

# The Instant House: A Model of Design Production with Digital Fabrication

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Through a novel design production system, we have developed the ability to produce highly customized wood framed buildings for rural communities in need of designed environments. A definitive need exists for a system that rapidly deploys small buildings such as schools, small hospitals and houses while tailored for a specific design within a community. This paper describes the relationship of digital fabrication to materials and rules for design and fabrication. By example, this paper presents a process of construction of a small house on-site from an initial computer model in sequential stages. Our case study in this paper will express possibilities with digital fabrication for building with designed variation.

## I. INTRODUCTION

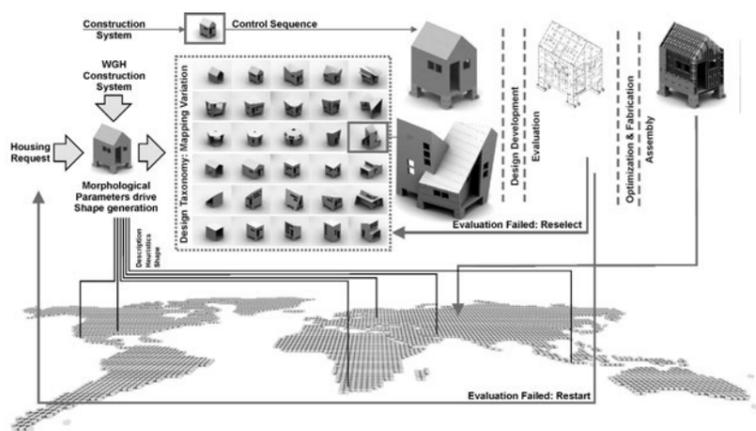
At some point the world will have to address the need for new housing and the replacement of housing that makes up for communities destroyed by natural disasters or in need of new construction in general. As part of that need is the desire to build based on design parameters for spatial hierarchies for that region. We aim to present a novel design and digital fabrication process that illustrates a production system used to build in mass customized housing for rural villages. The long term objective of our method will be to give agency to the end user to build a variety of building shapes made possible through an organized digital production system. The process deconstructs a design into components for digital fabrication on the building site (Figure 1). Our system considers that designs for non-western environments are shaped by many forces and that the construction system should accommodate social concepts that lead to a variety of building forms [1]. For many years the field of shape grammars has successfully illustrated methods to generate designs of a particular style or form with shape rules. Key examples of past grammar derivations exist in their final generated state as 3D models [2] [3] [4]. Missing is information that leads to a translation from a design shape to physical products as a building. This paper is a follow up with a generative design method-such as shape grammars-with a post-design, production process resulting in habitable building without. This paper explores a proposal for a new language of construction and a new way to fabricate designs on-site with high precision machinery (Figure 2). For expert and novice designers a goal beyond this paper is to automate the design model deconstruction process with software that generates construction geometry as a 2D file for CNC manufacture. An example is presented in this paper of a 3D design as the initial shape deconstructed into components for digital fabrication and finally assembled to build a working house/shelter. Defined as an *Instant House*, our case study is a digitally fabricated structure assembled by hand. Starting from a solid model as the initial shape, a predefined grammar is used to guide the subdivision of the initial shape into components based on a preset relationship between plywood sheets [5]. The dichotomous novelty of this process is that all components are fabricated digitally and then assembled manually by rubber mallet.

The purpose of this research is to understand ways to quickly produce a variety of designs with computer controlled machines and a traditional construction material. The process negates the use of drawings during for any stage of construction. In light of the recent frequency of natural disasters, design and reconstruction of small communities has taken a new priority at a global level, requiring effective response at a local level. Each community has its own design rules; desired building shapes and program constraints. Complementing this need for design variation is the need for flexible fabrication systems that produce desired building shapes with

technically feasible construction systems. Across cultures, communities strive for building identity through both vernacular expressions of shape and decoration [6]. Our goal is to use advanced technologies to bring design choice to environments typically inundated with generic forms of housing and community design.

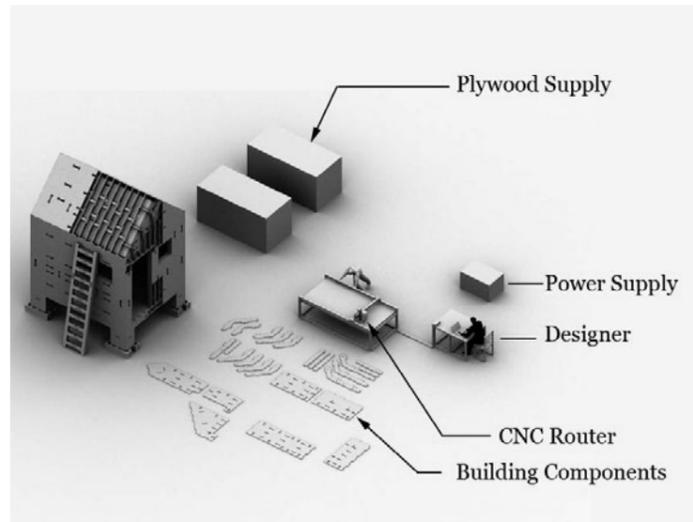
Novel findings in this work stem from discoveries in computer modeling, digital manufacture and most important, CNC cut precision wood joinery. This new type of joinery provides interlocking mechanisms between components for assembly sustained by friction only. Our approach to integrated wood joinery, takes advantage of available village labor by localizing building assembly. This application takes a page from Gershenfeld's text on Fablab by considering house manufacture as an extended function of the Fablab and localized labor as a village resource [7]. The most important benefit is that process lends itself to customization, embodying principles of lean production [8], flexible computer-integrated manufacturing strategies and reduced design cycle times, effecting rapid response times. In the long term our production system can be a direct instantaneous [9] link between generative design and fabrication and evaluation systems. The end user can participate in this decision process, without incurring cost beyond the initial technological infrastructure (a CNC router and computer).

The concepts listed above are demonstrated in our research results. This paper defines a conceptual delivery system that empowers the needs of people without access to the use of heavy machinery, yet in need of sophisticatedly planned environments. Covered in this paper is a background on current design attempts intended for developing environments as emergency housing and village design. Second, a brief discussion of a change in production, delivery and construction manufacturing is discussed as a method to support creative design production. Last, a case study is presented as example of on-site design production.



◀ Figure 1: Design production system for house manufacturing on-site.

► Figure 2: Example of on-site construction including materials supply, portable router, a designer with computer and building components.



## 2. MANUFACTURED HOUSING

Manufactured housing refers to homes produced in a factory setting of large deliverable assemblies as opposed to construction on the building site [10]. Indoor manufacturing offers exceptional degrees of control over the production of high quality building components for global distribution. There are two types of manufactured housing available to consumers. The first are mobile homes that leave the factory as a complete building products typically delivered to pre-cleared land. Second is the prefabricated home built of physically large components, delivered and assembled on-site [6]. A third type could be defined as manufactured emergency housing or rural village housing. These tend to be physically small, low quality, prefabricated housing built in a factory setting delivered by land and sea. Examples of this type include Shigeru Ban's Paper Log House, The Global Village Structure and the Ha-Ori Shelter by Joerg Student [11]. Ban created a paper log house assembly system successfully deployed in Kobe Japan, 1995. The same construction system was adapted to suit earthquake shelters in Kaynasli, Turkey in 1999. Ban's shape variation was driven by family size and stock plywood material availability, these partially prefabricated paper log houses requires 8-10 hours of on-site assembly. Moladi, a housing manufacturer in South Africa, is creating affordable two bedroom cast in place concrete houses (49-62 sq.m) for various international applications [12]. Both internal and external walls are cast within one day, with services embedded in the formwork for in situ casting. A concrete tiled roof completes the structure. The project was conceived to address macro scale concerns over the availability of suitable construction resources, such as wood, steel and skilled labor. The Moladi houses are reminiscent of the sprayed concrete GasCon

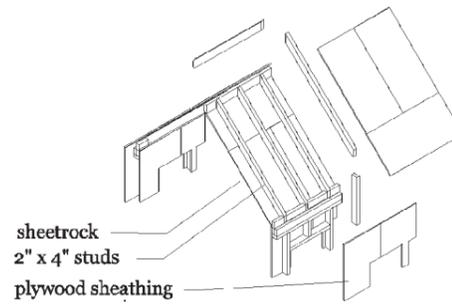
houses from Texas, which were implemented extensively in low cost housing initiatives in Jamaica, Iran and Mexico [13]. The GasCon houses utilized sprayed concrete walls, cast on the ground and then tilted upwards after 14 hours. At the other end of the spectrum, digital methods are extensively employed by Japanese prefabricators. They have all assimilated CNC manufacturing and customized lean production processes into their plants as standard, where human intervention is minimized providing oversight only. Their core competency is single family detached houses for the upper level Japanese market, designed and manufactured offsite and assembled on-site [6] [14]. A major factor in Japanese prefabricated construction is the extremely high standard in the quality of each component as they add up to high quality building assemblies. Architects in Japan are known for spending many hours in building factories monitoring the quality of their design. Manufactured housing is about process control within a closed environment either by the contractor or architect.

### 3. ON-SITE CONSTRUCTION

On-site construction for housing implies that building fabrication is executed through a manual translation of drawn instructions to building components with non-digital tools. Trade definitions are wood house construction, rough construction or finished carpentry [15]. Traditional tools are used to cut and assemble wood and associated frame finishing products such as waterproofing and standard building details. Typical on-site production is an effective way to produce wood frame housing quickly. With or without computers three factors can hinder or aid the speed and quality of the final building product. First, for large and small scale construction, western style construction documents for building require that skilled contractors work from drawing sets. Advantage of drawing is in construction planning and coordination. Negative points when using drawings are the many hours needed to draw and the skill to interpret. Second, wood frame homes are constructed of a vast array of building materials, each requiring special tools for processing and application. A typical wall section of a house built with a traditional wood frame construction method contains many layers of waterproofing, external plywood sheathing, sheet rock interiors and 2 x 4 or 2 x 6 stud supports (Figure 3). There are also many methods and variations of traditional methods for basic wood framing. These variations span from ways to represent wood frame members (studs, sheathing and weatherproofing) to variations in attachments between members (nails, screws and brackets). A third concern is that the translation in measurements from drawings to wood products during planning, cutting and assembly is labor intensive and potentially inaccurate. Complications of these types render on-site manufacture of non-traditional building forms costly and prohibitive. For western environments the traditional design and construction process has

in place many procedures for monitoring quality through drawings and check lists. For technical, political and financial reasons many factors limit the implementation of drawings for construction in rural environments.

► Figure 3: Conventional structures of a house roof framed by 2" x 4" studs and sheathing.



construction  
description

## 4. ON-SITE DIGITAL FABRICATION

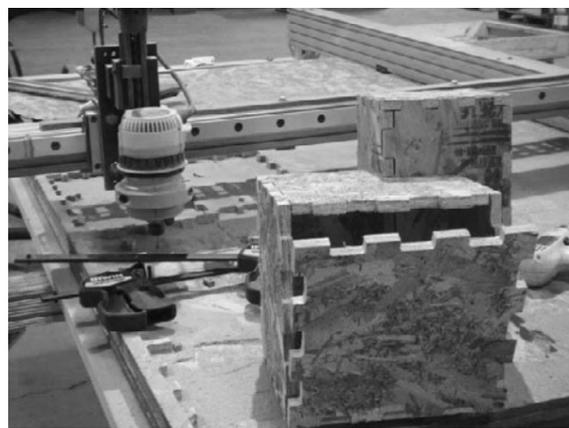
### 4.1. Delivery and description

We believe that design delivery with portable digital fabrication tools will simplify production and benefit rural construction with localized access to quality construction. Most important is that design variation of buildings shape, layout and structure in new construction is possible with this concept while maintaining factory quality component production. Our approach is to place precision digital fabrication machinery and computers onsite for a micro-manufacturing of building components. This is a return to traditional house construction where building supplies are delivered to the site as stock material for carpenters to process with hand based tools. By changing the location of controlled manufacturing, the need is removed for delivery systems of large pre-made building elements; a resource typically unavailable for most remote rural communities. The benefit of manufacturing on-site is that design can occur in the same contextual space as fabrication and assembly, thus aiding possibilities for design intervention while fostering creative development even in remote areas. Entire villages can be designed and manufactured in a single location without the need for excessive infrastructure. Two new factors in computing will make this shift in design production possible. First, portable digital fabrication machinery and second, new building descriptions in CAD suited for fast manufacturing and easy assembly of building components.

### 4.2. Portable digital fabrication machinery

Computer controlled manufacturing of architectural models has been found to be effective for physical production of designs [16]. Also, for wood

products, high end CNC milling for furniture, kitchen cabinetry and architectural detailing has just begun to make its way into the field of architectural construction and design products [17]. It is also possible to fully construct a building of SIPs panels with CNC machinery provided the information for the machine matches functions for the tool and materials [18]. Today there are small portable CNC wood cutting machines that can build furniture and cut many sheets of plywood in short periods of time [19] (Figure 4). These machines can be used to build delicate design models milled of thin plywood sheets with equally thin drill bits [both as small as 1/8" in thickness]. For house construction, these machines can also cut material as thick as 3/4" with drill bits as thick as 1/2". Onsite CNC router kits can be delivered by small truck, set up on-site, with information supplied from a computer supported by a small power supply (Figure 2). As with most digital fabrication devices portable CNC machines allow for precise manufacture of wood and metal components from CAD files.



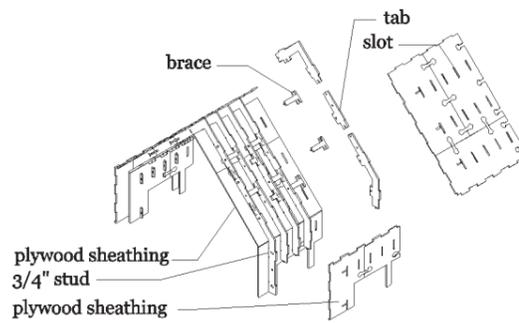
◀ Figure 4: Portable CNC router used to manufacture wooden boxes with friction based joineries.

#### 4.3. Production system for digital fabrication

For component and tool path descriptions, a production system is needed to enumerate complete sets of CAD information for CNC milling [19]. A production system is defined as a formal scheme that specifies information for production with a computer with conditions and actions [20]. This production system transforms a design shape as initial information to descriptions as constructible components for manufacture by a digital fabrication device. There are two considerations in a production system that will make on-site manufacturing with a digital fabrication device effective. The first and most challenging are specific descriptions for fabrication based on structure, assembly, specific CNC machinery and material limits. As Stiny notes, a design description is built on two factors, rules that define geometry and rules that describe the function of that geometry [21]. Rule structures here are for plywood components whose structure will support

a broader concept for design variation within the given rule sets; see: Sass 2005 for rules [5]. The grammar determines that descriptions for building components are flat geometries, since they are effective for cutting from planar material stock (Figure 5). Illustrated is an area of the *Instant House* built of flat studs and sheathing, each component serves a specific function as structure, joinery, etc. Initial studies as full scale digital mockups, determined that all building components are to be flat geometries translated from an initial design shape. The second factor is a production engine suited for digital fabrication that algorithmically subdivides initial geometry into descriptions based on rule structures and descriptions. Wood studs and sheathing will result from the production engine in two stages (Figure 6). First is the subdivision of an initial 3D shape (a) into 2D flat components within a 3D environment as studs and sheathing (b). Second stage is a reduction of the 3D object to 2D surfaces within the boundary of each plywood sheet for cutting (c). There exist examples of production systems that generate 3D CAD information as building detail models from which drawings can be extracted for wood frame construction [22] [23] [24]. Each illustrates a production system with conditions based on materials, structure and function however they are missing the direct translation to CAD CAM machinery and component manufacture.

► Figure 5: Description for digital fabrication of a roof framed with plywood structure and joineries.



digital fab description

► Figure 6: Deconstruction sequence from a starting shape (a) to a construction model of 2D components (b) to cut-sheets for digital fabrication (c).



#### 4.4. Joint design

The greatest benefit when working with portable machines and building components suited for digital construction is that complex field operations can be solved as part of the generative process. Here joinery and component attachment share the solution space when generating building components. Conventional wood frame construction is joined through a variety of methods from nails to screws, driven by hand or high powered guns. These tools require high levels of power and consumables (nails and screws). As a function, conventional assembly of each building component is a two part process consisting of component alignment and component attachment with secondary machinery (primary machinery was used to cut the component). Our research demonstrates a collapse of this two part process into one cut. Components in this research are manufactured with male or female attachments embedded in the tool path. Design of the attachment is critical in terms of placement as they are propagated throughout the house assembly. Most important is that once components are joined, a secure connection is sustained by friction alone; no adhesives are thus required between parts. There are three joint types used to meet a variety of attachment conditions, each an extension of the component (Figure 6). The benefits of components with integrated attachments geometry are that the attachments can be designed and controlled as part of the generative process. It additionally provides a means to calculate loading between each connection without consideration of secondary materials such as metal screws or brackets. The system allows for global control of joint tolerance throughout the macro assembly. A high tolerance setting determines that joints sustain assembly between components through friction only, while a lower tolerance transforms joints to self locating alignment tools in order to receive other forms of attachment; such as screws or liquid adhesives.

### 5. CASE STUDY

#### 5.1. Building design

This section presents the *Instant House*, an example of wood frame construction, digitally designed and fabricated using a CNC milling machine. The design goal of this case study was to build basic framing exclusively with a digital fabrication device, with the understanding that the user will add doors, windows, external waterproofing and exterior decoration themselves. A traditional house shape was desired to serve as a control from which alternative design shapes can be measured. Design features that make the building unique are windows placed at random on all sides and a single door. Interior dimensions are 8' x 10' the size of a common bedroom.

## 5.2. Construction measures

The shelter was designed and built in one month by four people, with five tools; computer and software, CNC router, rubber mallet and crowbar. From 114 sheets of rough grade 4' x 8' x 3/4" (1.21 x 2.43 x .076 meters) plywood sheets 984 parts were cut in 55, hours then waterproofed with a sealant (Table 1). The project was manufactured with a stationary Techno CNC router; plywood cutting and scoring was with a 1/2" router bit. Walls of the shelter were built with plywood sheathing on both sides and plywood internal studs 8" in thickness through out the shell (Figure 6). Design and construction modeling was performed with AutoCAD version 2004, individual cut sheets were exported from CAD to EZcam for G-Code generation. The Cartesian system was used for part labeling and spatial positioning of information. As for component labeling, +W1b3, translates to external (+) wall (W) number one (1), panel located in column b, row three. Subdivision of the initial shape into individual panels from stock meant that no sheet was bigger than 8 feet. Most panels were less that 6' in length and 4' in breath, no part was too large to be carried by an individual (Figure 8a). The subdivision operation breaks down the stud geometry into roughly 4'-0" sections, adding a generic T-brace between studs (Figure 6). The T-brace adds rigidity and serves as a stud spacer.

► Table 1 results of instant shelter case study

Control Model Measures			
1	Building Material	0.75" (.076 meters)	CDX Plywood
2	Plywood Waterproofing	12-15gal (45-56 liters)	Thompson's Water seal
3	Number of components	984	Parts
4	Days for cutting	55.4	Hours or 2 Day 7.4 Hrs
5	Days to assemble	35.43	hours
6	Cost	114	sheets x \$22/sheet = \$2,508 US

► Figure 7: Flat joineries used to assemble the Instant House, (a) edge attachment, (b) running attachment and (c) parallel attachment.



► Figure 8: Maximum size of single plywood sheet was 6' x 4' for easy carrying by one person, and assembly tooling with a rubber mallet and crowbar.





◀ Figure 9: Sequence of assembly starting with the waffled plywood slab concluding with a full sandwich of plywood sheathing inside and outside with plywood stud structure.

### 5.3. Assembly

Each component was aligned by hand/crowbar and attached by rubber mallet (Figure 8, right). Parts were manufactured and assembled in the sequence of normal construction starting at the buildings base ending at the roof (Figure 8). Also, on-site assembly parts were manufactured, but not optimized by total number of parts in the building. Parts were marginally optimized depending on assembly region, base parts are cut first and attached to masonry blocks, roofing components were fabricated last. Masonry blocks helped to distribute the buildings load evenly at the ground plane and also helped to elevate the building off the ground to prevent water damage. The house was assembled on a small lot, 20 feet away from the CNC router; because of weather the router was kept indoors. Starting with concrete blocks as the base footings, a grid of studs was attached to four plywood base posts (Figure 9, left). Girders, studs and floor panels are combined to form a structurally sound floor as a waffle slab of plywood. Corners that transition the floor to the walls are part of the internal geometry attachment between the floor and walls as an integrated assembly. For walls studs extending from the floor were assembled in a concentric arrangement, creating a rigid structural mesh between the walls and flooring. Continuation of walls to the roof was much like that of the floor to walls with studs built into walls extended to the roof (Figure 9, middle). The remaining assembly was a mixture of studs and sheathing. Component fabrication was in two parts. First, components were cut on the router, second weatherproofed with a liquid sealant to protect against rain. For workflow, the first four days of the week were devoted to component fabrication the fifth day of the week was for assembly. The constructed shelter was structurally sound and ready for habitation in less than a month (Figure 9, right). Furniture was added after the shelter was built, designed from the *Instant House* 3D CAD model, manufactured on the same router. The resulting shelter was that a complex system of interlocking components where strength between assemblies was gained by cross-referenced and self-correcting component assembly.

### 6. CONCLUSION

Demonstrated is a production system that can be used to transform a virtual design shape into a representation for digital fabricated based on

manufacturing rules. The shelter illustrates possibilities when physical production is considered as part of the design solution space. Most important, the case study illuminates the possibility of on-site manufacturing exclusively of one material and few tools. The research also demonstrated possibilities with rule descriptions that constrained components to 2D geometries for cutting and 3D assembly. As assurance of high quality in manufacturing, a physical walk through of built *Instant House* assured us that state restoration of a 3D computer is possible as a physical object.

Social patterns in the home and symbolic concepts for design vary from village to village and country to country, imperative are production systems that support design variation. Application of this research will empower people in rural settings with tools that allow for the design and fabrication of schools, stores, hospitals and houses. Past works in shape grammars have demonstrated how designs can be generated and shaped by rule descriptions based on a particular style a recent example supports this claim [2]. The case study in this research follows up on Duarte's grammar by starting with a fully generated design shape in a similar state that his grammar terminated. As demonstration an alternative design was generated that can be built with the same production system as the *Instant House*. We argue that alternative design shapes are possible with structured constraints illustrated in this paper (Figure 10).

Limitations in our production system relate to mouse and keyboard driven modeling as it was laborious, but possible to formalize [5]. A formalized model of production will lead to computer programs that generate geometry for digital fabrication from an initial design shape. However formalizing rules and rule functions based on machinery and materials require exploration beyond this paper. An effective generative production system is needed that supports the following operations:

1. Subdivision of geometries to constructible components as 2D shapes in 3D space.
2. Translation of 2D geometries to horizontal positions for digital fabrication.
3. Optimized geometries as 2D tool paths by part number based on ordering of assembly.

► Figure 10: The Instant House as control model (a) and design variation (b) based on principles of construction with digital fabrication.

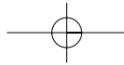


## Acknowledgements

We would like to thank the many students who have contributed to the construction of artifacts for this study Nicolas Rader, Victoria Lee, Diana Nee and Maggy Nelson. Also The Center for Bits and Atoms for their generous funding facilitated through support of NSF CCR-0122419.

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