A wood frame grammar
A generative system for digital fabrication
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A novel design system is presented that generates information for house construction exclusively from 3/4” plywood sheets. A shape grammar routine is employed to subdivide an initial solid shape into constructible components for desktop digital fabrication and design evaluation as a physical model. Once approved final construction can happen with components cut on a CNC wood router after the design has been validated by a laser cut model. Shape grammar rule format is used to design functions that build geometry later converted to a scripting language in CAD. Future goals for the grammar are to develop a complete CAD program that translates 3D designs to 2D drawings for flat digital fabrication. The ultimate goal of the program is to automate the translation of solid models to information for digital fabrication. Currently a manual process the translation allows the designer to focus on the visual aspects of evaluation at any scale with little concern for constructability.

**Keywords:** CNC, shape grammars, scripting
1. Introduction

As designers consider digital fabrication to build and evaluate high quality physical artifacts or to construct buildings (Figure 1) new design systems are needed to make the constructive aspects of the process efficient and affordable. These new design systems will generate CAD geometry that includes the inherent properties of rapid prototyping and CNC machinery as part of the generative process. The system considers materials representation and translates ill-structured 3D designs as building shapes to determined geometries as components for building construction. The exploration in this paper is in response to a question of software feedback based on materials and shape constraints as part of a parametric or solid modeling process. The wood frame grammar is a design system that generates geometry for design and construction manufacturing with digital fabrication devices; laser cutters and CNC (computer numerically controlled) routers (Figure 2). These devices are referred to as 2D DF devices. The wood frame grammar complements traditional shape grammars that generate building shapes [1], [2], [3] by demonstrating how a primary shape can be subdivided into constructible buildings components through automation. This paper outlines a theoretical framework for the integration of shape grammars with design and construction automation. An example of the process is presented at the end of the paper.

2. Generative design and digital fabrication

Effective DF of any type (rapid prototyping or CNC fabrication) necessitates some level of automated information processing in order to generate manufacturing information (machine tool paths). Automation here
refers to 3D model generation and 2D drawings translated from 3D models versus manual model generation by entering commands from the keyboard and mouse. Wang and Duarte [4] considered a design system for a DF device that incorporated shape grammar rule structures. Results of their program (3D shaper) were 3D structures generated as CAD models then manufactured of plastic. Their program is a framework for generation and fabrication of early stage building massing models. It demonstrated how shapes and shape relationships too complex to generate by hand can be generated and fabricated with a rapid prototyping device. The program is a stand alone software (Open GL Java script) that generates 3D graphics for manufacture with an FDM 2000 3D print device. In principle, 3D shaper can support a creative design process by empowering the designer with the ability to redesign and remanufacture architectural models within a reasonable amount of time. A shortcoming of their method was that models were physically too small to describe architectural space. More detail is needed within the program to create models with distinctive architectural features: internal spaces, doors, window openings, etc.

A second paper presents a computer program that generated information for manufacturing lightweight parts for electronic products [5]. Rules for this program were based on material and assembly properties of sheet metal and CAD CAM operations. The grammar includes rules for notching, bending and punching based on materials and machine operations. A variety of stereo case designs can be generated and manufactured with the program.

Last and most recent is a computer program that generates a puzzle connection between two flat or curved CAD surfaces [6]. The program calculates the relationship between surfaces areas then generates new geometry built of semi circular extensions and subtractions. Each extension fits into the subtraction of the opposing sheet. The program generates zipper joints of varying scales based on the level of curvature between the two surfaces. As an example, two 1/4” thick sheets of aluminum were waterjet cut from the generated CAD file. After, components are assembled with a rubber mallet assuring a water tight, permanent connection between the two metal sheets.

These three papers describe novel generative methods that bridge the relationship between computation, materials and CNC machinery. The wood frame grammar captures aspects of each method in order to present a complete architectural process.

There is also a commercial application that transforms a 3D design geometry to 2D geometry for fabrication (www.laminadesign.com). The software is used to produce physically large models or sculptures of free form surfaces. This software translates surface models of developable curves to flatten geometry for CAM manufacture with 2D cutting devices such as plasma, waterjet and laser cutters.
3. Generating models of construction

Computer models that represent large buildings, houses and sculptures for construction with DF devices are built of many unique components. These models are referred to as a construction model or as a master model, they are very complex and extremely laborious in making [7]. Computer modeling of this type involves the construct of many objects of similar shape with slight variations in component sizes. For example, consider a small house built of many unique sides where the main modeled materials are studs and outer sheathing, when modeled many studs are added all of unique sizes and orientations. Assuming the designer always starts the design process with a 3D CAD model for design representation once a shape or design concept is determined there are two means to translate the 3D model to information for construction.

First and most common is manual modeling of 3D components using the overall 3D shape as a guide for the translation of a shape to a construction model (master model). The process ends with information from the 3D model represented as 2D tool paths. For example, to fabricate the house in figure 3a the solid model (the overall 3D shape) is translated to a model of plywood components all 3/4” in thickness. Outer and inner surfaces of the 3D model (3b) are converted to 3/4” thick solid shapes first. Next, 3/4” thick plywood studs, 12” on center with assembly mechanisms (Figure 3b & 3c) are inserted between the inner and outer surfaces. The conversion of walls, flooring and roof surfaces results in a model of construction embedded with a means of assembly as well. Components in 3D are then translated to a horizontal plane for 2D CAM cutting (Figure 3d). The final cut sheets are fabricated and assembled as a laser cut model (Figure 4a) at a scale of 1” = 1'-0” with 1/16” cardboard. Components can also be fabricated of 3/4” plywood from the same CAD files (Figure 4b). In summary, manual translation of early stage design models to models of construction for digital fabrication require many hours of repetitive modeling. Models of construction require that each surface is modeled to precision. The process consumes many more hours of information gathering. 

**Figure 3.** (a) Solid model (b) sample area (c) 3D construction model as 3/4” thick components, (d) 9 horizontal cut sheets from 3D construction model.
than it might for 2D drafting of the same building. One advantage of manual modeling is that its random and sculpture like in nature allowing for models to be constructed of any shape and of any level of complexity. With manual modeling it is possible to build components outside of rule boundaries. With manual modeling techniques after the construction model is complete redesign and remodeling with new design criteria can be difficult and at times near impossible. This problem limits the number of design studies and design variations for a project.

A second means to produce models as solid objects is to prescribe functions (scripts) to objects within existing solid modeling software. These functions can add to or subdivide basic design shapes into a collection of components for 2D DF. Functions here are built from specific rules based on an understanding of the DF devices, materials used by that machine, and assembly methods. Starting with a 3D shape, the concept to construction process is divided into two phases;

Phase 1 Scripting – Building of 3D geometry (construction model)
Phase 2 Scripting – Reduction of 3D geometry to 2D construction shapes (tool paths)

An example of a set of generative functions that transforms a shape to a set of components is demonstrated (Figure 5a – 5d). This set of functions is defined as a Phase 1 script and is executed in Rhino NURB Surface Modeling Software. Written with Rhino VBA language, Phase 1 script execution starts by subdividing an existing shape into corners and side panels (Figure 5b). Next the script further divides corner sections into equally spaced rectangles at the corners removing every other rectangle on each side. Results are 6 discrete components with embedded assemblies on each side. In summary, the Phase 1 script generates geometry for digital fabrication with 3/4” plywood or 1/16” cardboard. Alternatively, Phase 2 script scans the collection of components previously generated by Phase 1 then copies each object to a horizontal position for 2D DF. Generative functions that work with existing solid modeling programs produce information for digital fabrication in a timely fashion with precision.

However, sophisticated model translation (models with many complex
angles) requires extensive programming skills in order to output high quality assemblies and finishes between parts. The script used to translate the solid modeled box to a collection of components is one page in length. Sophisticated shapes such as the houses found at the end of this paper require many pages of scripts or alternatively a computer program.

Generative methods to build components by material constraints are needed to translate early stage design (Figure 4a) models into constructible parts with embedded assemblies. Results of the two generative modeling phases can yield information such that each component is manufactured quickly with high levels of precision.

4. Properties of digital fabrication and interference assemblies

Digital fabrication devices are highly precise machines that operate at the desktop and factory levels. A major benefit of DF is that the relationship between CAD representation and component manufacture is direct where buildings or architectural models can be fabricated from CAD files without the need for 2D drawings. There are two benefits attached to paperless design and construction methods.

The first is the potential of scale-less tool paths for different types and sizes of machines. Drawings used to run laser cutters can also be used to manufacture the final design of 1:1 constructible materials. For example, a cardboard model laser cut and glued demonstrates a method to construct a
4" square box at a desktop level from a CAD model (Figure 6a). The box was modeled in CAD of 1/16" thick solid modeled sides. When scaled 12 times its original size the same 3D model and tool paths can be used to cut a box of 3/4" plywood with a CNC wood router (Figure 6b). The wood frame grammar considers all components to be 3/4" in thickness cut from a maximum stock size of 4' x 8' sheets. Constraints such as materials thickness assures that small scale design models built at 1:12 can also be constructed at a 1:1 scale for building construction. The scale at which the 3D model is constructed matters due to the relevance of materials and assembly.

Second, highly precise machines enable a new type of construction referred to as interference assemblies or friction fit connections between components. These connections are embedded into each component to encourage manual assembly. Glue is used for design models and a rubber mallet is all that is needed to join building components at a 1:1 level. Interference refers to overlapping or connecting geometries in CAD typically define by advance CAD programs as a collision or interference between shapes. Here tolerance levels between plywood components are set for very tight connections between parts such that metal fasteners are not needed. Staggered wood joinery with high level tolerance connections between each tab assures a very high surface area at points of interference (Figure 6b). For example, a box built of 5 plywood sheets with staggered tab connections at the corners (typically referred to as box joinery) can support itself with no need for liquid adhesives or metal fasteners (Figure 6c & 6d). Highly precise machinery enables high tolerance-interference connections between components advantages of friction fit connection are...
a reduction in on site machinery, no on site measuring during assembly and higher overall building strength. The wood frame grammar is an expression of the language of interference connections between building components. There are three different types of interference connections used in this grammar:

1. box joinery (staggered tabs)
2. dado joints
3. biscuit joints

5. Shape grammars for digital fabrication

The novelty of the wood frame grammar is that real world materials and assemblies are considered as part of a generative design method. Shape grammars are used in this paper to express shape translations to components. Constraints for the grammar are based on material thickness, possible bending, maximum size of available stock and component assembly. Composed of predetermined objects with determined application rules, the grammar does not consider emergence from one shape to other possible shapes. By nature a grammar of this type is deterministic containing a finite set of rules that guide the transformation of shapes. What can change or can be allowed to emerge is the over all shape of the house; the system of construction (this grammar) always remains the same.

The purpose of using shape grammars for DF is a visual expression for component generation and assembly order. Traditional code writing of computer program functions are written as lines of text or expressed as sentences in the form of pseudo code. For object translation as physical components this method of representation does not describe real world methods to translate a shape. For example, assembly of a corner composed of studs, inner and outer sheathing is too complex to describe by text alone, some form of pictorial representation is needed to describe shape transformation and assembly. The wood frame grammar is a spatial expression of computer functions in preparation for CAD scripts. Each function adds to subdivision activities that transform one large shape (Figure 3) into hundreds of smaller shapes with interference assemblies. Although the wood frame grammar contains functions for Phase 1 & 2 scripts the grammar in this paper only generates Phase 1 3D models (building 3D geometry).

6. Design and construction grammars

Considered are two levels of shape grammar representation when generating information for housing design; a design grammar and a construction grammar. The process starts with a design grammar to generate a collection of new designs based on visual rules and visual evaluation [8] [9]. A design grammar is a computer program or theory that generates 3D descriptions from shape rules defined by the user. Results of a
Design grammar are models with architectural features (doors, windows, etc). Design grammars do not define materials, assembly methods, tool paths for machines or construction methods. For this study a design grammar results in designs that express form and some detail. As with most shape grammars a variety of building designs within the boundary of a particular style can be generated from the grammar.

A construction grammar subdivides a design model into constructible shapes or building components. The grammar starts when the user selects a particular 3D design from the corpus generated by the design grammar. After the wood frame grammar (1) subdivides the 3D design shape into specific components first. Next (2) the grammar further embeds assemblies as objects and cuts within each component. Last, (3) 3D components are translated to a flattened position for digital fabrication of sheets of cardboard or plywood. For design study, cardboard models are fabricated with laser cutters and assembled by hand. For construction the same information used to construct the cardboard model is also be used to build the final building of plywood (Figure 1).

The wood frame grammar considers walls, roofs and floors as panelized assemblies built of many smaller plywood components joined by interference assemblies. Most assemblies between components are not fixed in their representation they are parametric with opportunities to adjust tolerance between components as part of the grammar. For two reasons the grammar considers the entire house to be constructed of one material; in this case 3/4” plywood. First, one material means that rule constraints for component geometries are always bound to 3/4” in thickness. This is critical for function programming in order to minimize the number of variables in the program. Second, once the house has been manufactured it can be packaged to fit flat within crates for shipping as a true flat packed house. As an alternative to walls typically built of 2" x 4" framing with 3/4” plywood sheathing walls in this paper are completely cut of 3/4” framing and 3/4” sheathing. Studs are cut from 3/4” plywood sheets with assemblies embedded within each stud. Matching slots are cut into the outer sheathing enabling interference connections between 3/4” studs and 3/4” outer sheathing (Figure 7). Studs are cut with 3/4” extended tabs that connect to corresponding slots in the outer sheathing, components are assembled with a rubber mallet. Tolerance adjustment between wall components is decided within the original 3D CAD model. High tolerance fittings means studs and wall connections are very tight, alternatively low tolerance fittings means parts can fit together by hand. Shape grammars for assembly representation means that shapes are symbolic in nature with little concern for critic of appearance. One advantage of employing grammars to represent symbolic areas of a building allows for object repetition with functional outcomes.
7. Wood frame grammar

Traditional shape grammar methods are used to transform an initial shape based on shape rules \( a \rightarrow b \) (Siny 1980). The focus of the wood frame grammar is to present the rules of Phase 1 scripting; rules that define functions in order to build 3D geometries. This script is composed of 5 stages of functions that subdivide a house into components all of one material (Figure 8). The first stage subdivides the initial shape into (1) 1/2” walls. Next corners (2), end walls (3) and wall panels (4) are built then the program terminates (5). Stages 2, 3 & 4 contain many levels of functions that subdivide corners, end walls and panels into components outlined in the grammar below.

The rules of this grammar are set to build component geometry for desktop models of houses at a scale of 1” = 1'-0". Rules 1 – 4 subdivide an initial shape into corners, end walls and panels (Figure 9 example a). The rule assumes an initial shape where \( t = 1/2" \); the thickness of all sides at a scale of 1” = 1'-0". Symbols are used to identify the insertion point of each panel type, * for corners, • for end walls and \( \) for flat panels. There are two corner types depending on base angle \( \theta \), for a flat roof rule 1 is applied, if \( \theta \) is greater than 90˚ rule 2 is applied. Rules 5 through 14 explain corner functions in detail. Rules 5 … 9 subdivide typical corners into components with variables for 3 sides (a, b, c). Rule 8 defines the method for stud and dado application connections between the sheathing and studs. The dado in the stud and sheathing gives the double plywood wall its strength. Rule 10 … 14 are rules for specially shaped corners that join end walls on three sides.

Rules 15-19 define end walls with dado connections between flat panels as well as connections between studs and panels (Figure 10). Box joined edges for panels are created using rules 7, 12 and 17. Rules 20-25 define straight walls with notched studs, example e describes the addition of wall units to create a full infill wall of many panels. Rules 25a-25c erases insertion symbols. Rules 26-35 are clean up rules that join the outer
Figure 9. Rules used to subdivide the initial shape and build corners.
Figure 10. Rules used to define end walls, wall panels, windows and doors.

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Example d (end wall)

Example e (wall panel)

Rule 15

Rule 16

Rule 17

Rule 18 (outside view)

Rule 18 (internal view)

Rule 19

Rule 20

Rule 21

Rule 22

Rule 23 (outside view)

Rule 23 (internal view)

Rule 24

Rule 25a: \( \langle \text{wall}, (0,0) \rangle \rightarrow \langle \text{wall}, 0 \rangle \)

Rule 25b: \( \langle \text{wall}, (0,0) \rangle \rightarrow \langle \text{wall}, 0 \rangle \)

Rule 25c: \( \langle \text{wall}, (0,0) \rangle \rightarrow \langle \text{wall}, 0 \rangle \)

Rule 26

Rule 27

Rule 28

Rule 29

Rule 30

Rule 31

Rule 32

Rule 33

Rule 34

Rule 35

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sheathing of panels in order to make one clean wall. For example, rule 26 describes the fusion of an end wall to a straight wall panel by removing the line between the dado notches. Rules 30-35 are rules for the addition of architectural features such as windows and doors.

8. Generating a room

A demonstration of the process is presented resulting in a construction model of a small house (Figure 11). If this were a computer program or script the user would be prompt for variables such as a prompt for the initial 3D shape. The initial shape in this example is a room with a pitched...
roof. Rules are run on a model scaled to 1" = 1'-0". Rule 1 is applied to the initial shape of a 10" x 15" room with a 16" high ceiling, walls "t" are 1/2" thick. This rule is used to generate corners at the bottom and ridgeline of the roof. Rule 2 generates corners for the roof angle while rule 3 and 4 divide the model into end walls and panels. Rules 5-9 transform 1/2" thick walls into 1/16" thick panels with internal studs with dado notches into inner and outer panels. Rules 10-14 divide the corners at the spring of the roof. Rule 15-19 creates end walls with dado corners followed by rules 20-24 that create straight wall panels of dado notched studs. This phase of the grammar is terminated by applying 25a-25c to erase symbols used to insert panels. Windows measuring 2" x 2" are applied by placing a • symbol to the left of the window at the bottom of an adjacent notch. Door insertions also use a • to mark the insertion in this case at the bottom of the floor below, 1/2" from the edge "t". Phase 1 of the grammar is terminated with the application of 25a used to remove the window and door symbols.

Phase 2 (not a part of this grammar) of the process translates all objects in the 3D model to a horizontal position. Each panel and stud is translated to a horizontal position then numbered based on the parts location in the 3D model. Walls are broken into regions north, south, east and west followed by a set of numbers for all parts within each region. After the geometry is flattened and numbered, each part is positioned within a 4" x 8" panel to be cut from 1/16" thick cardboard. In this derivation of a room there are 132 – 4" x 8" panels or (4' x 8' x 3/4") sheets of plywood (Figure 12).
9. Conclusion

The wood frame grammar demonstrates an effective way to generate designs and construct housing with two types of shape grammar routine (design grammar and construction grammar). The grammar also demonstrates that working with 1/16” cardboard and laser cutting is scalable to 3/4” plywood (Figure 13). The full process starts with a 3D CAD model and ends with 2D drawings of building components generate from shape rules. Digital fabrication is used to manufacture models from the 3D drawings as a desktop design model or as a 1:1 building representation. An example of the process was demonstrated by fabrication with a laser cut model of a full scale roof section (Figure 13). This 1:1 model demonstrates a means of assembly and concept of full scale performance. For a complete understanding only a full scale construction can define the full scope of the buildings water resistance.

Shape grammar design systems constrained by the principles of construction transform building concepts to constructible solutions. Designing with this system expands the possibility of complex design languages of new geometries by assuring construction in the earlier stages of design. This new system can enable house designs of non-Euclidian shapes where wall and roof angles can vary dramatically (Figure 14). The novelty of this process is the precise notching of studs assuring a clear interference fit between outer and inner panels. A new shape for a space is presented in figure 14 that is far more complex than that of the model in figure 13. Future research explorations will demonstrate CAD scripts as functions for each rule set, where initial shapes generated in 3D will be translated by scripts for subdivisions. These house shapes are far more complex than the basic shape used to define the process. These new shapes demonstrate new shape possibility with limitations based on software and material constraints.

The ultimate goal of the wood frame grammar is a design system that generates information for two processes; design prototypes as desk top models and wooden houses of any shape and size. For design prototypes are probably of most importance for they allow for rapid exploration of many concepts at the desktop level. Mistakes and design possibilities can be captured and resolved in the design office before the project reaches the field.
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References


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