Plane Delivery: Towards a Physical Grammar for Large-Scale Digital Fabrication

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Introduction

There will come a day when computers and robots will participate regularly in designing, fabricating, and delivering homes as customized kits of parts (Sass 2008). They will not replace builders. Instead, one possible future is where computers and robots operate as intelligent assistants, discovering, reasoning, and inferring the best solutions using large language models (LLMs). This language will be vector-based on points, lines, and planes of the type Stiny described (Stiny 2006). A standard design and builder language is a first step towards automation. The proposed system is a Lego-style approach to physical house production, used to manage costs, enhance design variety, improve design quality, and, most importantly, facilitate building.

For over two decades, research in design-to-fabrication demonstrated that homes can be delivered directly from computers and machines. In this context, a short version of design-to-fabrication aims to create systems for affordable wooden housing across design scales. Demonstrated is a physical grammar of rules as computer functions that can replace traditional handcrafted design and construction. These rules are executed by keyboard entry in any CAD software. The expectation is 3D modeling of planar elements that CNC machines can manufacture. The challenge for this grammar is programming and coding rules to reduce and eliminate 3D modeling by keystroke operations. A physical language for design to fabrication computing is an impactful way to reduce cost by empowering the design with a measurable design system.

The Instant Cabin, constructed at MIT in 2005, is the first example of a design-to-fabrication digital product. It was designed and modeled on the computer, then manufactured

◁ Opening Figure. Hand-guided assembly of interlocking planar elements of an exhibition structure in Sweden. (Credit: All figures by author.)

△ Figure 1. Assembly of the Instant Cabin at MIT, 2005.

by a computer-controlled machine (Sass and Botha 2006; Sass 2007) (Figure 1). Production of the model was keystroked and guided by specific rules from 3D modeling to 2D manufacturing, ensuring components were prepared for hand-guided assembly by number. The Digitally Fabricated House for New Orleans is a physically larger example of a structure built by interlocking rules (Figure 2). It was constructed of over 5000 interlocking elements, using the same construction language as the Instant Cabin (Sass 2008; Sofia and Blair 2019). This exhibit structure showcased the potential of digital fabrication, constructed of mega-size interlocking planar structures. It was a 640 sq. ft. (60 sq m) enclosed structure created for the Museum of Modern Art in 2008 (Bergdoll et al. 2008).

Both projects began with a solid or mesh 3D model and ended as 2D tool paths. This model of thin planar elements is then remodeled multiple times, with each iteration incorporating finer and finer detail. The Digitally Fabricated House for New Orleans was created through five core steps (Figure 3). An initial model is designed, and 3D printing is done as a desktop model (a). Framing is modeled as a lattice attached to external planes, all generated by keystrokes informed by the initial form. This process of Planar Modeling and decomposition of the form to elements is more than slicing layers through a solid model. A house framing model has two parts. An internal lattice (b) of interlocking contours is attached to external plates (c). Plates and lattice elements are decomposed by plane splitting into elements small enough for a small person to carry. Tool path and assembly information are 2D drawings where each element is numbered, developed from 3D to 2D, sorted, and packed to fit within specified boundaries (d and e). Advanced Design Fabricators can generate 3D and 2D data with some automation through well-written scripts, short computer programs, or visual programming systems, like Grasshopper.

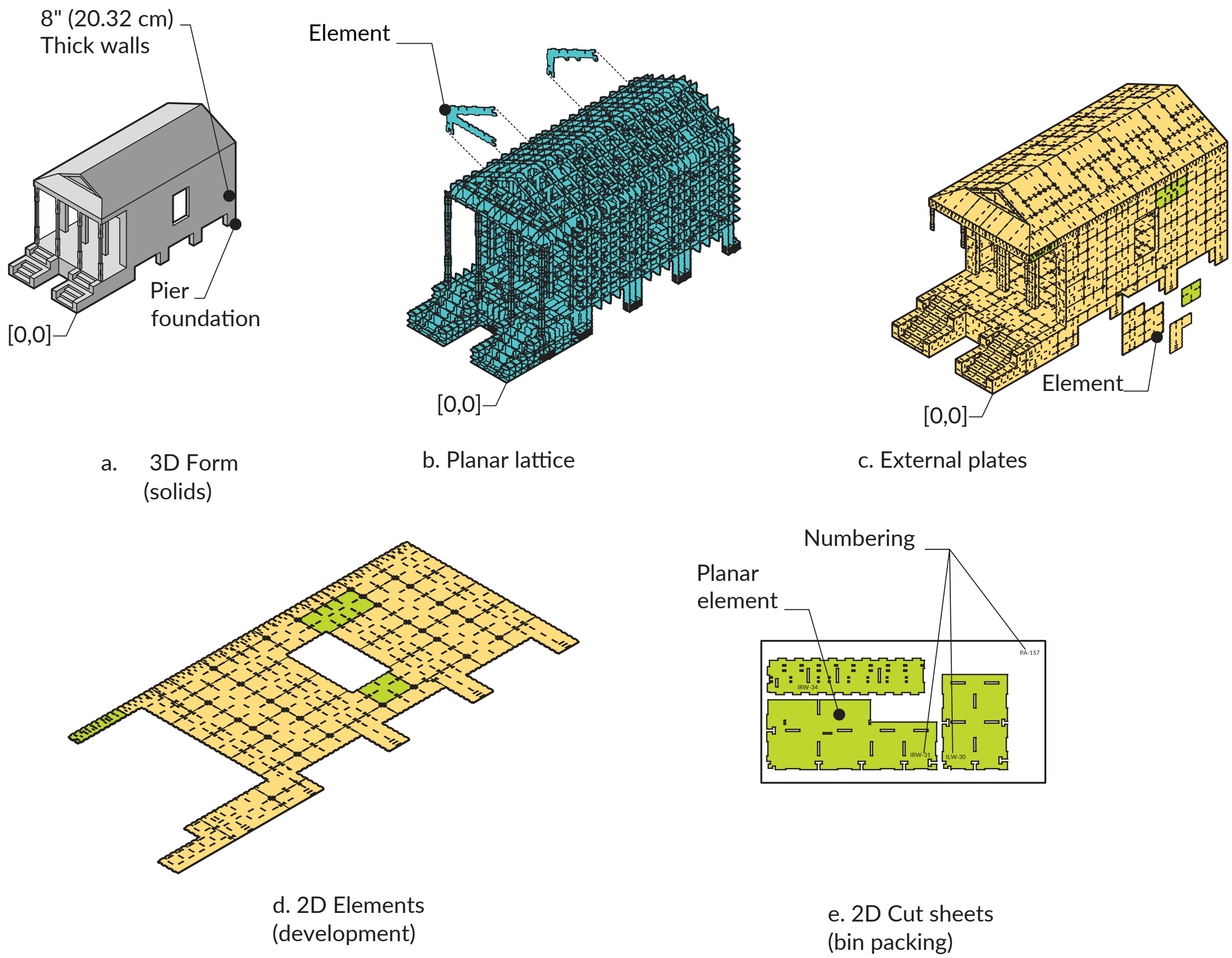
△ Figure 2. Digitally Fabricated House for New Orleans at MoMA, 2008.

Professional Digital Fabricators

Professional design fabricators have produced innovative examples of structures that function as actual houses. As early as 2007, Bruce Bell, Founder of Facit Homes in the UK, demonstrated the potential of digital fabrication as a reliable form of home delivery (Bell and Simpkin 2013). This development antedates the work of Wiki House (Parvin 2013), SI-Modular, Veneer House, Unbuild, and Construx in South Carolina. These professional examples are primarily digitally fabricated versions of wood framing (Albright et al. 2017). It is unclear if these companies have also digitally fabricated house details and finishes or if they were handcrafted.

Traditional, handcrafted wood frame construction presents many challenges. An enclosed house must withstand various forces from multiple directions. Carpenters construct the house frame using dimensional lumber and flat sheathing by standards and guidelines for wood framing (Sennett 2008). Most decisions are made not solely by applying rules; spontaneous decision-making is critical in a carpenter's thought process. Framing manuals, training systems, and shared knowledge are available among trade members. However, the digital models discussed in this paper do not encompass decision-making systems for structural modeling. It is questionable if they ever will. A significant challenge for the digital fabricator lies in discovering new forms of framing that will ultimately evolve beyond handcrafted fabrication into algorithms and machine languages for robots.

Facit Homes, U-built, and Construx have demonstrated that planar wood frames can be generated as professional products. However, a universal approach to modeling is missing. A universal grammar created explicitly for housing and digital fabrication



△ Figure 3. Decomposition for the Digitally Fabricated House for New Orleans from a form to elements ready for CNC fabrication.

will accelerate construction and reduce the initial steps in building structure production. A builder's grammar could also lead to integrating building finishes and framing.

Framework for Fabrication

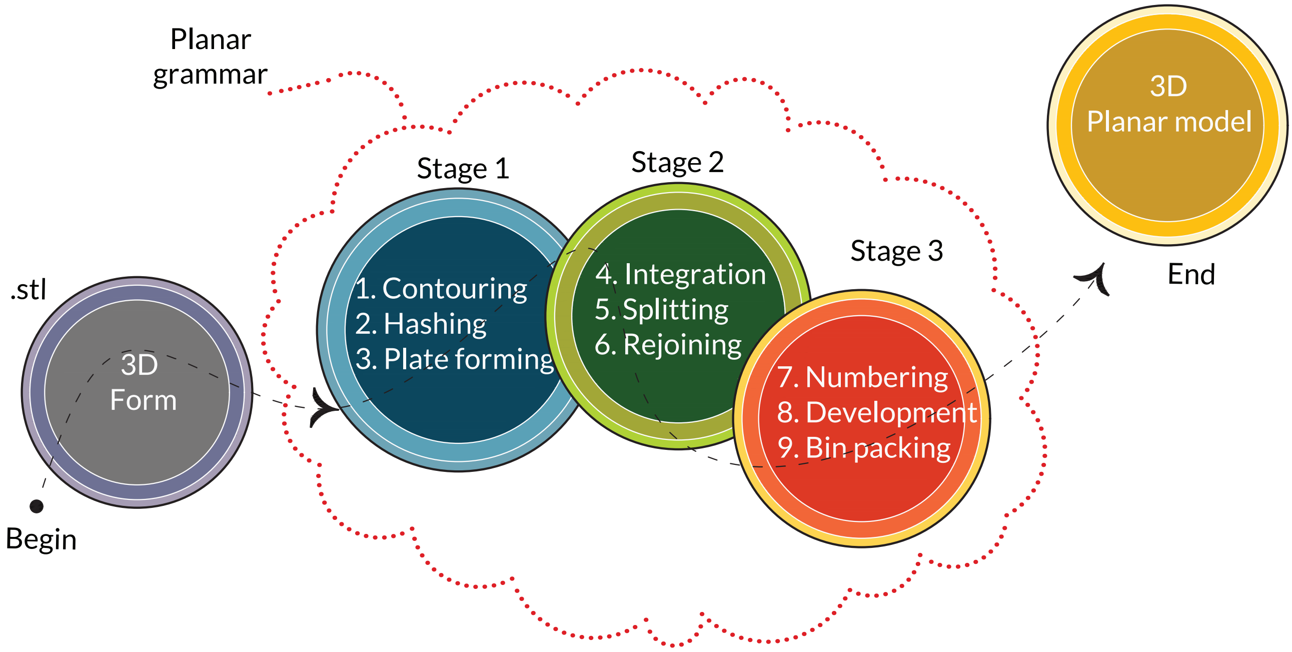
The early 2000s fabrication movement provided a conceptual foundation for the design and construction of the Instant Cabin. Gershenfeld defined the term "Fab" as a personal manufacturing initiative driven by the rise of digital fabrication and robotics (Gershenfeld 2005). He claimed that almost anything, from electronics to houses, could be produced through digital fabrication. However, his ideas on digital production were missing design, mechanical, and material decision-making systems.

A productive system is akin to a Shape Grammar, offering a geometric protocol for keystroke operations (Stiny, 1980). Shape Grammars are mostly visually based and not helpful for digital fabrication. A parameterized grammar, not a shape grammar, with rules that relate to physical needs and decision-making, is critical.

Last, a fabrication framework should include principles that guide the assembly of elements or Design for Assembly (DFA). A methodology borrowed from mechanical engineering aims to reduce the number of elements in a product (Boothroyd 2005). A framework for fabrication is systematic element generation, measuring, and quantification within any 3D modeling environment.

Modeling an enclosed structure for digital fabrication, such as a house, involves manufacturing thousands of associated planar elements in CAD. Each element serves a unique function and occupies a distinct position in physical space. Some elements in a physical frame must resist significant structural live and dead loads, while others brace openings in walls and floors. Each component must also include various assembly features of many types and purposes.

Generating a model of such complexity requires that the fabricator discover, reason about, and infer the purpose of each element and group of elements. Unfortunately, modeling each element for a specific need is cognitively overwhelming. An essential step in model production is element verification, which is achieved by visualizing on screen and through physical prototyping with laser cutters and 3D printers, necessary to verify that each component assembles correctly.



△ Figure 4. Planar Grammar stages and functions.

A Planar Grammar

A framework for producing the interlocking elements of a wood-frame house is presented. Following the grammar reduces cognitive overload and manages the modeling steps. A Planar Grammar applies rules for decomposing a starting 3D form into numbered interlocking elements in three stages. It is a linear grammar with starting 3D and ending two-dimensional requirements. The result is a Planar Model composed of 3D interlocking geometries similar in geometry, behavior, and time to assemble across scales and sizes. In other words, a desktop, laser-cut Planar Model requires a similar amount of time to assemble as a full-scale CNC (computer-numerically controlled) structure of the same geometry.

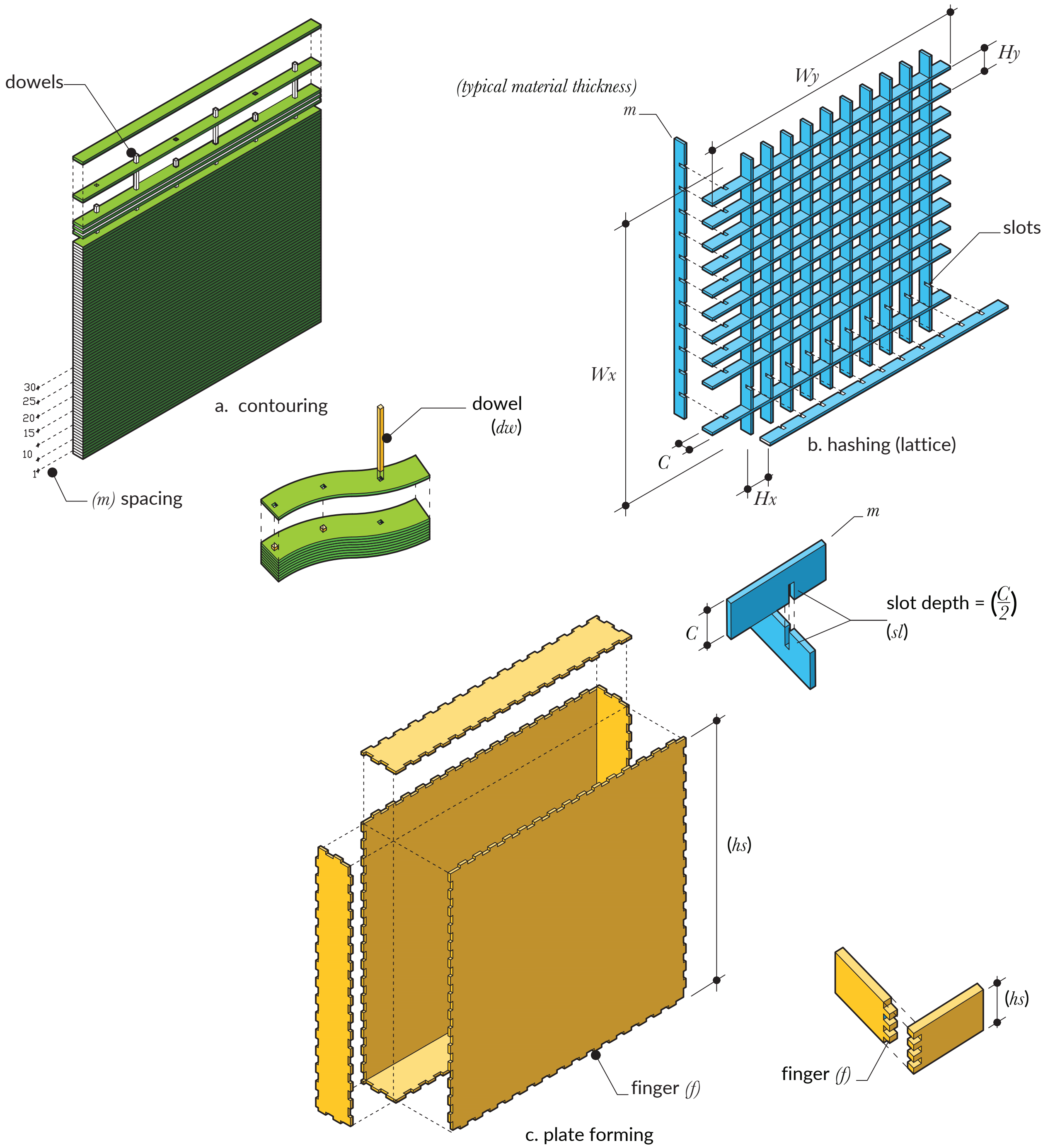
This Planar Grammar is a parametric system comprising graphical symbols, fixed constraints, and programmable procedures (Knight 1980). It resembles the commercially available generative software ArcGIS CityEngine (2021). A Planar Grammar is not a Shape Grammar because it does not allow for the varying forms of shape emergence found in a Shape Grammar (Knight 2003).

This Planar Grammar embodies physical constraints and rules from computing and mechanical engineering (DFA). The modeler applies these rules to a watertight mesh model to generate hundreds of thin, interlocking planes over three stages (Figure 3). Each stage serves as a significant moment in the decision-making process, requiring complex information. It is not possible to show the entire Planar Grammar here. A summary of the three stages within a Planar Grammar is illustrated (Figure 4).

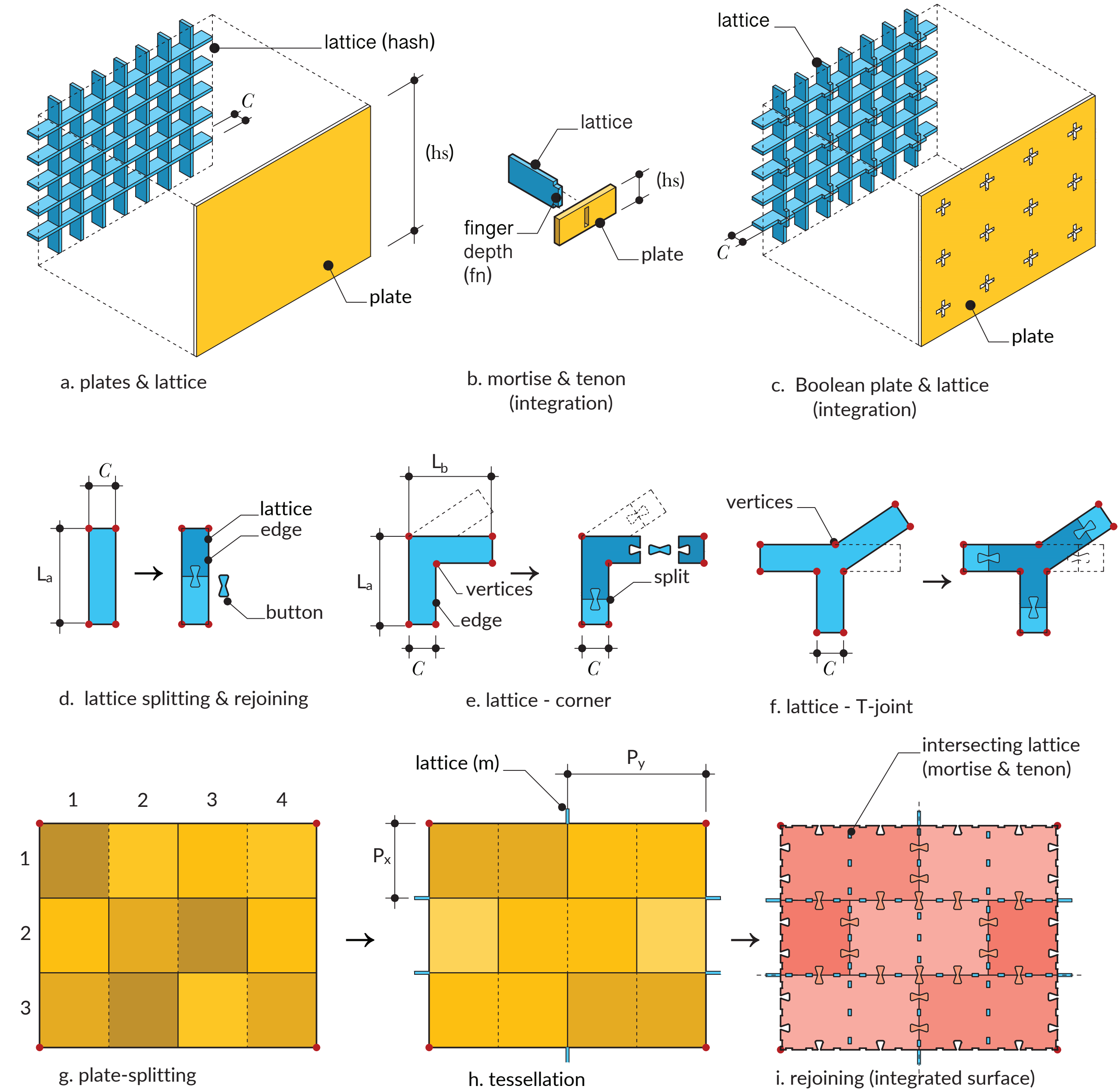
Stage 1: Primary planar descriptions are models built of interlocking, flat elements (Figure 5). First is **contouring** (a), followed by **hashing** (b) and **plate-forming** (c). Primary planar descriptions are assigned primary assembly features to the edges and intersections of each plane. These joinery systems are integral to each element and are a measurable method for controlling time and assembly strength (Messler 2011).

Dowels for contoured shapes (a), slots (b) for hash structures, and fingers (c) for plates are variable and affect assembly time depending on tolerances. These three primary descriptions can be formed by keystroking or can be programmable. Computer programs and scripts exist for generating these three descriptions (Wonka et al. 2003; Müller et al. 2006; Martinovic and Van Gool 2013; Sass et al. 2016).

The result of this stage is the construction of an internal lattice using a hash function and the external assignment of plates with finger joints together. The two structures in Figures 1 and 2 are walls, floors, ceilings, and roofs built by combining these surface and assembly descriptions. A wall typically combines hashing (lattice) and plate forming, with finger joints adjoining or ending walls. The walls of the Instant Cabin and the MoMA exhibition structure rest on a set of contoured elements attached to a concrete base. Each description works with a material of *(m)* thickness. In all cases, each assembly and wall type is computable and can be created generatively. These three primary descriptions are programmed into commercially available software, LuBan3D (2019).



△ Figure 5. Primary descriptions and assembly schemas.



△ Figure 6. Integration of lattice planes with plates and splitting methods.

Stage 2: The outer plates are **integrated** with the internal lattice by modeling mortise and tenon connections between the elements (Figure 6a–c). Mortise and tenon joinery are created by a Boolean difference when modeling. For computer programming, this type of connection is calculated mathematically.

Scaling a 3D form from an abstract desktop model to a full-scale structure requires **splitting** and **rejoining** elements to ensure a solid and strong object. Splitting the primary planes into small elements is guided by a boundary, such as a standard sheet of plywood. The boundary is also governed by weight. Lighter components are more straightforward to assemble by one person. Elements can be easily assembled, provided they do not exceed one square meter or exceed lengths La and Lb. After the parts are split, buttons rejoin plates along the seams.

Lattice splitting (d–f) cutting perpendicular to a plane's edge. Splitting does not occur inside corners (vertices) or where two lines meet. Plate splitting is similar (h–i).

△ Figure 7. H22 Structure as desktop prototypes (a and b) and finished structures (c and d).

However, plate length should also be limited to Px and Py and tessellated for added strength. Plates and lattice elements are rejoined to each other by buttons. Planar integration, splitting, and rejoining are the most challenging and not programmed stages in Planar Modeling. Splitting and integration between the lattice and plates are discovered by observation and assumptions, and tested by physical prototyping of laser-cut parts.

Stage 3: The final stage is generating data for machining and preparation for hand-guided assembly. The **numbering** of each element in 3D starts at the bottom front of the structure and increases in size by elevation. The challenge is numbering the plates in association with the lattice. Numbering is also organized from bottom to top, left to right. **Development** and **bin packing** functions copy elements from 3D to 2D with a specified number. Once all components are regenerated in 2D as polygons (not solids), elements are sorted linearly, from the largest to the smallest. Lastly, elements are packed within a defined boundary, with the largest element assigned to a sheet or boundary first.

Despite the challenge of learning how to compute graphical functions, Stage 1 (contouring, hashing, and plate forming) and Stage 3 (numbering, development, and bin packing) have been computer-programmed in LuBan3D (2019). However, splitting and rejoining functions, as well as integrating the plates and lattice in Stage 2, are not coded into computer software. The production of small elements and the assembly of a structure larger than square meters (> 3 m^2, >32.29 sq. ft.) requires material splitting and integration. The grand challenge of Planar Modeling is to devise a method that applies the nine functions to a starting form, thereby creating 2D elements as a single function.

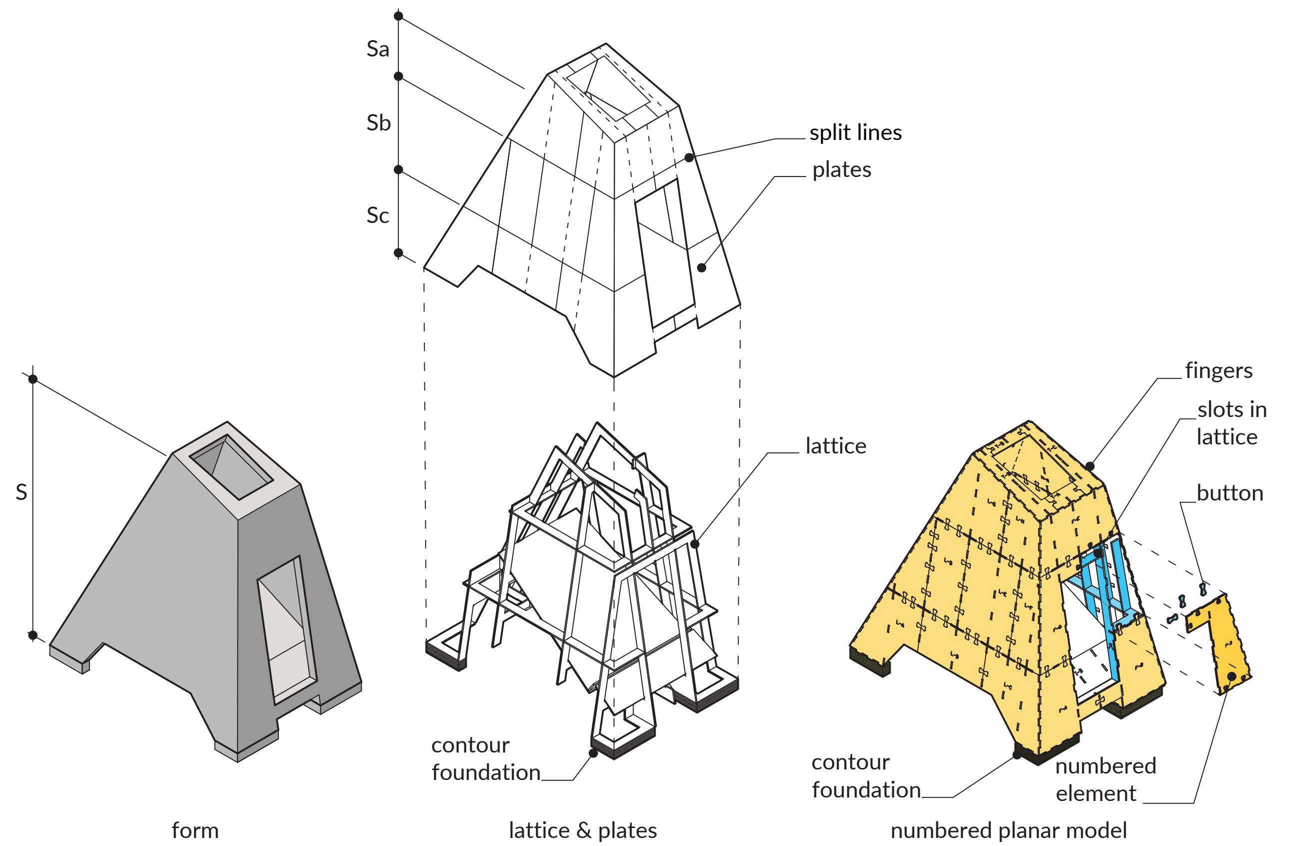
The grand challenge of Planar Modeling is to integrate these nine functions (Figure 4) into a single algorithm that builds functional walls, floors, and ceilings, producing an integrated surface (Figure 6i). We now utilize 3D modeling and high-level physical rules, symbols, and procedures, employing a Planar Grammar, to create structurally sound surfaces for objects exceeding three meters in square footage. 3D modeling allows the designer to discover, reason, and infer the best solutions when integrating, splitting, and rejoining planes.

Scalable Prototyping

The H22 festival in Helsingborg, Sweden, in the summer of 2022, provided a new opportunity to challenge Planar Modeling, prototyping, and scaling. MIT students were commissioned to design and build three shelters in the forest. In summary, six students designed three shelters in groups of two. I generated three Planar Models from the students' 3D forms and emailed the machine geometry (2D) only to Poland for fabrication by a subsidiary of IKEA. Six students and I assembled the three shelters on-site in Sweden for 10 days as a group. Incremental scaling from desktop to full-scale construction provides a measurable error detection system in modeled geometry.

This project demonstrates the random and spontaneous nature of lattice and plate splitting. Many desktops, planar models were constructed to explore design form, lattice construction, planar splitting, and modeling efficacy across a few scales (Figure 7). Photos of the process show a 3D-printed desktop model (a) and a one-eighteenth full-scale model, used to examine and confirm the overall shape of the design. The second model, one-seventh full-scale, was a Planar Model constructed of interlocking, laser-cut elements (b). The full-scale finished shelter of the yellow structure is in the photo just beyond an adjacent structure (c). Each of the three shelters was crystal-like in shape.

The stepped process used to decompose the first structure (yellow) is shown in Figure 8. A formal model is our starting point, culminating in interlocking, numbered, planar elements. The exterior surfaces or plates of this structure were angled inward, held in place by an interlocking internal lattice. Plates and the internal lattice are not perpendicular to the ground plane. Decomposition was constrained by the limited size of the stock material from which the elements were made. Decomposition was also limited by the weight of each component, where larger parts are found at the base of the shelter and smaller parts at the top.



△ Figure 8. Shelter splitting and rejoining.

Prototyping, like modeling, enables a deeper level of understanding when it comes to computation. Design Fabricators who generate models by keystroke and mouse must discover modeling errors and confirm geometry through physical prototyping, such as laser-cutting a scaled Planar Model. For example, a Planar Model CNC fabricated at full scale of 19.05 mm (3/4 in.) thick planes can be scaled by 1/7 and fabricated from material 3.175 mm (1/8 in.) in thickness. Incremental scaling, of this type, is a method for prototyping, measuring, managing, and correcting errors in digital models before full-scale digital manufacturing (Figure 9).

Planar Computing

As we explore the potential roles of AI and machine learning in design, this paper's examples demonstrate the potential of large-scale digital manufacturing of planar elements, rather than construction with dimensional lumber. It also shows how a high-level, visual Planar Grammar can scaffold 3D modeling and programming decisions for construction. This production method should lead to a fully programmable model of the planar output, where most complex decisions are resolved spatially by a large language model (LLM). LLMs for design and construction will be composed of vector-based visual rules. Ideally, a fully programmed Planar Grammar can be a recursive generative system for 3D modeling of hundreds of homes from unique forms (designs). Until then, 3D modeling and physical rules, a Planar Grammar, provide a system to evaluate the production of elements and machine code. Most importantly, this Planar Grammar provides methods for computing our designs for real-world production.

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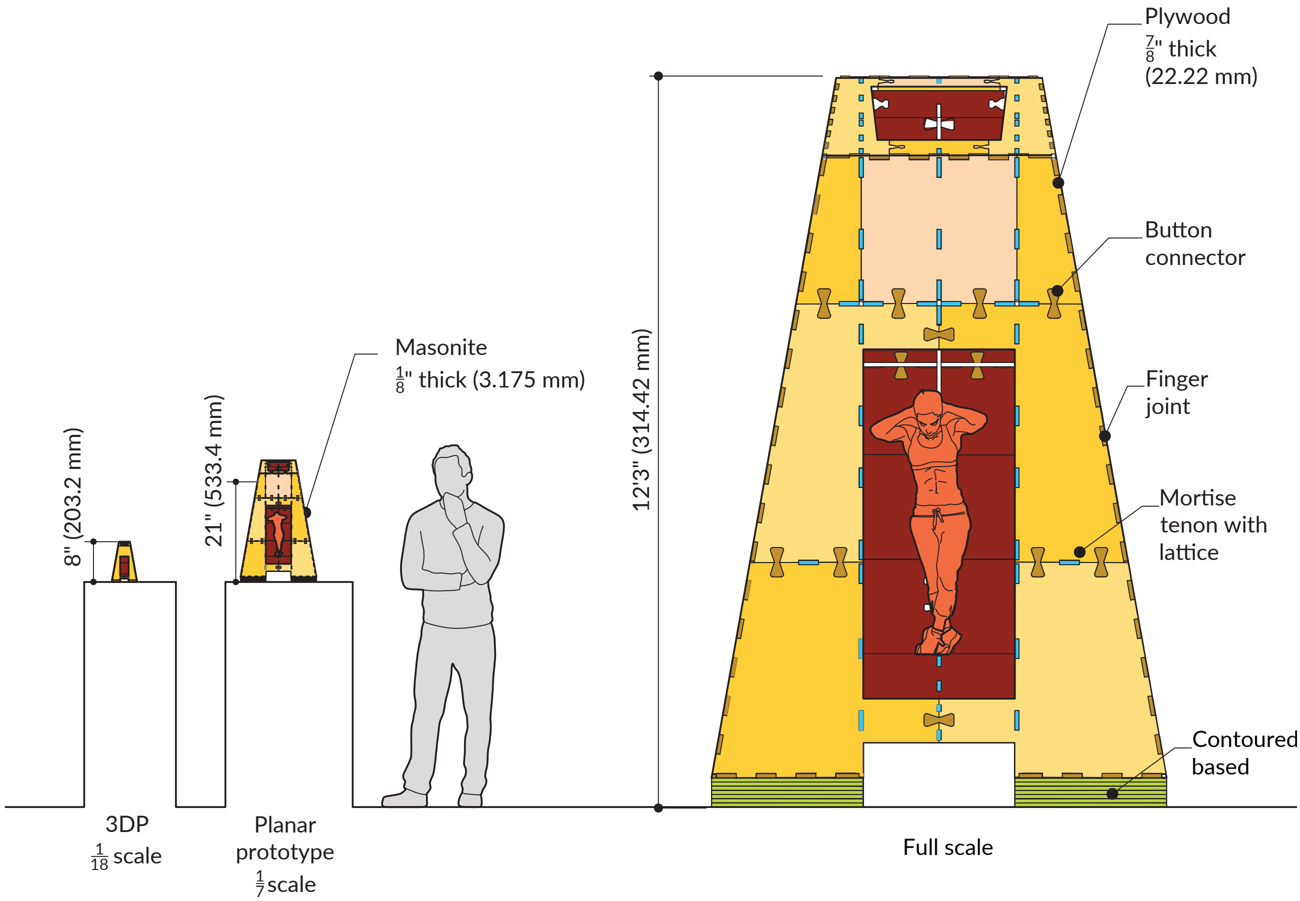

△ Figure 9. Planar modeling description from abstract prototyping to full-scale.

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