benefits of Constructionism are focused learning for children a similar process can also be advantageous for expert and novice designers. *Construction kits* of sorts such as Lego/Logo or most recent programs like *Scratch* are rich learning environments for children with physical and virtual building elements. With the exception of Lego blocks, these kits come complete with prebuilt elements (components) that can be altered by the user or built anew (Lego blocks cannot be physically altered). Creative discovery of new sound paradigms in *Scratch* are by combination and recombination of existing and new elements in the kit. A kit for architectural design can work in a similar way. Unfortunately the unpredictable, undetermined process of architectural design means that combination and recombination of standard shapes is not possible. An architectural construction kit requires production tools flexible enough to build components of any size, shape or function. Most important is that the programs should accommodate the need for new shapes to emerge from existing shapes. Here we proposed a flexible system of building parts for the kit with parametric modeling and rapid prototyping tools for flexibility in manufacturing.

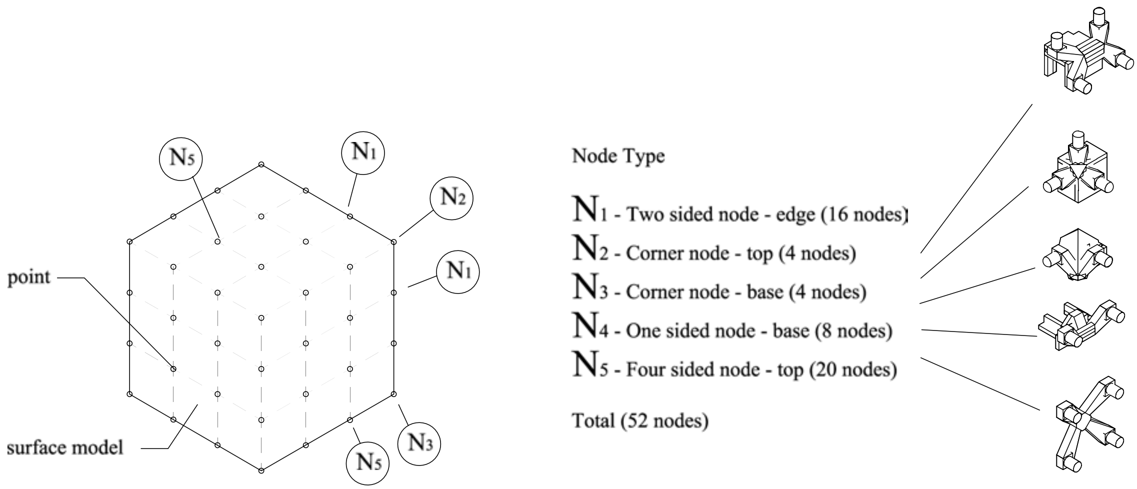
2.2. Constructive models

We defined models built from construction kits as *constructive models;* a model designed and evaluated by physical and visual criteria. We started the model building process by production of a model larger than the common build envelope of a rapid prototyping device (30.5 cm x 30.5 cm x 30.5 cm) (Figure 3). The cube was built of laser cut acrylic sheets as surfacing and structure assembled with FDM (fuse deposition modeling) printed assembly nodes. The model was larger than the envelope of a basic rapid prototyping device which meant that the model had to be produced in parts. AutoCAD 2000, the primary modeling software was used to model 52 nodes, 45 panels and a base.



► Figure 4. Object library built prior to generating the shape model.

The starting (initial) shape model was generated as a set of points in space with surfaces between the points. Next was design and prototyping of a library of objects prior to manufacturing of final model components (Figure 4). A generic node was designed as the starting point for design and remodeling of different types of nodes. Since the cube was going to work as a building model each corner required its own node type (Figure 5). For example, variations of the generic node (N5) were generated (N1-N4) to support the structure and clear panels at a variety of points around the cube. Location around the cube determined placement of each type of node. The resulting model was a high quality plastic model with few errors in assembly. However, the final model required many hours is redesign of components at the prototyping level. Redesign challenged the strength at connection points between elements in the cube. Size limitation of parts at full scale governed the shape and size limits at the prototyping scale, for instance the largest panel was 1.21m square at full scale; at model scale the panel was 10.2cm. We discovered from this study that many design iterations of small parts translated to successful assembly of the final model (Figure 3). From the pilot study we created a 4 step workflow for manufacturing any model from elements in a library and from a design shape modeled in CAD (Figure 6).



▲ Figure 5. The initial shape - subdivided and nodes used to physically assemble surface elements.

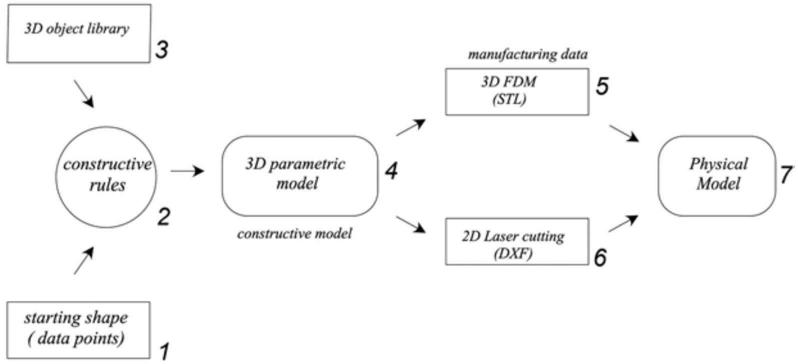
2.3. Complexities in production

The pilot project uncovered many challenges. First was the laborious data entry and data manipulation in conventional solid modeling software. Second, translation of geometry from 3D position to 2D for machining was challenging for a model of less than 100 components. It can be assumed translation from 3D to 2D will be unfeasible for models built of more than 100 components. Third was complexity in automating the process of assigning specific components with specific functions in the kit to specific areas of the model. For example, in the cube model node N3 is assigned to work in corners at the bottom of the model. Although a majority of the elements in the model appeared the same, the physical descriptions for each component differed. Without a systematic assignment system production of hundreds of components of various sizes, locations and functions will make the reality of a construction kit ineffective. Core research questions, developed from the pilot study centered on best methods to produce construction kits for architectural design where change and variation is a given. How to develop sufficient workflow between modeling software and rapid prototyping devices? How to create a platform for reflection on design and elements of the kit prior to manufacture of the completed model?

3. Process

Generating a constructive model from a shape model as a series of steps (figure 6) is presented. The process begins by definition of the starting shape, in this case with a primary computer program (eifForm). Next is formulation of constructive rules and testing of elements for the construction kit. To challenge the system asymmetrical dome structures are generated as design shapes followed by a translation to parametric

► Figure 6. Map of a design translation from a starting shape to a finished *model*



components. We study asymmetrical dome structures opposed to symmetrical as a way demonstrate the constructability of the complex and the not so complex symmetrical dome types, as defined in [21]. The challenge will demonstrate the flexibility of the system and the physical aspects of the transformation from shape to constructive model.

3.1. Starting shape

We used eifForm software demonstrator (experimental software) to generate the starting shape and needed data points sometimes referred here as the *design grid*. The software generates complex shapes as dome structures of all types rapidly based on a desired size and building form [22], [23] [24]. eifForm generates structural geometry as optimized sets of members based on a type of structural optimization called Structural Topology and Shape Annealing (STSA) [25]. Figure 7 is a demonstration of four starting shapes generated with eifForm. Note that the size of each structural member varies in thickness depending on loading. There have been two attempts to physically construct designs generated in eifForm at full scale in Los Angeles (USA) [23]. Both examples were hand crafted open air structures assembled from hand crafted wooden members and metal assembly nodes. In both cases short comings in constructing these domes emanated from imprecise hand measured, hand cut structural members. Imprecision in physical production results in unexpected labor hours to hand craft each structural member. It also requires many hours to hand craft each panel if waterproofing of the domes is required. In this study the design goal is to manufacture domes similar to the rendered structures in figure 7, inclusive a clear panel and structural members.

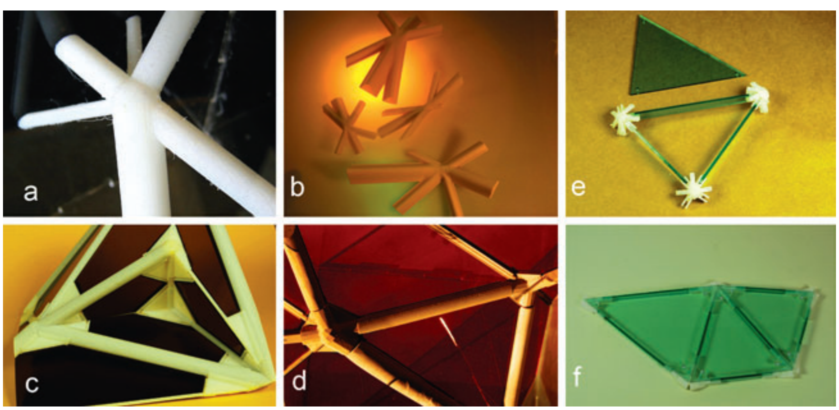
3.2. Designing the object libraries

The construction kit starts by production of elements in the object library. Adjustment and redesign of these elements will occur after a basic schema is presented. The object library was designed by review of component goals, materials and machining methods. The complex angles of each section

◀ Figure 7. Dome shapes generated with eifForm software

presented a challenge to make parametric assembles with flexible points of contact between components. It was assumed that every assembly is different. This is alternative to mass manufacturing and the assumption that most assembles are the same. Results of the first study presented standard parts for the eifForm dome.

Prior to the final elements for the object libraries was design as a series of test models by five designers prior to settling on a final set of components (Figure 8). Early study models (a) – (d) became objects-to-think-with when designing new elements. The test models were built to satisfy structural integrity, assembly compliance and constraints related to manufacturing. The first set of object libraries were built of solid models with no mechanical features. Problems in the first set inspired a new



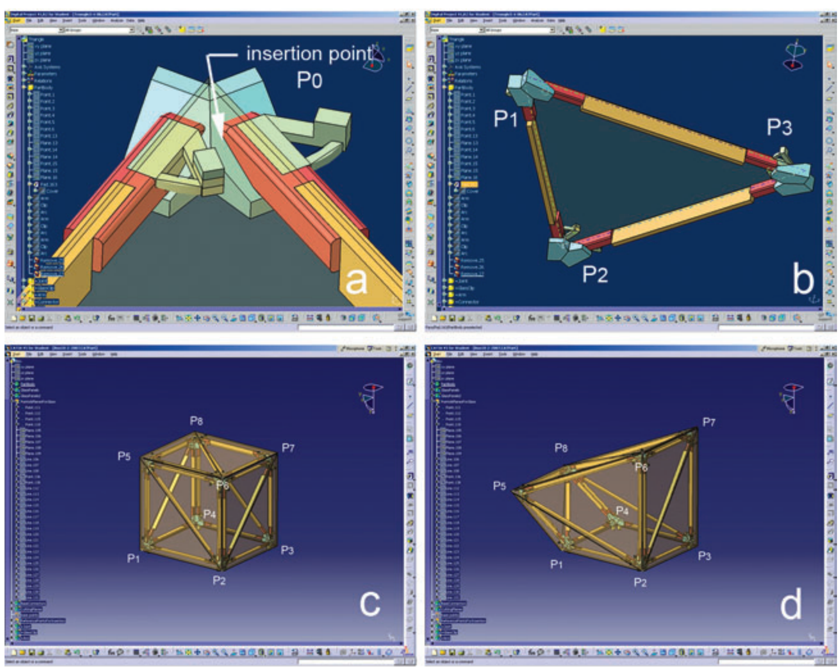
◀ Figure 8. Examples of object libraries designed by different students, (a) FDM 3D model, 3D printed objects, (c) FDM and acrylic model and (d) milled foam and acrylic model (e) & (f) componentized versions.

example later built as an assembly of parametric components; structural members, assembly node and panel. For speed in design the examples were built in solid modeling software.

3.3. Parametric flexibility

Components for the construction kit were rebuilt in parametric modeling (CATIA v5) software and assigned to points from one of the starting shape in figure 7. Parametric description of the assembly node included a major point of insertion and minor insertion points for the panels and structural members (Figure 9). Two assembly nodes and a structural member create an element set (node, panel, and structural member) designated with two insertion points - beginning and end. For example, the element set in figure 9a include structural members and clips that allow for insertion of the element at a key insertion point *P0*. Application of multiple structural nodes is illustrated in figure 9c and 9d. Also possible is adjustment of elements after assignment to points – 9c & 9d. The cube in figure 9c & 9d is built of 12 sets of elements assignment to an 8 point (P1-P8) starting shape.

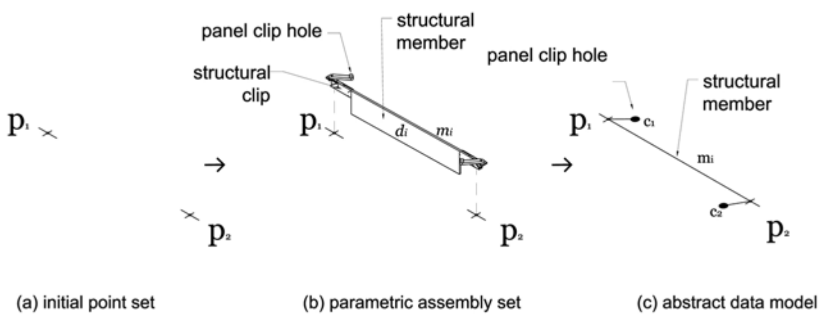
In script writing the power copy command in CATIA allowed for assignment of a parametric element to multiple points in sequence. In contrast with a solid modeling program the variability of geometry in a parametric modeling system is maintained. Shapes can stretch or be compressed based on the initial set of constraints. Best is that the power copy command maintains the constraints and assigns multiple elements as



► Figure 9. Parametric models as a collection of elements from the construction kit; each node is attached to a set of points in space. Moving the points allows the designer to transform the shape (d).

part of an automated feature in CATIA; as opposed to keyboard and mouse insertion of each element one at a time. Generation of repetitive members can be built in a matter of sections by automated scripting.

The construction rules in this section are spatial in nature and best described in Figure 10. They are similar to the shape rules found in the field of shape grammar. In order to assign many element sets to multiple points taken from the starting shape (more than 20) an automated approach is presented (Figure 10a). As part of the assignment process adjustment of assembly nodes and structural members for its length (*m1 – distance between two datum points*) and depth (d1) [where is the verb in this phrase?]. Both are variables that can be taken from the eifForm model (the starting shape). Since our final goal is physical production from data extracted from the finished model, a line abstraction of the parametric assembly set is rendered with a variable*(Mi)* representing the overall length of the set (Figure 10c). For generative modeling and automation an abstract representation of the type in figure 10c will allow for increase speed in assignment and adjustment of components to points.



◄ Figure 10. Differing representations starting with data points taken from the initial model to an abstract representation for generative modeling.

3.4. A physical grammar

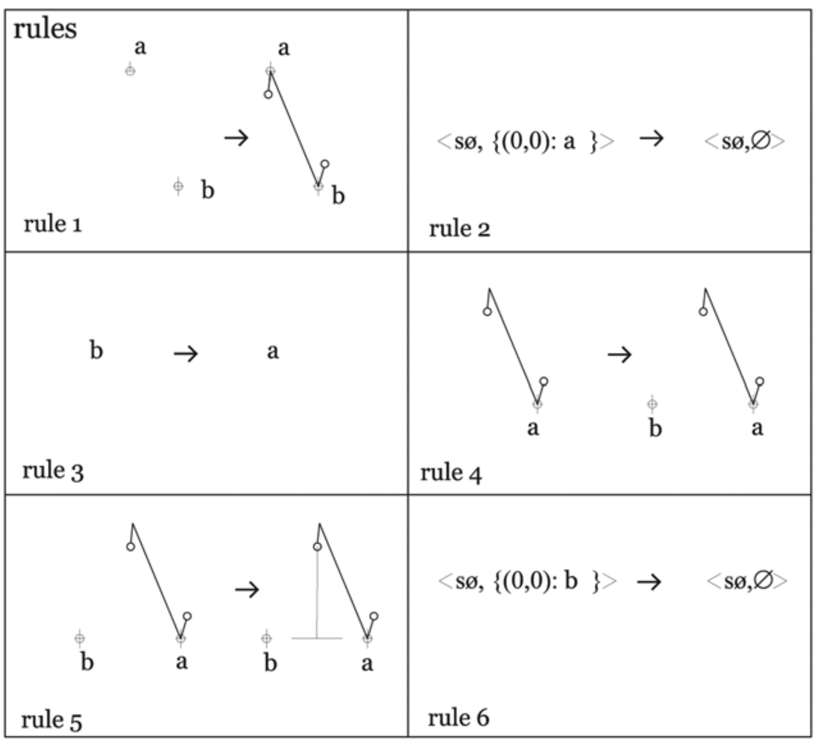
A physical grammar is used here to generatively apply the abstract data sets (figure 10c) sequentially to points (*P1, P2*...) taken from the starting shape. Physical grammars are noted as a way [???] to guide the generation of geometric data when transforming a shape model to a model of components [26]. This process is similar to shape grammar methods that use shape rules used to generate new designs from starting shapes [27]. Rule-based generation assures that alternative elements in the construction kit can be assigned to points depending on the point location in space. For instance, rules for assignment of non-standard assembly sets that attach the dome to the ground plane or assembly sets at operable window or door will differ from generic assembly sets. Here physical rules, shapes and a design grid are combined to reassign a starting shape. The derivation of rules will assist illustration of rule success prior to hard coding functions as scripts or computer programs.

3.5. Constructive rules

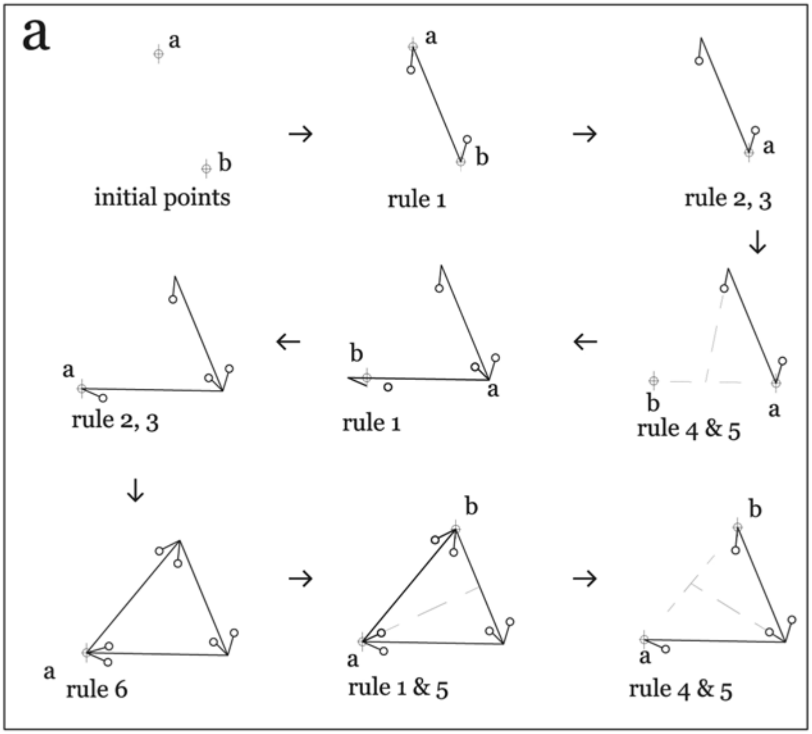
Six constructive rules are applied recursively to data points taken from the starting shape. Starting with the first labeled "a" and "b" - a & b is substitute in this section for *P1, P2* .... (Figure11) in the first panel *rule 1* assigns the first member between labels "a" and "b". *Rule 2* erases the label "a" after *rule 3* takes label "b" and substitutes for a new "a". *Rule 4* assigns a new line end point (from the line index) "b" to follow "a". *Rule 5* aligns the glass clip from member (***mi***) perpendicular to the vector "a b". *Rule 6* is used to erase "b" when needed. To construct the second triangle rules 1-6 are applied to the next point in the sequence.

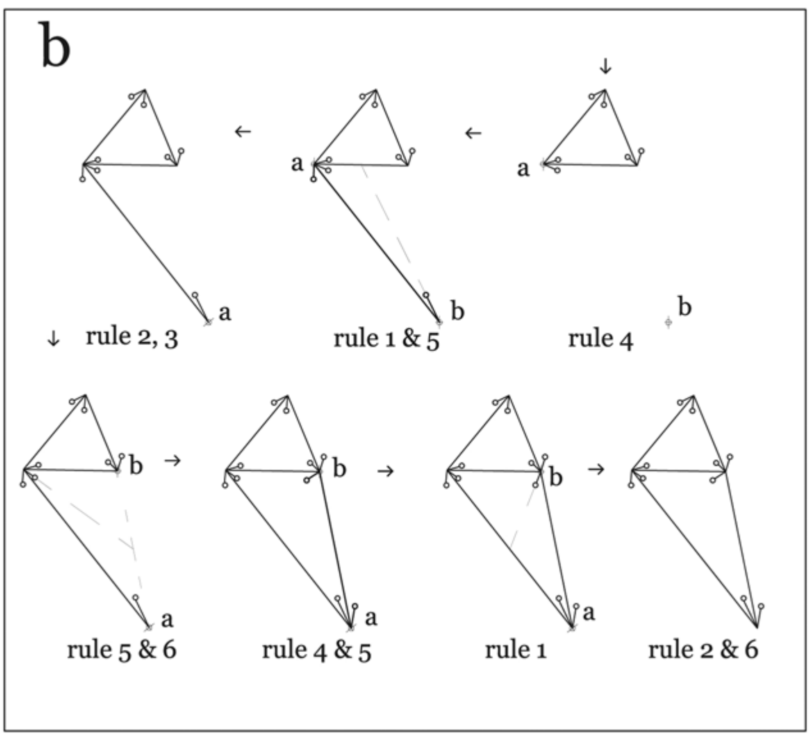
Figure 11a shows application of rules 1 – 5 for the first three points, rule 6 is used to close the triangle. Next is generation of the adjacent triangle and more importantly orientation of the panel clip as part of the rule set, shown in figure 11b. Last, 11c shows generation of the third set of triangular elements in the set. The resulting set of triangles contains lines representing the structure and points within each triangle as center points for pins that support the outer panel of acrylic. The resulting model is a collection of members, assembly sets and panels. A second set of constructive rules guides the generation of *panels* and holes for attachment to each assembly node. This rule builds triangles from abstract member data m1, ***m2***, ***m3***......
Figure 12 is the demonstration of a transformation from member

► Figure 11. Constructive rules for application of structural members to a design grid and derivation (a-c)

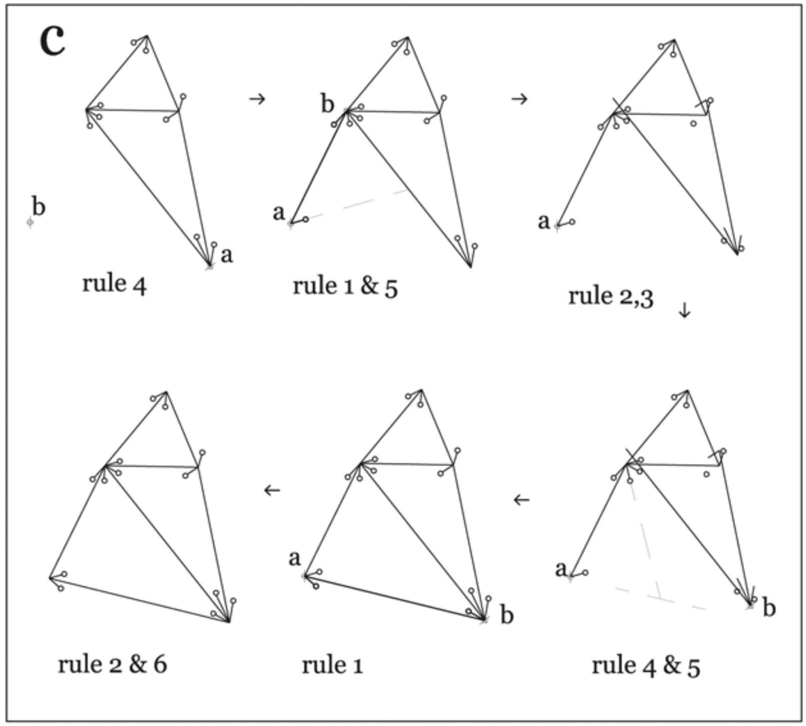


◀ Figure 11. *(continued)*

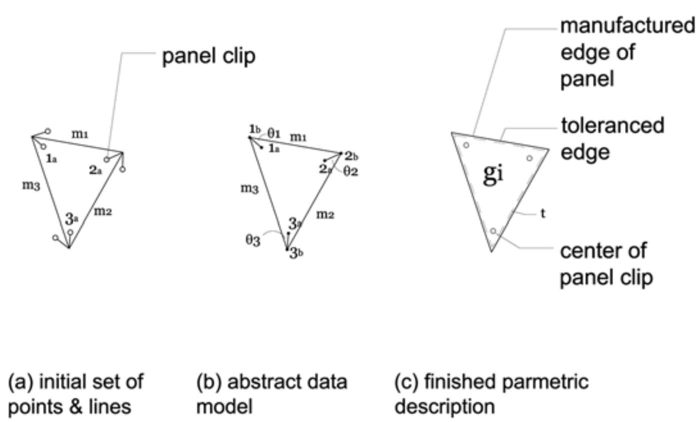




▶ Figure 11. *(continued)*



▶ Figure 12. Constructive rules for application of a glass panel to the structural grid.

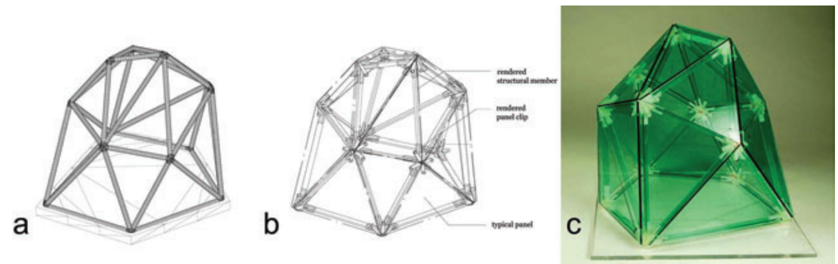


assemblies to lines for the arrangement of panel clips and the finished parametric shape.

4. Physical production

4.1. First instance

To evaluate the grammar and construction kit a small 16 sided dome was produced of cylinders and points in eifForm (Figure 13a). The model was 3D printed to verify that all the cylinders were in proper alignment and that the model was stable enough to support itself. After application of the physical grammar to the point set a rendered image (Figure 13b) demonstrates the full extent of a completed parametric model built in CATIA. In this case the power copy command in CATIA was used to install sets of elements. Translation of shapes from the 3D model to the 2D laser cut sheets was executed by CAD scripts. Functions used to translate geometry from three-dimensions to two-dimensions are development functions found in the field of descriptive geometry, commonly know n to most CAD systems as unrolling. Next, FDM printing and laser cutting elements were labeled according to its position in the overall model.



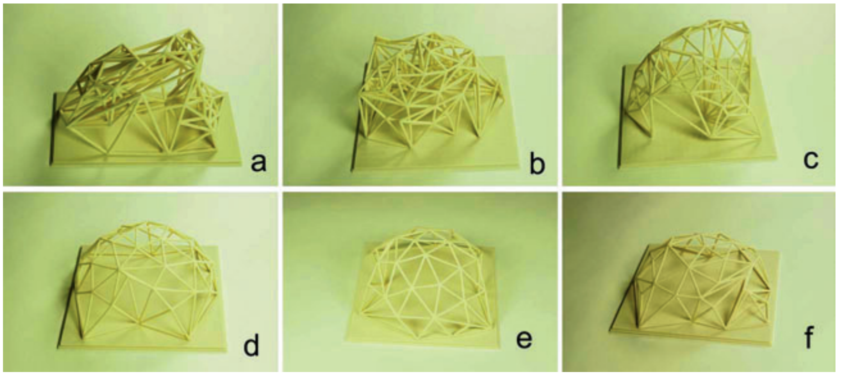
◀ Figure 13. (a) starting shape generated in eifForm, (b) finished CATIA model and (c) the finished model manufactured of FDM plastic nodes and laser cut acrylic panels & structure.

Components from the kit assembled rapidly without liquid adhesives between connection points; assemblies were sustained by friction only. As a virtual model, parametric components make possible the option of variation in geometry after the model is generated. An example of parametric variation of the design is shown in Figure 14. The second model is a parametric variation of the originally manufactured dome in Figure 13. Here a new model is generated and manufactured that satisfies our first research question on the possibilities and success of design variation from the construction kit.

◀ Figure 14. Parametric variation of the same geometry both manufactured from laser cut acrylic and FDM modeled plastic assembly clips.

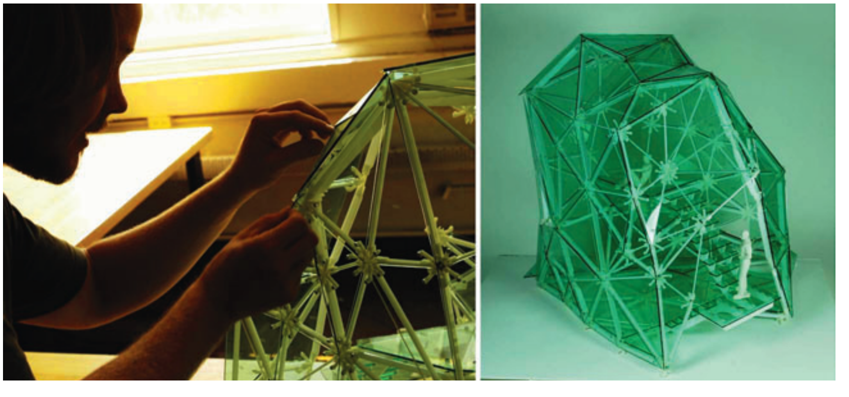
4.2. Mass production

The first instance challenged the relationship between physical modeling and design variation with parametric modeling. This attempt challenges diverse sets of outcomes for efficiency from the construction kit and an automated application of the grammar. Also challenged is the ability to build large forms for evaluation of internal spaces. Six models were produced in eifForm; the intent of each iteration was creation of an ever more complex dome structure (Figure 15). For greater clarity each design model was 3D printed; models with intersecting members or over simplified forms were rejected. Figure 15c was chosen because of its complexity as a form and success as an internal space. A few nodes in the model were altered or removed in order to simplify the application of elements from the construction kit.



► Figure 15. Six models generated in eifForm with attached bases.

The challenge in producing this example was application and manufacturing of over 200 sets of assemblies to points in the starting shape (Figure 16). The power copy command was used again to insert elements in sequence based on point numbering from the starting shape. Most challenging in manufacturing this dome was organization of laser cutting and FDM printing. Components were label during the 3D transformation phase, however part of them also required labeling in the 3D CATIA model as well.



► Figure 16. Assembly of a constructive model acceptable tolerances allow for adhesive-free component fittings.

5. Results

Our final model demonstrates that accurate delivery of physical models as a kit of parametric elements is possible. From the construction kit and grammar we were able to rapidly generate parametric data and rapidly manufacture a model as an assembly of precise parts. The process demonstrated that highly complex model making is possible as an assembly of parts. The process satisfied a constructionist approach to learning by doing across many areas of thinking. First the starting shape worked well as scaffolding for application of elements from the kit. Detail prototyping of elements provided tools-to-think-with and digital data allows for knowledge sharing between old and new designers.

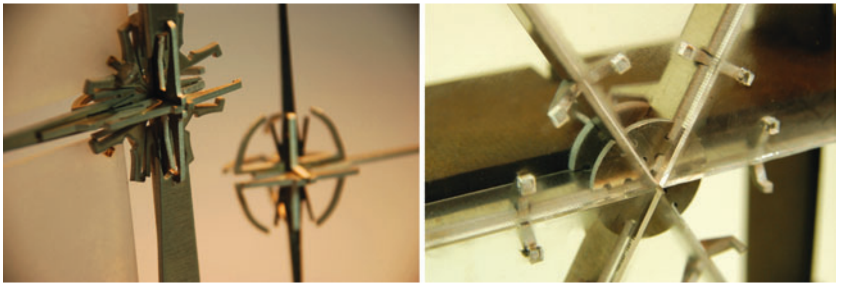
Short comings in our process and the construction kit stemmed from the symbolic nature of parametric modeling and material waste from the one-of-a- kind prototypes. In spite the flexibilities afforded parametric modeling of specific geometries meant that elements could not emerge into new components with ease. For example, it was not possible to add new geometry to existing elements in the kit; for this a new parametric element was built. Compensation for this problem was by designing parts with solid modeling software first. Parametric models were built after successful prototyping and design of all possible variations in the element. Last, each model in the study was unique. Manufactured models could not be recycled between iterations. It was not possible to exchange physical components between models. After the models were built and evaluated they were disposed.

6. Conclusion and future work

In this presentation we did not seek to demonstrate speed in design and production. However, it was a result that could go unnoticed. The speed in production does change our understanding of the design and inspire us to extend our interests in building new design variations of previous ideas. This process explores new ways to generate flexible construction kits for successful assembly of objects of infinite shapes, sizes and materials. The constructive grammar enables design control and application of elements in the object library. We believe that this component based approach to design will greatly impact the process of production because it introduces ways that designers can contribute to the building process. Construction kits for designers make possible exploration and discovery of novel construction systems in addition to design systems.

The first in a series of next steps is computer programming of new parametric systems for design production with construction kits. New computer programs focused on kit building and production from the kit will focus more on knowledge building and knowledge sharing, less on visualization and analysis. Next steps are exploration of building systems with objects manufactured of recyclable materials and geometries. A few attempts in this direction are models built from flat aluminum stock manufactured with waterjet cutting machines. Figure 17 is a demonstration of an assembly of 2D elements manufactured with a water jet cutter. After design evaluation aluminum models can be recycled and recast. A second advantage is that a successful design can be scaled from small models to full scale components for CAD/CAM manufacturing of steel.

► Figure 17. Aluminum nodes built from water jet cut parts.



A claim is made that future studies will show how construction kits and building assembly design will advance BIM software to work more as a tool for design and construction, and less for visualization and data warehousing. The first advance can be in the form physical BIM models manufactured by rapid prototyping machines with building geometry evaluated for quality in preparation for CAD/CAM fabrication. Constructionist modeling assures that knowledge is shared and that the fiduciary responsibilities of the model are upheld through physical production. This also means that adjoining trades can also design, evaluate and challenge the BIM through their own construction kits. To do this future research will need to focus more on automation in the creation of elements for construction kits and automation in the generation of the constructive model.

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