Materializing a Design with Plywood

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This paper is presentation of resulting physical models that were used to explore the relationship between design modeling in CAD and digital fabrication with plywood sheets. We explored a process in making tabletop models with digital fabrication machines and thin plywood sheets. Each was built from combination of predetermined wood joining techniques and structures. These models are believed work as simulation of full scale constructs that inform CAD modeling. Results illustrate the limited potential of parametric modeling and inform fabrication and assembly of design variations.

Keyword*: Digital Fabrication; CAD modeling.*

1.0 Introduction

Manufacture of wood product such as boats, musical instruments and furniture has been transformed from handheld tooling to computer numerically controlled (CNC) tooling. This new process starts with a design model built with a computer aided design (CAD) program and ends with a tool path drawing used to guide a CNC router tool bit. Producers of wood products use CAD models and CAD drawings to run machines from refined CAD descriptions. The results are products of high quality, high product volume and low variety between each manufactured artifact.

Wooden buildings (such as houses) are some of the last remaining wood products to be manufactured with handheld tools. The advantage of handheld machinery is the process allows for high levels of design variety at high cost. This concept applies to hand construction in-situ and in factories. Handmade products are limited in quality and not so easy to integrate with other trades in the field. Handheld construction tools extend production time in artifact construction because some long term decisions require completion of previous of a task. The greatest limitation in handmade housing is its unpredictable costs due to the high variation in labor from region to region. An important research question asks how we can produce wooden structures of high quality, high variability and high volume of a reasonable cost with machines.

The recently published Instant House illustrates a means to manufacture a structure completely of plywood with CNC machinery. Each component comes complete with an interlocking joinery (Sass 2006). The cabin illustrates that it is possible to build and enclosed structure with CNC machinery. Supporting papers also illustrate that it is possible to build for design variety from the same parametric CAD file components (Botha & Sass 2006). Second, an unpublished example also of a Paris Bus Stop was built by the design lab at MIT of plywood with interlocking plywood components. Joining between components in the bus stop was also sustained by

Figure 1
CNC Cut Bus Stop starting with the initial shape in CAD (a), CNC cut components assembled by hand (b) and the final artifact (c)

friction only (figure 1). A third example is described as a method to design and manufacture furniture and toys of plywood sheet (Oh 2003). A major benefit of the production system used to fabricate the three products is the quality of the cut components is high. The system also illustrates the possibility of reproduction in high volume, with some variability between designs if a parametric design description is used. This approach to rapid design production of plywood structures from CAD models and CNC machines is defined as materializing a design.

Materializing a design is a four step process starting with (1) an initial shape generated in CAD. Next, (2) a new CAD model is generated of smaller components. The goal of this step is to maintain the initial shape as a collection of interlocking smaller shapes. The geometry of each component is constrained by the size of the machine used to cut the component. This model is defined as a construction model. Third, (3) components are regenerated in as a two dimensional geometry in a horizontal position for cutting. This set of drawings is defined as machine tool paths. The last step is (4) component cutting and hand assembly. The final result of this translation and manufacturing is an artifact as a collection of highly precise interlocking components.

2.0 A question of fabrication and assembly

Current trends in design materialization with CNC machining also illustrate a similar four step process. Starting with a (1) 3D shape in CAD translated to (2) a construction model of components. This is followed by translation of each part from a 3D position to (3) 2D positions for CNC cutting. Components are (4) assembled by hand. The difference between this materializing system and the system listed above is that most methods use mechanical tools and fasteners such as screws, nails or bolts and metal plates to sustain assembly (Iwamoto 2004). A problem found in these examples is the disconnection between the physical artifact and its description in CAD. Goals to build descriptions with physical attributes such as assembly mechanisms and structural geometry are not considered part of the subdivision process. There may be two reasons for this. The first reason is that attachment features such as screws, plates and nails are difficult to model and compute. Second, building concerns such as assemblies and structural compliance are typically left to the builder or structural engineer. For designers shortcomings when not considering assemblies or structural compliance as part of shape subdivision are that the design is open to alteration by builders or engineers. Attachment mechanisms such as screws and nails are particularly difficult to model and are not considered an important feature to model unless they are a specialty feature. Also when assemblies are modeled there is little assurance of execution in the field by the workers to match the modeled assembly.

Our research explores ways to subdivide an initial shape in design for digital fabrication and assured hand assembly. Research solutions will contribute to systems for materializing a design by the designer quickly with structured rules.

3.0 Behaviors and systems

Explored here are ways to characterize physical building components as sub-shapes and structurally compliant shapes with assembly features for snap fit connections. Conventional solutions in CAD illustrate ways to model a building shape, next to subdivide that shape with solid modeling or parametric model software into parts as unique solids. Seldom discussed is an integrated approach in model generation inclusive of the three functions; shape subdivision, structural calculation of a shape and assembly modeling with reusable joinery. These three functions are typically separate problems and separate computations. Characterization of the three functions should reduce the complexity found in conventional building systems. A successfully materialized design is built of shape descriptions in CAD measured against three factors. First is visual correlation between the virtual model and the physical artifact; does the artifact look like the object on the screen? Next, can the artifact physically stand on its own without fastening mechanisms introduced during physical fabrication or assembly? Last does the artifact assemble with ease? Because this research works with designs built exclusively with plywood and a specific machine process, the challenge is proper characterization of physical components that lead to a successful construction modeling that simulates physical behaviors found in construction.

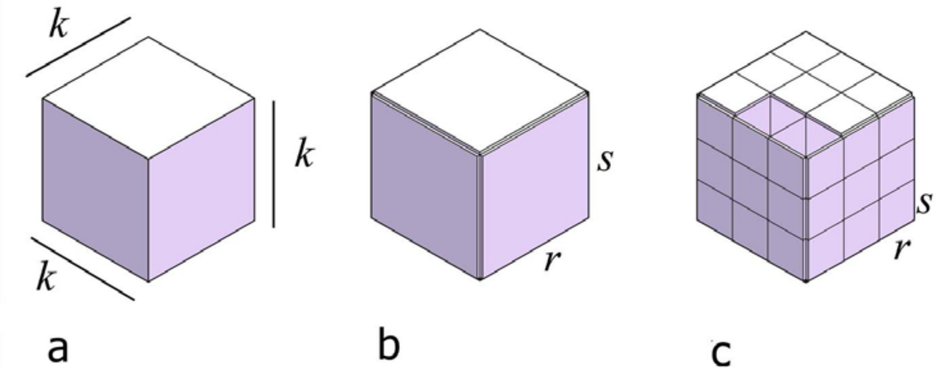
4.0 Characterizations

There are two types of characterizations listed here, types for model surfaces as plywood sheets and model structure also manufactured of plywood sheets.

4.1 Surface objects

A Surface Object (SO) is a component or sets of components that surfaces an artifact. It can be one large surface that covers each side or a series of smaller objects used to build one side (figure 2). A common method to generate geometry in CAD is a divide and conquer approach of an initial shape (a) into smaller sub-shapes (b & c) defined here as objects. An artifact is the sum of all objects. Past research examples treat sub-shapes as surfaces. in contrasts subdivided shapes are treaded as solid objects here. Calculating object maximum and minimum sizes is constrained by (a) the machine used to cut the object and (b) the maximum size of the material and (c) the material structure. These three factors are defined as object constraints. Object manufacturing methods are the result of the object constraints and the length and width of the initial shape. For example, the box in figure 2a is a six sides of a box subdivided into 6 (b) or 54 objects. Needed are ways to join object to objects and objects to a structure for very large products based on object constraints.

Figure 2
Surface subdivisions



4.2 Structuring Systems

Characterized here are three layered structural systems used to materialize a shape.

Lateral Layering (LL) is the current state of the art in materializing a design model, commonly defined as rapid prototyping or layered manufacturing (figure 3). A layered model is both structure and surface together. Layered manufacturing starts by software subdivision of a virtual shape into evenly (*k/x*) distributed horizontal slices along the z axis. Each sliced layer is sent to a computer controlled machine one layer at a time. A shape is manufactured in 2D then mechanically adhered to the previously manufactured shape as part of the process. There exists many years of literature on software processing from an initial shape (Gibson 2002). Models built of layers are stable and can be used for a variety of design functions. Limitations relate to physical model scaling. Layered descriptions for a tabletop model do not work well for a building. This method of materialization is not possible for plywood. Automation of cutting and assembly is not possible with a finished sub straight such as plywood. Examples of sculpture pieces and furniture built this way were CNC cut and assembled and adhere by hand.

Bilateral Layering (BL) is subdivision of *k* with a spacing factor *c & q* and as part of interlocking geometries along two axes *c & q* as illustrated in figure 4. Software translation of a shape to tool paths is a two part process. Generating geometries start by first sections through a model spaced by variables *n* and *m*. After, each section slice is redrawn with an interlocking attachment feature. The new section drawing is used to cut each section separately. Artifact assemble is by hand. An assembly of objects is sustained by friction the quality of the attachment is based on tolerance between sectioned layers. Tolerance features can be controlled globally when modeled parametrically. Computing a bilaterally layered structure is defined as a semi-automated system. Possible is a mathematical approach to modeling for automated translation from a shape to components,

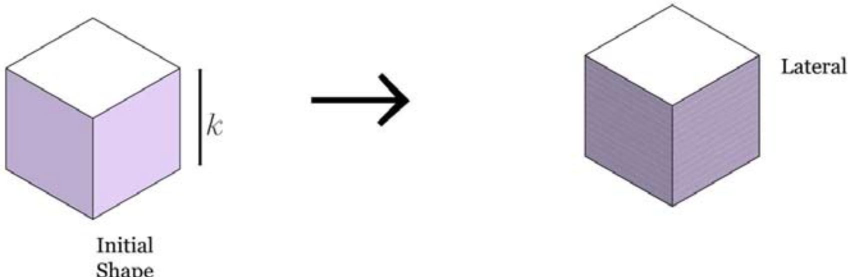


Figure 3
Laterally Layered manufacturing

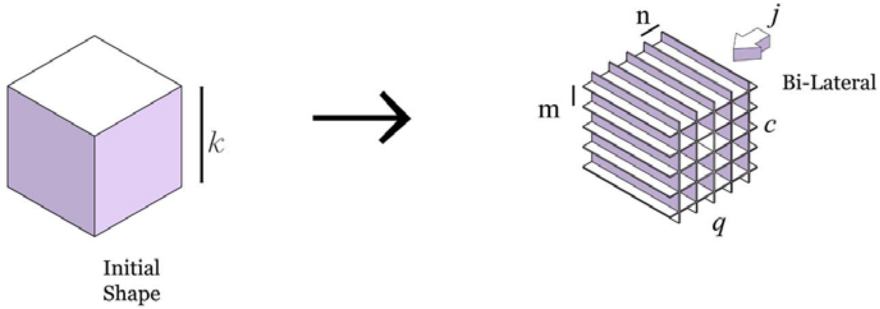


Figure 4
Bilateral subdivision along both the x and z axis

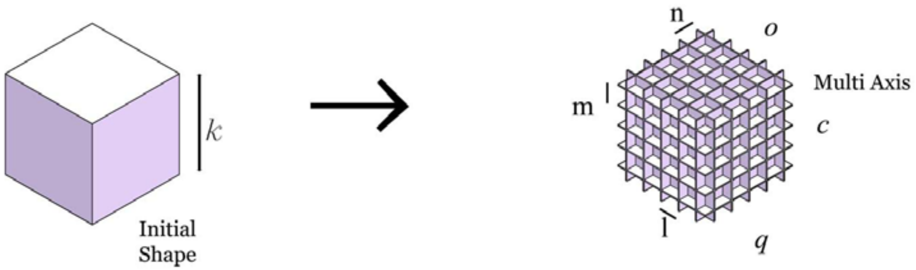


Figure 5
Multi laterally subdivided shape along axes l ,q & c and z

however manufacture and assembly is manual (Kenfield and Sass 2005). The bus stop project in figure 1 is a built example of a bilaterally layered design. This structure is built of many layers of 7.62cm plywood along two axes spaced 3" apart. Unfortunately, as discovered after completion of the bus stop the structure was unstable along the x-x axis when using bilateral structuring only. This structure embodies the potential of collapse with a small amount of horizontal force *J*.

Multi Lateral Layering (MLL) is modeling, manufacture and assembly processing of material structured in three directions. Assembly between interlocking geometries is also sustained by friction. A virtual shape model is systematically subdivided along axes *c, q* and *o* with spacing variables *m, n* and l (figure 5). Although it is not illustrated here possible is parametric variation along controlled axes. This structural method is best described by (Popescu et. al 2006) as an assembly of predetermined parts defined as GIK (Great Invention Kit) assembled by hand. Assembly of the artifact is sustained by friction. Expected application of GIK structures are scientific, and yet to be proven as applicable to building construction. Also computing of GIK components as a construction model has yet to be define.

Past studies have demonstrated that high levels of complexity are found in joineries for MML structures; meaning it is difficult to assemble. Proper characterization of joineries is needed in order to more accurately model interlocking components in CAD.

4.3 Attachment systems

The third system is a method to join structure and surface objects. We assume that attachment methods contribute to artifact quality (Messler 2007). Attachment strategy in this research is analogous to integral attachment theory, which may be defined as an assembly system that integrates the object body with the object's assembly. Typically considered as a feature-based approach to object design, integral attachments are snap-fit assemblies with a semi-mechanical function. The geometry for an integral attachment is designed for strength, assembly motion, robustness, locking, and the ability to mathematically shape attachments. There are three common attachment types listed below. Each attachment is computable (figure 6). Connections schemas are illustrated in figure 6a-6c, the first is call a connection edge *(CE),* connection running *(CR)* and connections lateral *(CL)*.

Implementation of modeled joineries as rapid prototype artifacts is illustrated in figure 7. The photos demonstrate a range of variables for edge

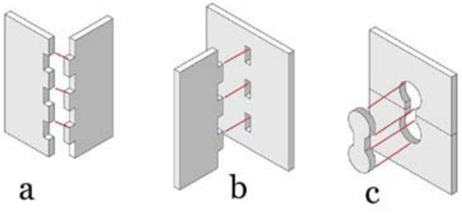


Figure 6
Attachment types compatible with plywood assembly

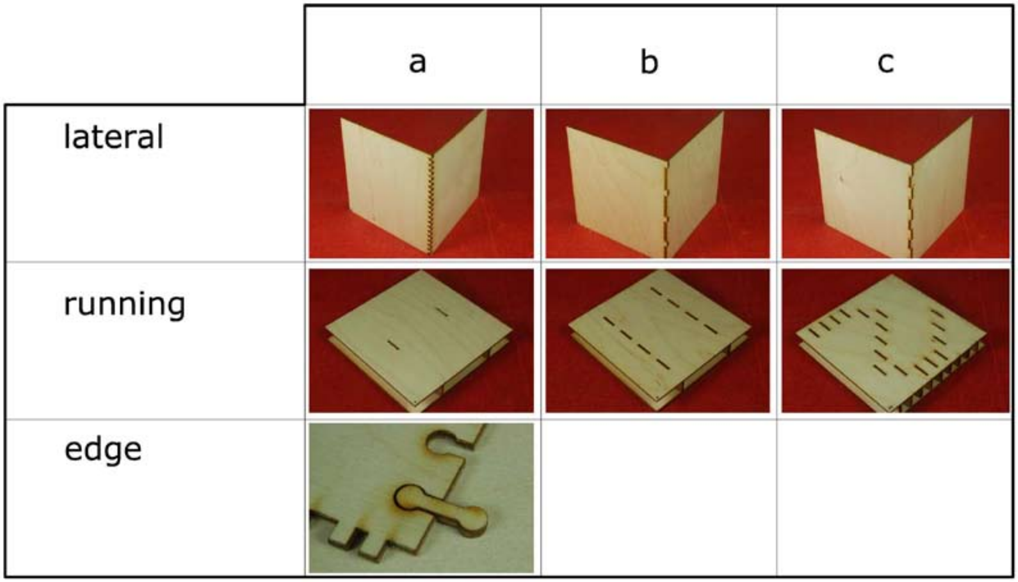


Figure 7
Study models testing for variations between the number of attachments between surface and structure

joinery and running joineries. Each model was cut from 1/8″ (2.54 cm) plywood boards with a 100 watt laser cutter. A collection of 10 edge and 10 running assemblies were built to test for ease of assembly and structural integrity once assembled. Discovered was a relationship between the number of attached surfaces, the area of surface to solid material and the tension between the two surfaces. Surface tension at the point of contact between parts was the most important finding. It was the variable that controlled strength and assembly quality.

5.0 Box models

The next challenge was study of structural, surface and assembly systems as one integrated system. Three plywood models were built to investigate relationships between an initial shape, subdivision of that shape and a resulting physical construct. Each model contained the same number of ribs and the same number of external surface objects. Explored is an assumption that the same model structure can be reused for new box shapes. Also assumed is that

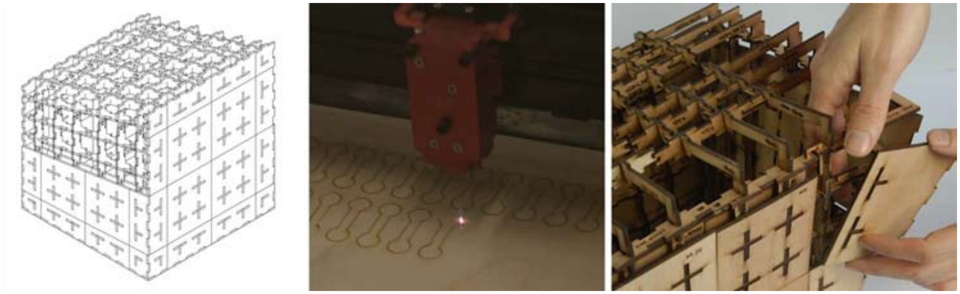


Figure 8
Materializing process, a construction model, laser cutting and physical assembly

these models could simulate assembly and structural behaviors and that each model will represent the same behaviors. Each artifact was build as a solid model using AutoCAD v2007. The process starts by construct of a solid cube 10” (25.4 cm), later translating the solid information to drawings. Components were added to the CAD model based on characteristics listed above. All objects in the model were attached to the outer skin in both the virtual and physical models (figure 8). Each model was built in a matter of weeks. Structural elements varied between models, in particular at the corners. The first box was constructed as a perfect even sided square. Box models #2 & #3 had uneven sides.

6.0 Results

We explored bilateral layering and the three attachment types in virtual and physical form. Three box models were built starting with a square model ending with a model whose sides were non-orthogonal, all of the same material and laser cutting methods. All parts were held together by friction, liquid adhesives were not used to sustain joining. Tolerance values were the same for all attachments. Critical observations found in the progression between models relate to an increase in complexity between models. As the relationship between the sides of each box became less orthogonal the level of complexity in modeling and assembly increased (figure 9). For all three models joining between the outer surface and structural members had to maintain a perpendicular relationship. However as the angle of each side changed so did the relationship between the structural members and the surface objects. To solve this problem, new mechanical joints were built at the corners of model #2 & #3. As illustrated in figure 11 as long as the number of internal ribs and surface objects remained the same the structural geometry for each corner connection had to change. Attempted was a consistent parametric description between the outer surface objects and the internal structure for all three models. This was not possible because of the physical relationship between the inner structure and outer objects changed as the outer shape changed. Solutions were found by redesign and remodeling of structural geometry. New descriptions were built at the corners of models #2 & #3. This problem is related to issues in evolution of structure related to the external evolution of the outer shape.

7.0 Discussion

The final models were far more difficult to generate than expected. Often solid models were generated in CAD and cut with difficulties in assembly. There are two functions in assembly, first is alignment between a male and female component. Second is sustained attachment. In some cases some objects could not be aligned because geometries in virtual space differed in non obvious ways from geometries in physical space. From observation it is believed

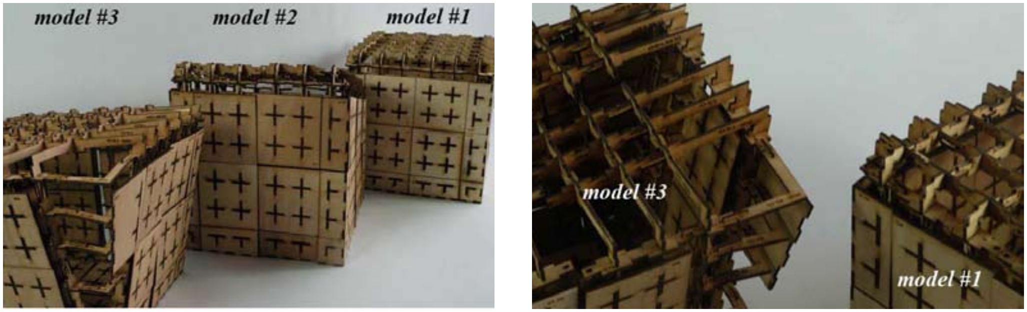


Figure 9
Box models generated from a solid modeling program

that parametric descriptions are not possible for design variations of this type. This is because variation in shape requires new learning in materializing. In summary shape exploration and exploration in materializing a form are different forms of study. An appropriate research question is can learning in shape and form studies work as an integrated learning set with physical models studies. A second problem in the study of each box was the time and efforts taken in repetitive modeling of solid descriptions in CAD. The problem with repetitive modeling grew ever more complex as the number of components in each model grew. In the end our hope is for faster methods to materialize a design as a tabletop model in order to better understand the complexity in construction. Specifically with plywood that understanding will allow for shorter design cycles and greater opportunities for increased quality of the built artifact.

References

Botha, M. and Sass, L. Instant House (2006) Design and digital fabrication of housing for developing environments, CAADRIA 2006 Kumamoto (Japan) March 30th - April 2, 209-216.

Gibson, I., Kvan, T., Ming, L., (2002) Rapid prototyping for architectural models, Rapid Prototyping Journal 8 (2) 91–95.

Griffith, K., Sass, L. (2006) A strategy for complex-curved building design: Design structure with bi-lateral contouring as integrally connected ribs. Sigradi Conference.

Iwamoto, L (2004) Embodied Fabrication: computer-aided spacemaking, In Association for Computer Aided Design in Architecture: Fabrication: examining the digital practice of architecture (Eds, Beesley, P, Cheng, NY-W and Williamson, RS) ACADIA, Toronto, pp. 269-281.

Messler, R., (2006) Integral mechanical attachment: a resurgence of the oldest method of joining, Burlington, MA, Butterworth-Heinemann.

Oh, Y., G. Johnson, Gross, M., and Do, E. (2006) The designosaur and the furniture factory: Simple software for fast fabrication. International Conference on Design Computing and Cognition, Eindhoven, the Netherlands.

Popescu, G,. Kunzler, P. and Gershenfeld, N., (2006) Digital Printing of Digital Materials, Society for imaging Science and Technolgy, Denver, Colorado, September 17 Digital Fabrication 2006, p. 55-57.

Sass, L. (2006) Descriptions for integrated digital fabrication, Automation in Construction, Vol. 16, No. 3.