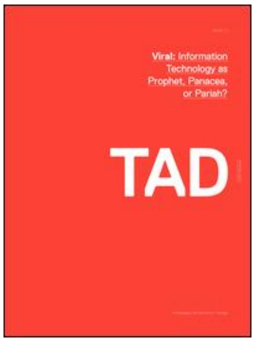

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Assembling the Digital House by Hand: Lessons from Deep Engagement and Guiding the Experimental Impulse

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The potential impact of digital fabrication for housing has been an intriguing topic of speculation for many years. Working prototypes and production models, however, are still few in number. Meaningful innovation in this space requires deep knowledge of conventional light-frame construction methods and available industrial fabrication technologies. Solutions must also present a compelling combination of economic, environmental, and social advantages. Designed to balance "high-tech" production technologies with accessible "low-tech" material and assembly solutions, the Indigo Pine project and its associated flat-pack construction systems offer a reference point for comprehensive development, deployment, and evaluation of new digitally fabricated technologies.

Introduction

In an essay accompanying the influential 2008 *Home Delivery* exhibit at the Museum of Modern Art, curator Barry Bergdoll contemplated the emerging role of digital tools for prefabricated housing. While recognizing the power of design computation, he also noted the need to marry this "algorithmic prowess" with a "logic of making." He concludes with a challenge:

> The challenge for the next generation is to pursue a deeper engagement with the techniques of fabrication and an expansion of the range of issues that the experimental impulse is poised to tackle. (Barry Bergdoll, *Home Delivery*)[1]

The development of the Indigo Pine House and its *Sim[PLY]* framing system could be characterized by its relationship to the dual facets of this challenge. The result of a two-year cycle of design research and iterative prototyping, the house employs computer numerical control (CNC)-fabricated assemblies throughout (Figure 1). This was not a goal from the outset but rather became the ideal path to realizing other critical performative and social objectives identified by the design team. As a guide to this form of production, project faculty worked to train students' focus on the internal logic of the assembly systems themselves rather than getting preoccupied by potential external applications. Therefore, the expanded "range of issues," in this case, related more specifically to questions of material economy, embodied energy, user accessibility, ease of assembly and disassembly, construction safety, and thermal and structural performance.

Platform framing with dimension lumber has been the dominant construction method for detached housing in the United States for over sixty years.[2] It is also widely used for multifamily and light commercial applications, and its techniques have been increasingly utilized for off-site prefabrication. Today, the widening availability of CNC routing tools opens the door for new forms of light construction, which couple the benefits of prefabrication with unique opportunities for front-end optimization and customization. This article presents a new CNC-fabricated plywood building system, details of its mechanics, and observations from full-scale prototype structures, all while addressing each of the previously stated range of issues and considering how its performance in these areas represents certain advantages over conventional light framing methods.

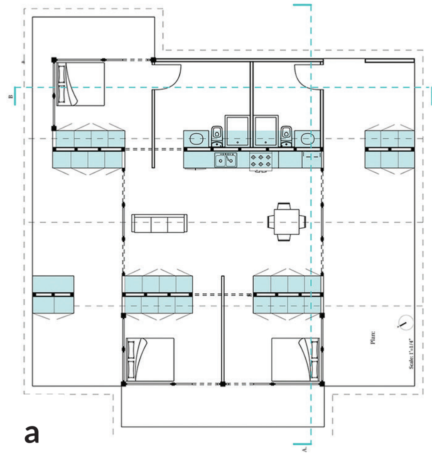
The Sim[PLY] system was developed through a faculty-directed student project at Clemson University. While not the focus of this paper, the educational environment and certain related strategies are necessarily presented here to contextualize system developments and the stages thereof.

Project Setting

The 2015 Solar Decathlon Competition,[3] for which the Indigo Pine House was designed, provided an ideal framework for identifying and addressing the topics of carbon footprint, constructability, and performance alluded to above, and an ideal setting for testing our unique delivery and assembly solutions. While the competition focus is limited to balancing end-use energy consumption with solar energy production, its format presents other demanding constraints that we identified as opportunities for broader innovation. Namely, the team faced a short window for on-site assembly, connection, finishing, and furnishing (9 days), a shorter window for disassembly and removal (5 days), all with unskilled student labor, and on a site in Irvine, California, that is 2,300 miles (3,701.49 km) from our campus.

With such parameters in mind, competitors routinely turn to off-site modular construction, accepting the negative trade-offs of carbon-intensive shipping and top-down final assembly with heavy equipment and trained operators. Alternatively, we imagined lighter methods of on-site construction that balance speed, accuracy, and safety—methods that front-load external equipment needs and minimize energy required for transport and assembly. This article provides an overview of the resulting systems, the digital fabrication techniques leveraged for their manufacture, and the essential space of the hand for working and joining the elements.[4]

◁ Figure 1 (Previous page). CNC-fabricated framing. Photograph by Neely Leslie. Reproduced with permission.

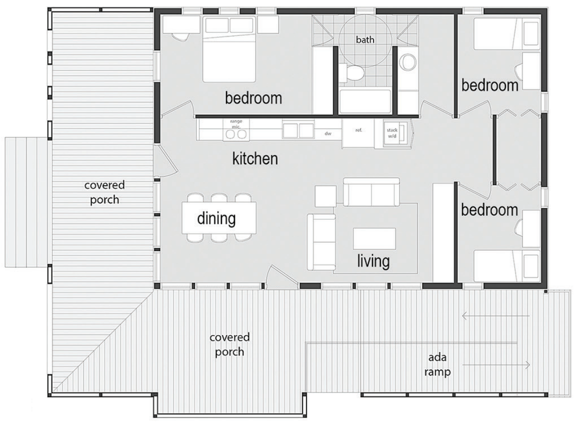


▷ Figure 2. Floor plan progression: (a) the Cabinet House by Kendall Roberts (reproduced with permission); (b) Indigo Pine House, schematic design; (c) Indigo Pine House, as-built.

Foundations

The driving incubator for this project was the revolving graduate architecture studio. An initial studio featured an exercise, titled the *Haiku House*, in which students designed small prototype houses with dual emphasis on prefabrication and adjustability to local conditions. This introduced a kind of systematic thinking and led to concepts for panelization, parametric façade elements, and flexible interiors. Throughout these maneuvers, students were encouraged to maintain an economy of form and material. This was reinforced through simple kirigami paper models that invoked automated cutting (with cutting printers) and manual folding, operations that persisted through each of the developmental phases to follow.

One resulting scheme provided an intriguing floor plan organized around reconfigurable cabinet subassemblies. Subsequent developments never strayed far from this plan and its strategy for dividing spaces (Figure 2). Rather, it was the means and methods of assembly that became the primary research focus of the project.



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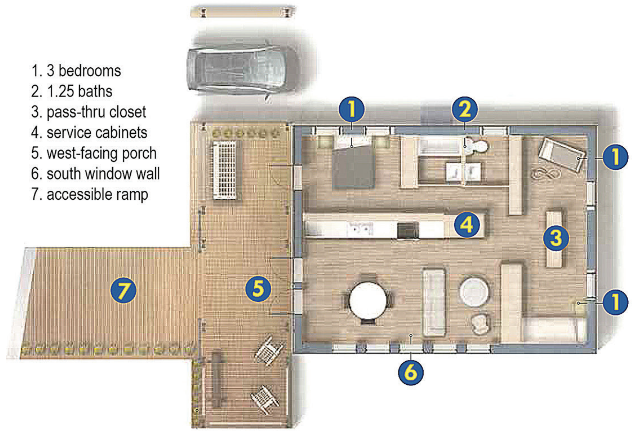

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Framing Questions

The second studio began with a detailed analysis of conventional light wood framing methods. The vehicle was a full-scale building exercise. The *Solar Shed* study utilized in-line construction with dimension lumber and required a sequence of preassembly, transportation, and final reassembly. This pushed students to explore prefabricated wall and roof panels, their connections (both within-panel and panel-to-panel), and their documentation. The exercise ultimately led the team to question these methods and articulate a set of specific concerns.

Regarding execution, there were concerns with conventional tools of the trade, such as nail guns and power saws, which present safety hazards, are loud and energy consuming, and require distinct skills. The nails, while fast, also render the construction irreversible. Additionally, wall and roof panels were heavy and difficult to set without external equipment.

Regarding thermal performance, even the most efficient in-line framing scenarios contain frequent thermal bridging and are limited in cavity depth. "Advanced framing," for example, is an efficient in-line technique using 2×6 studs at a 24" (60.96 cm) on-center spacing, plus single top and bottom plates. For an average 4 ft (1.22 m) wide by 8 ft (2.44 m) tall section of wall, this equates to 378 in^2 (0.24 m^2) of direct thermal bridging (or 8.2 percent), including top and bottom plates, while the maximum cavity depth for insulation is 5.5 inches (139.70 mm).[5] Alternative techniques, such as double-stud and Larsen truss framing, provide deeper cross sections with limited bridging, but at the expense of added materials and complexity.

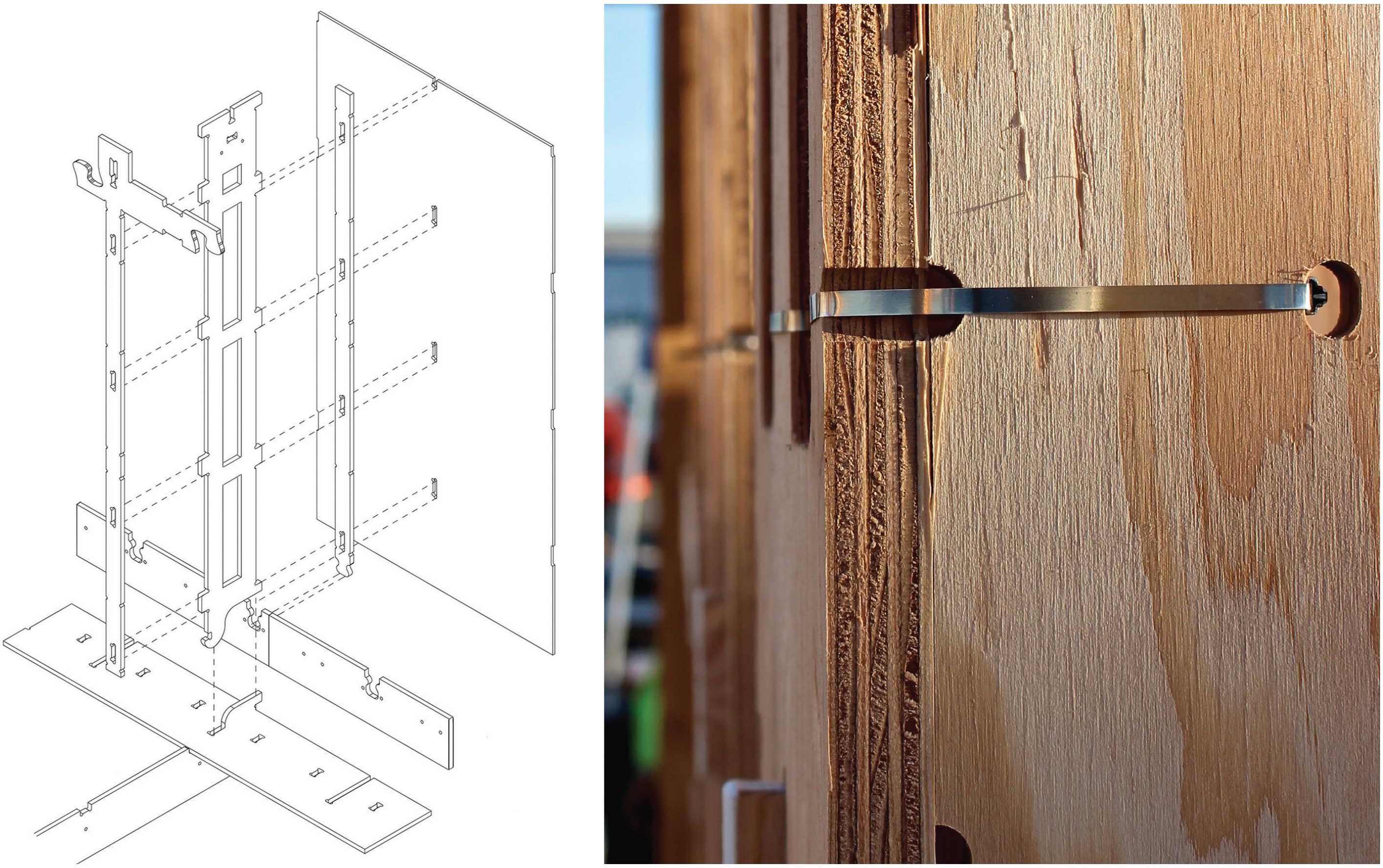
Finally, regarding transportation and on-site logistics, there were competing concerns regarding shipping options, construction time, and carbon footprint. Utilizing prefinished panels could reduce assembly time through prefabrication and allow for transportation by rail, a carbon-efficient method. Alternatively, off-site modular construction could reduce final assembly time even further, but at the expense of added transportation energy if module sizes exceed the limitations of rail transport.[6] Quick calculations using an average single-story house weight[7] of 50 psf (244.1 kg/m^2) and the 972 ft^2 (90.30 m^2) footprint reveal that shipping the Indigo Pine house in modules by truck to the competition site would expend 14.43 US tons (13.09 tonnes) in CO_2 emissions.[8] This equates to 193.4 percent of an average household's annual emissions from electricity use.[9] Moreover, both modular and panelized scenarios require heavy, energy-intensive equipment and experienced operators at both ends of the delivery chain for moving the constructed elements. Both also require spacious, clear construction sites for positioning and setting these elements.

These concerns led the design team to contemplate alternative methods that could combine the best attributes of on-site and off-site construction. The team targeted new construction solutions that could offer the speed and ease of in-line framing; the performance of highly insulated, thermally broken walls; the precision, efficiency, and waste stream management of prefabrication; the site sensitivity of lightweight, ground-up assembly; the benefits of nondestructive disassembly; and a safe, smooth, and accessible job site. These goals served to guide the development of the Sim[PLY] framing system and other compatible technologies employed in the Indigo Pine House.

Digital Alternatives: Systems Overview

In response, and over the course of three more semesters, the design team turned to CNC prefabrication to deliver comprehensive alternatives. In the tradition of wooden kit houses, and the more recent examples of Botha and Sass's digital house[10] and the open-source WikiHouse project,[11] among others,[12] the Sim[PLY] framing system comprises a network of precise, numbered components cut from 3/4"-thick (19.05 mm) structural plywood sheets—a widely accessible and standardized industrial product with relatively low embodied energy.[13]

A viable plywood framing system demands careful connection strategies, addressing a range of geometric conditions and load-transfer scenarios. For example, an edgewise orientation for wall, floor, and roof members is essential for efficient performance,



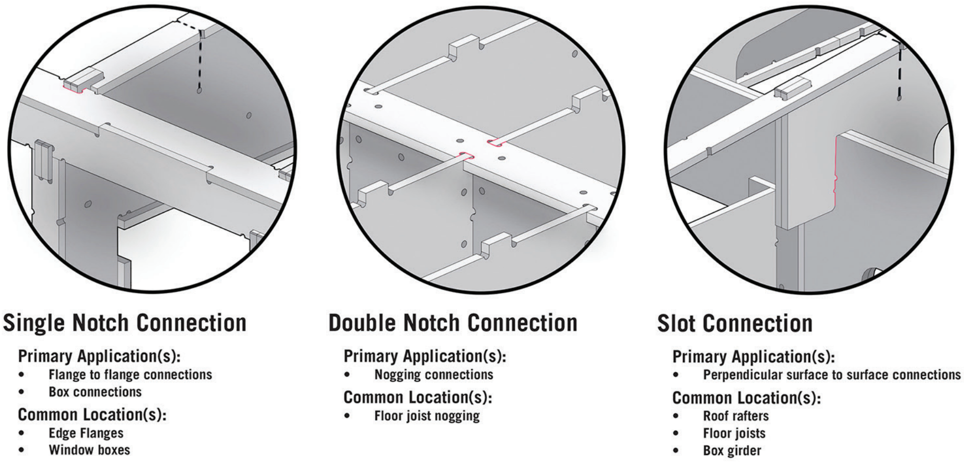
△ Figure 3. Sim[PLY] stud details. Drawing by Rebecca Wilson; photograph by Neely Leslie. Reproduced with permission.

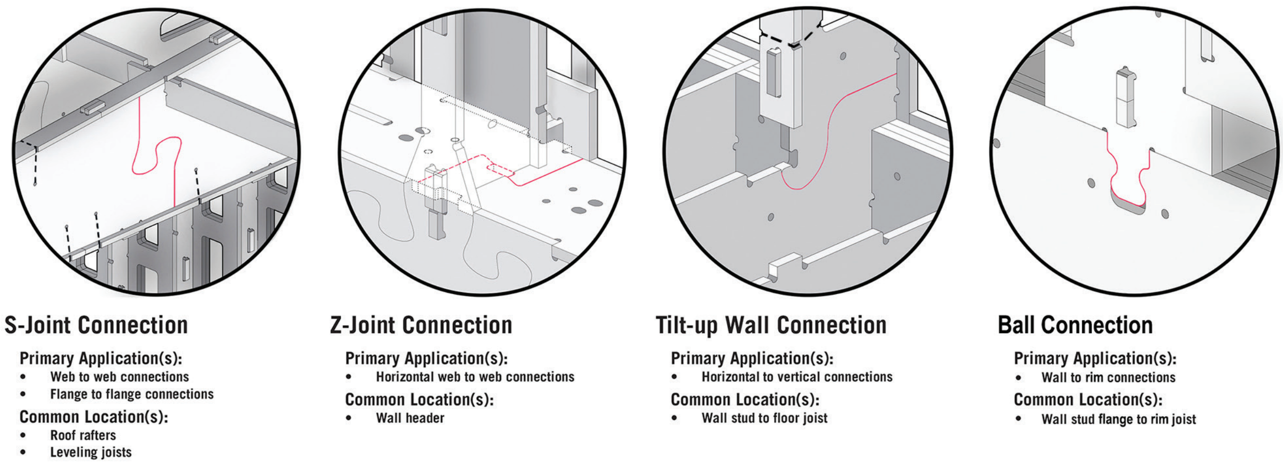
both structurally and thermally. However, fastening into the edges of plywood causes splitting and tear-out. Therefore, Sim[PLY] studs, joists, and rafter subassemblies employ perpendicular flanges to receive exterior sheathing and interior finishes. Flanges are fastened with tab and slot connections and stitched together with steel cable ties to prevent out-of-plane slipping or withdrawal under negative wind pressures (Figure 3). Final assembly requires only simple, hand-powered cable tie guns and rubber mallets, promoting an energy-efficient, quiet, and safe workflow.

Super-insulated envelopes are easily accomplished by managing the depth of the web members in the cut files. The 12" (304.80 mm) walls of the Indigo Pine House achieved insulating values of R-33 to R-39 from the insulation alone, depending on the combination of cellulose batts, which are available in 3.5" (88.90 mm) and 5.5" (139.70 mm) thicknesses. R-42 is possible with a full 12" (304.80 mm) of blown-in cellulose. Moreover, thermal bridging is mitigated by extracting unnecessary web material, a measure that also provides for integrated passage of electrical wiring and other services. Using the Sim[PLY] framing system, an average 4 ft by 8 ft (1.22 m × 2.44 m) section of wall has only 108.75 in^2 (0.07 m^2) of direct thermal bridging (or 2.4 percent).

Beyond the basic tab/slot/tie combination, additional joints were utilized to address other unique framing conditions (Figure 4), such as the S-joint for in-plane splices. This joint is used for rafter spans longer than 8 ft (2.44 m). To prevent buckling, Sim[PLY] rafters use a double web with offset S-joints. The tilt-up and ball connections, on the other hand, serve to guide and then lock the walls into standing position (Figure 5), while providing basic uplift resistance and mitigating the need for temporary external bracing—a nuisance and hazard on typical construction sites. A void at the base of the ball is sized for a pry bar. This, like the use of the cable ties, enables rapid and nondestructive disassembly,[14] a distinct advantage over other methods.

Interior divisions in the Indigo Pine House were comprised of reconfigurable cabinetry units. Cabinet walls and soffits were also designed for CNC fabrication and, like the structure, can be flat-packed for on-site assembly or can be preassembled off-site into larger subassemblies for rapid installation. Cabinetry components are non-load-bearing, so final assembly, in either





◁ Figure 4. Sim[PLY] connections. Drawing by Allie Beck and Jeff Hammer. Reproduced with permission.

scenario, is conducted inside the completed envelope.

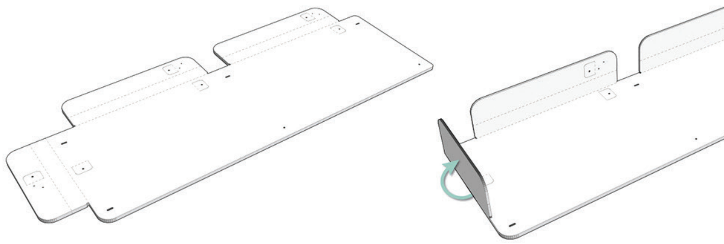
The exterior skin followed conceptually from the fabrication techniques of the frame and cabinetry—beginning with the structural sheathing panels, which were prerouted to receive extended stud and rafter tabs for a self-aligning installation, and prepiloted for the engineered screw spacings. For speed, interior wall and ceiling panels worked the same way as exterior panels. However, in other applications, web tabs could be truncated in the CNC cut files to accommodate drywall or other conventional finishes. The selected exterior sheathing product featured an integrated moisture barrier. All seams and exposed tab/slot locations were taped for continuous protection.

Façade panels were precut from 4 mm thick aluminum composite material (ACM) to precise dimensions and also scored in the CNC operation to make fold lines. The folds are executed by hand and secured with pop-rivets to produce a rigid rainscreen panel, with an integral 2" (50.80 mm) spacer for ventilation (Figure 6). Once folded, the panels are screw-fastened to the sheathing and riveted to one another at the overlaps. Window surrounds were similarly fabricated from ACM components. They provided passive shading and supported simple, commercial planter boxes—one illustration of the vast potential for customization offered by digital fabrication (Figure 7). In the façade, as in the structure, the recurring cycle of automated processing followed by distinct manual operations recalls the early kirigami models and makes space for active end-user participation in pre- and final assembly operations.

Workflows

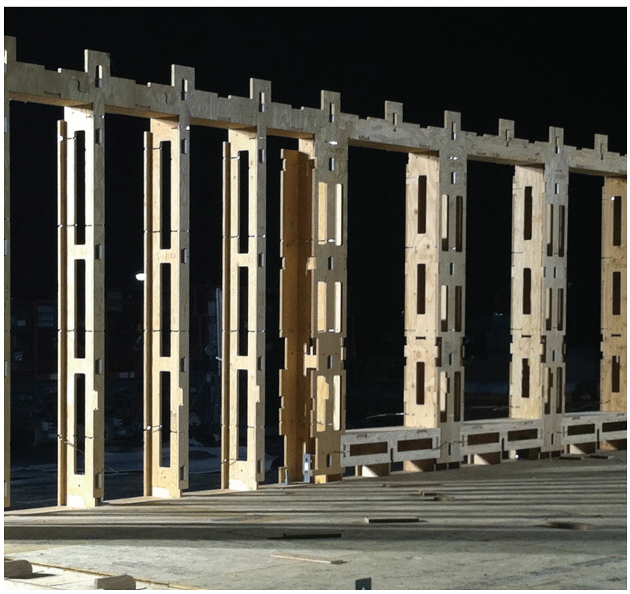
This sort of oscillation between digital and physical realms was also a key factor for successful concept development, and for establishing patterns of deep engagement with issues of fabrication. Needless to say, the design team did not arrive quickly or even linearly at the solutions described above, but rather through cycles of 3D visualization, translation to 2D production files, and physical prototyping from cut files. In this scenario, BIM was an essential tool in which every virtual component carried an identity and specific data, such as number of occurrences, linear perimeter, and volume. This information was useful for everything from shipping considerations to embodied energy estimates.

The translation from 3D BIM elements to 2D cut files involved its own subroutines, most importantly encoding the CAD line types for specific bit sizes, speeds, and routing depths, as well as nesting operations for optimal material efficiency. Nesting software works by placing a distinct set of component profiles onto sheets of a given size in an arrangement that minimizes wasted material, or "drop."[15] Drop material is easily managed at the point of fabrication, where it is collected for recycling. Both plywood and ACM sheet goods are fully recyclable.



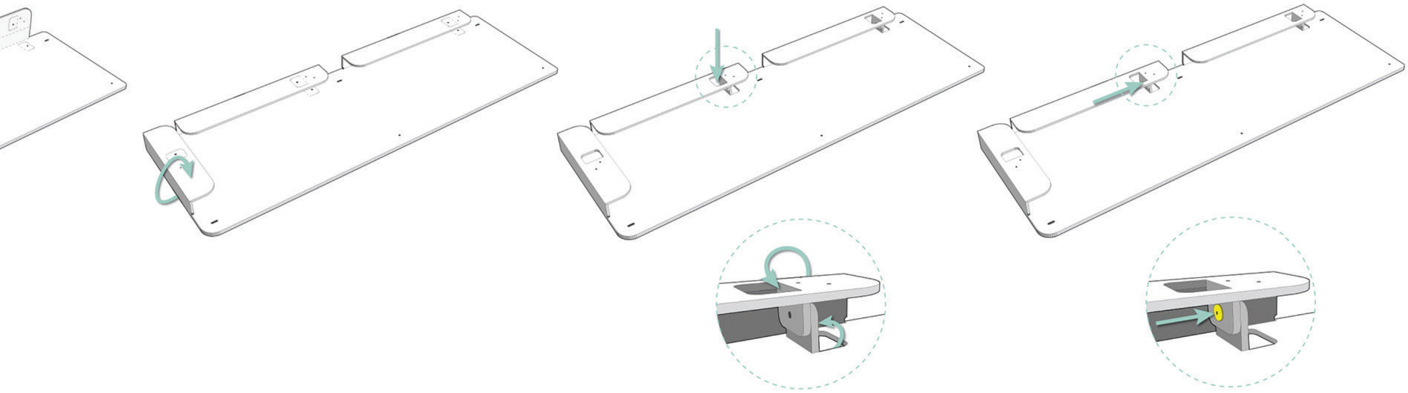
The Role of Prototyping

Prototyping was conducted at multiple scales, depending on the particular questions at hand. Scaled laser-cut models were quick, inexpensive, and useful for mimicking proposed construction sequences. Iterative full-scale mock-ups, on the other hand, were critical for understanding material qualities, connection behaviors, and constructability issues.



Over the course of the Indigo Pine project, and leading up to the competition house, full-scale prototypes ranged in scope from numerous partial assemblies to two completed structures. Smaller assemblies were fabricated using in-house three-axis machines, promoting rapid cycles of design development. Within the span of a single studio session, students were able to move from the BIM model to producing physical parts, assembling those parts, and noting any modifications warranted for future iterations (Figure 8). Modifications adhered to the following set of governing criteria: improved structural performance; easier to assemble and/or disassemble; reduction in complexity; reduction in material; reduction in unique parts; and improved durability. Adjustments often related to tolerances and fit. The ball joint void described earlier was made for disassembly but also improves assembly and durability by reducing unnecessary joint friction, all without diminishing structural performance, as bearing area is maintained where it is needed to resist uplift. Most significantly, early mock-ups revealed the limitations of balloon frame schemes, which offered no good options for spanning openings and relied too heavily on S-joints for vertical continuity—joints that are difficult to execute in place. These schemes gave way to platform frame models with structural headers, in which any necessary S-joints run perpendicular to the webs and are executed facedown on the deck before erecting.

Specific prototypes were also produced for the purpose of structural testing, which was necessary to verify code conformance. In addition to prescribed gravity loads,[16] the Sim[PLY] system was designed for the high lateral forces of Seismic Design Category D2,[17] and the 135 mph (217.26 km/hr) winds of coastal South Carolina. A series of physical, "single-fastener" tests were performed to examine the strength and behavior of discrete system connections. This included shear tests of the tab and slot joint (Figure 9a), tension tests of the cable ties (Figure 9b), and both shear and withdrawal tests of the sheathing screws (Figure 9c and 9d). Structural grade 3/4" (19.05 mm) 7-ply Douglas Fir-Larch plywood was used throughout to match material available for the competition house. Tests followed recognized ASTM protocols,[18] and NDS factors of safety[19] were applied to inform the number, frequency, and location of these basic connections within the framing. For example, the average factored shear capacity of the tab and slot connection



◁ Figure 5. Sim[PLY] wall erection. Photographs by Alison Martin and Dustin Albright. Reproduced with permission.

△ Figure 6. Façade panel preparation and installation. Drawing by Allie Beck, photo by Neely Leslie. Reproduced with permission.

was 613 lbs (2.73 kN), and failure occurred at an average displacement of 0.4 inches (10.2 mm). Using these results and the maximum expected lateral loads, the Sim[PLY] wall studs required 0.0425 tabs per square foot (0.4575 per m^2) at the critical east and west walls. Similarly, the cable tie tests demonstrated an average ultimate tensile capacity of 268 lbs (1.19 kN). It was determined that one cable tie per 4 ft^2 (1.22 m^2) is sufficient for resisting negative wind pressures.

Other structural testing was performed on full subassemblies, including 3-point rafter bending tests and shear wall racking tests. Bending tests of the 13 ft (3.96 m) south rafters followed ASTM Standard D4761-13[20] and were critical for analyzing the performance of the offset S-joint. Specimens demonstrated adequate stiffness, and the average moment capacity of 6,431 lb-ft (8.72 kN*m) far exceeded the required capacity of 2,062 lb-ft (2.796 kN*m), indicating that the rafters were, in fact, overdesigned—something to consider in the future.

Racking tests were performed on two 8 ft × 8 ft (2.44 m × 2.44 m) Sim[PLY] shear wall assemblies (Figure 10b). These tests followed ASTM Standard E564-06[21] and examined overall wall stiffness plus the interrelationship between specific joint behaviors. The racking displacement was measured at the upper left-hand corner, opposite the applied load. Other measurement locations verified that the walls were adequately secured during testing (Figure 10a). Results showed that the walls resisted an average ultimate load of 1,230 plf (17.95 kN/m) before failing according to the following sequence: compression failure in stud farthest from load application; tension failure at the top of the nearest stud; tension failure of the bottom of nearest stud. The ultimate load and failure mechanisms were within the accepted range of behaviors. Tests also demonstrated that the integral hold-down mechanisms of the tilt-up and ball joints are effective but should be supplemented with periodic external hold-down anchors[22] in order to satisfy the requirements for initial stiffness set forth by the most stringent lateral force resistance standards. This additional measure was carefully observed for the subsequent Indigo Pine competition house. All test results and conclusions[23] were reviewed and approved by the project engineer of record and the Solar Decathlon building official.

In addition to the partial assemblies from the load testing, two full structures were completed using the Sim[PLY] system prior to the October 2015 competition. Both spurred further development of the physical details while also providing critical audits on the processes of fabrication, assembly, disassembly, shipping, and receiving. The first full structure was the *Crop Stop* kitchen, a for-rent commercial kitchen prototype for farmers in nearby Greenville, South Carolina (Figure 11a). This project was made up of two volumes framed with Sim[PLY], this time with 8" (203.20 mm) wall cavities. It also included an outside canopy of conventional lumber construction. The Sim[PLY] components were routed, packaged, and shipped by an external fabricator, giving the design team a first chance at coordinating with industry professionals and their protocols. The volumes were assembled in separate locations using separate crews of students, and later disassembled, repackaged, and transported to Greenville for reassembly on the project site. This process yielded maximum experience with assembly and disassembly, and in the packing and transportation of components.

The second full structure (Figure 11b) was version 1.0 of the Indigo Pine House, called *Indigo Pine East (IPE)*. Outside fabricators were used again, acting in turn as subcontractors and advisors, giving the team clear pictures of costs and production coordination. The construction of the IPE house was treated as a dry run for the competition. On-site sequencing (described in the following section) was carefully planned, and competition safety procedures were strictly followed. As it progressed, the build suffered various delays stemming from misalignments and other geometric flaws in elements that had yet to be tested physically.

Necessary modifications were again identified and followed the previously stated set of criteria. Numerous superfluous tabs would be eliminated throughout the frame to ease assembly and reduce complexity. The integral slotted joints, already an improvement over external joist and rafter hangers, would later be tapered to better receive framing members. Similarly, all tab corners would be rounded to make flange and sheathing installation easier, while also reducing the likelihood of crushed corners, thereby improving durability. S-joints in the header stiffeners, which had posed problems for sequencing, would be replaced. The resulting solution reduced complexity and enabled flexible, incremental installation after walls are erected, rather than ill-fitting wholesale installation beforehand (Figure 12). The corner panels of the façade system at IPE also provided an instructive case, as their lengths had not been adjusted to account for the overlapping between courses. This caused incremental stress accumulation at the corner seams and resulted in splitting at upper courses. These and other cases punctuated the realities of material thickness and behavior, and the importance of tolerances and designing for in-the-field adjustment, all of which can be overlooked or masked in the digital design space.

Evaluation: The Competition

The Solar Decathlon competition was a unique design constraint that dovetailed well with the team's objectives of increased energy consciousness and social engagement while also providing the added pressures of short on-site assembly and disassembly schedules. Given the number of parts to produce, as well as the benefits of industry involvement and feedback, the team again opted to work with an outside CNC fabricator for the production of the competition house, *Indigo Pine West (IPW)*, this time pairing with a nearby start-up fabricator/design-build contractor. In this scenario, our partner contributed its general experience in the digital production of building assemblies plus specific oversight in the areas of tool path preparation and the nuances of their equipment.[24] This was the case for all of the CNC-fabricated components of the house, including the Sim[PLY] frame, cabinetry, and façade panels. From this facility, the finished components were organized and flat-packed for shipment by rail to California for the competition.

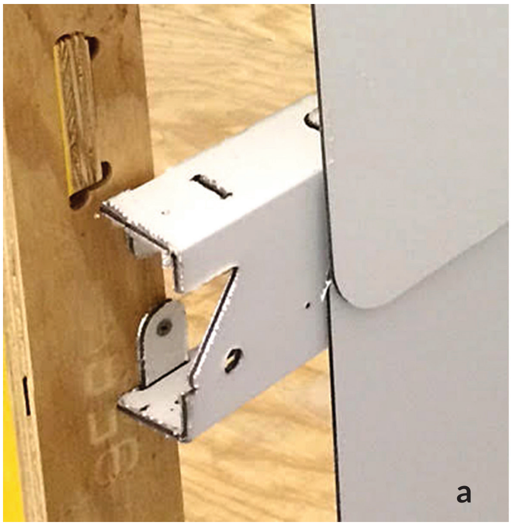
At the build site, the team laid a unique mat foundation system consisting of staggered, side-stacked CMU blocks, which was designed as a thermal mass air plenum to provide passively cooled or heated air to the condenser of the mini split system. Atop the foundation was added a continuous layer of underfloor sheathing. Next came the perimeter leveling joists, and, from this point forward, the entire Sim[PLY] frame was self-indexing and self-leveling, requiring no further measurements, an advantage over conventional framing.

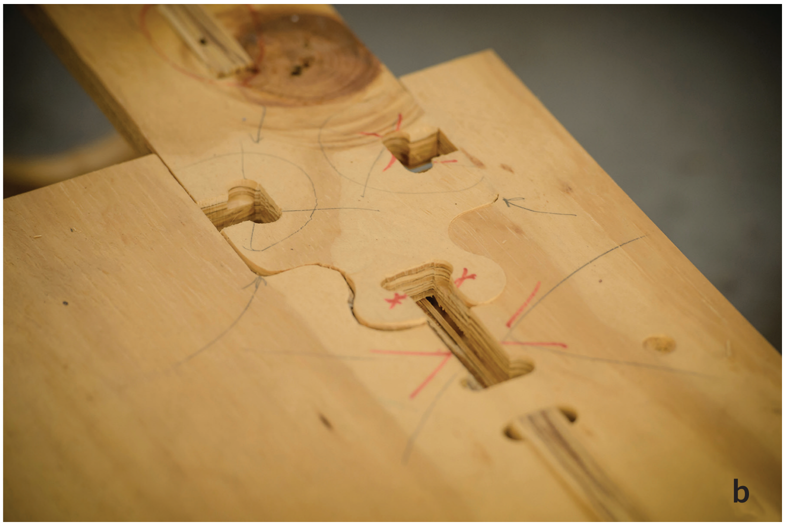
Interior joists and floor insulation were followed by nogging strips and prerouted decking panels, which received the extended joist tabs. While the deck was completed, the Sim[PLY] south wall was assembled and all of the necessary cable ties were tightened to lock the components together.[25] This 36 ft (10.97 m) wall was tilted into place on the deck, after which the ball joint connections were secured into place at its base. The north and east walls were similarly completed, picking up speed with familiarity. The team erected the walls as single units, but, in the case of a small assembly crew, shorter sections could be erected and fastened together sequentially.

Next, the lightweight, prefabricated Sim[PLY] box girder was moved onto the deck and lifted with manual hoists. The west wall was quickly assembled and erected before the box girder was lowered into place, aligning with tapered slots on the east and west walls. The girder consisted of parallel, double-layer Pratt truss walls, and interior stiffeners, and it spanned the length of the house, allowing the interior to be open. The trusses were the only elements in the frame to use an adhesive, a precaution taken to maximize stiffness. Preassembled rafters were installed the following morning, fitting easily into the tapered slots along the box girder. With this last step, the Sim[PLY] frame was completed by the middle of the third shift (approximately 24 working hours).[26] Sheathing was completed and the house was dried-in during the fourth shift. Roofing and façade panels were installed throughout day three (Figure 13). The remaining work, from MEP installation to PV wiring, to porch construction, cabinetry, and finishes, was completed over the remainder of the 9 day assembly period (Figure 14).

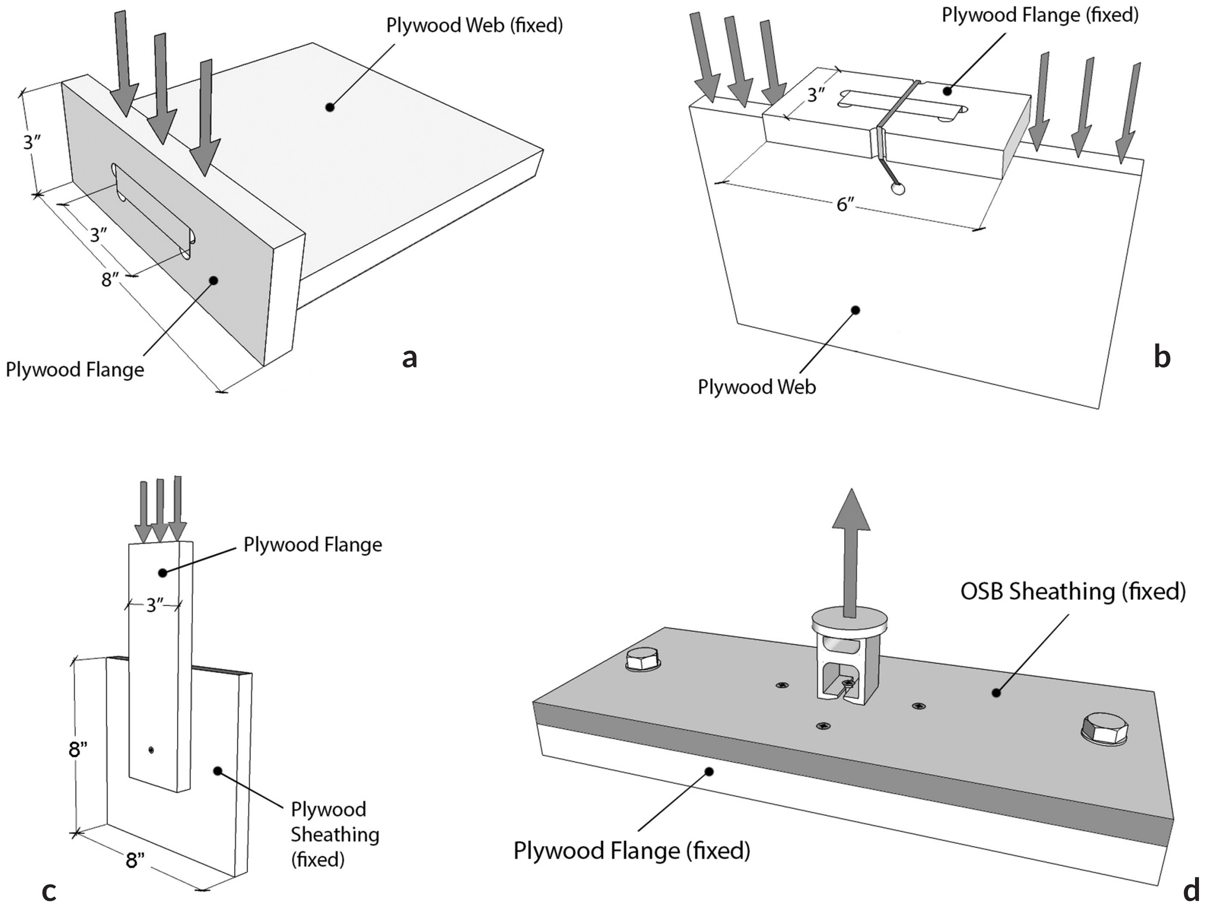
Outside of genie lifts for accessing high points along the perimeter, the house framing and cladding were completed entirely with simple hand tools from the ground up. This was in side-by-side contrast to the top-down, large-module approach of our competitors, which required heavy lifting equipment and trained crane operators. Paradoxically, while the Indigo Pine building site remained nimble, safe, controlled, and quiet, it was methodically active and both physically and mentally engaging. The hand tools and easy-to-handle components simultaneously leveraged aggregate labor and singular engagement. The space of the hand was retained, and the

◁ Figure 7. ACM window surrounds. Photo by Dustin Albright.





▽ Figure 8. (a) Early façade iteration; (b) early Sim[PLY] joint mock-up. Photographs by Allie Beck and Clemson University. Reproduced with permission.



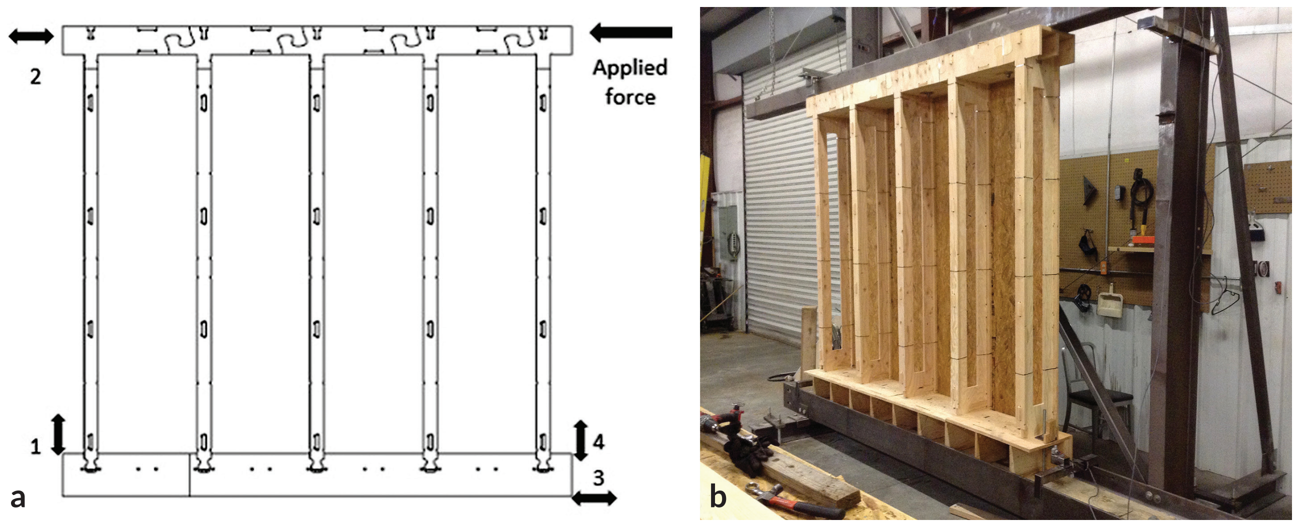
△ Figure 9. (a) Tab and slot shear test; (b) cable tie tension test; (c) screw shear test; (d) screw withdrawal test. Drawing by Dustin Albright.

scale of the individual was respected.

These observations extend equally to the disassembly process, which was designed to be efficient and nondestructive in nature. After the sheathing panels were unscrewed, and the steel cable ties cut and removed, the various Sim[PLY] joints proved to be easily undone using mallets and pry bars. In this way, the disassembly process was itself a constructive act, as this “undoing” embodied the lightweight nature of the system and further emphasized the importance of designing for the whole life cycle. The entire IPW house and its contents were disassembled, packaged, and ready for transport after 3 days (six shifts).

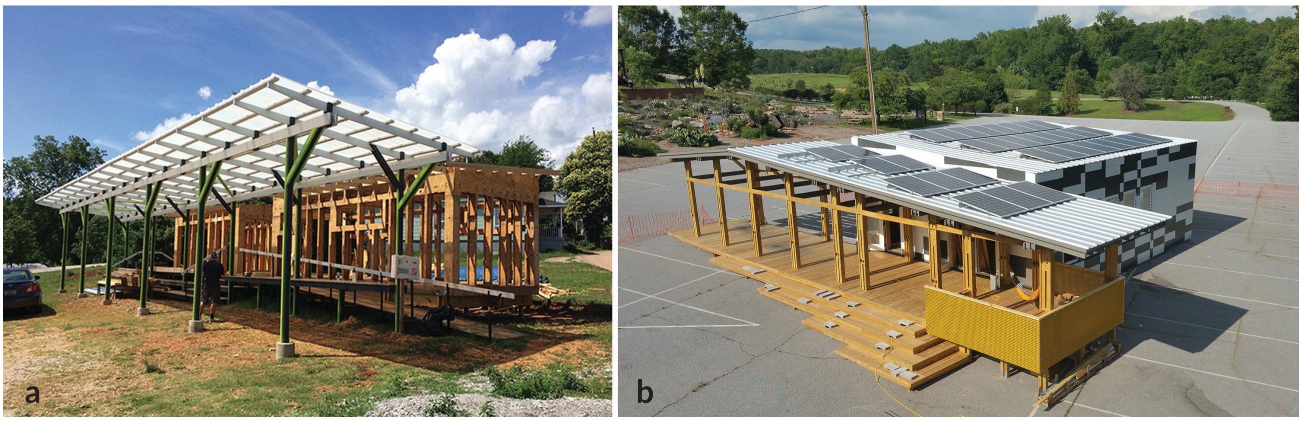
Outlook

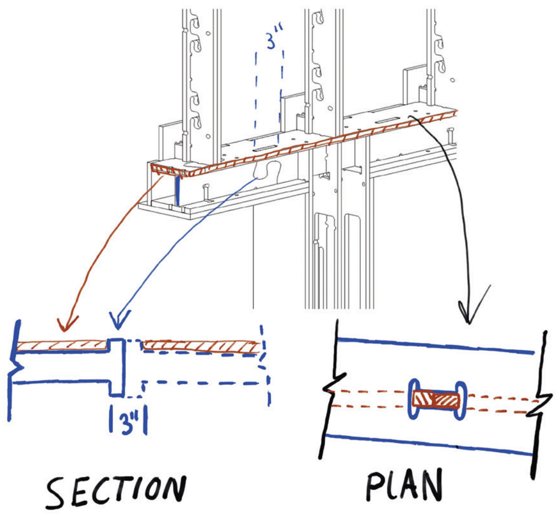
By focusing on the internal logic and mechanics of the Sim[PLY] system, the team succeeded in creating a foundation for widespread application beyond the Indigo Pine project. Thinking broadly, Sim[PLY] represents a customizable, kit-of-parts system that is produced on-demand and delivered just-in-time to the building site. Assembly of the numbered components would follow interactive pictographic instructions and require only manual tools, eliminating power tools, compressors, and their associated cords and energy sources. Construction would be intuitive and safe without sacrificing ease and efficiency—to the point that it could be accomplished at low risk by unskilled labor, including perhaps the owners themselves, and their friends and neighbors. There would be no need for measuring or cutting in the field, thereby reducing construction time and managing the waste stream. Nesting operations employed during fabrication would maximize material efficiency, and



△ Figure 10. (a) Racking test diagram showing sensor locations; (b) racking test. Drawing and photograph by Michael Stoner. Reproduced with permission.

▽ Figure 11. (a) Crop Stop Kitchen under construction; (b) IPE house. Photographs by David Pastre and Eric Balogh. Reproduced with permission.





▷ Figure 12. Modification to header stiffener. Sketch by Jeff Hammer. Reproduced with permission.

Beginning Day 2 Beginning Day 3 Beginning Day 4

△ Figure 13. IPW construction timeline. Photographs by Anthony Wohlers. Reproduced with permission.

▷ Figure 14. Completed IPW house. Photograph by Dustin Albright.

any unused material would be diverted for recycling at the factory. MEP considerations, from runs (see Figure 12) to outlet locations, would be integrated into the cut files and numbered, eliminating any guesswork from subcontractors, and providing for faster installation through segregation and organization. Design files could likewise be parameterized for customization, such as door and window configurations or alternative building geometries. Or they could be parameterized based on specified performance criteria, such as R-value or structural capacity.

The whole project delivery scenario could operate through local networks of CNC fabricators engaged in competitive bids on a project-by-project basis. Or it could favor enterprising design/fabricate/build contractors such as our partner on IPW. Neither the raw materials nor the CNC routing tools are exotic, and the industry is poised for this type of advancement. It all depends on systems like Sim[PLY] that effectively connect the dots between design, fabrication, and constructed performance.

Conclusions and Future Research

Working first from experiences with traditional framing, the Indigo Pine team turned to digital fabrication techniques to address common construction barriers and performance shortcomings. The resulting construction systems, including the Sim[PLY] framing, were rigorously developed through an iterative design process that was both deeply engaged with digital fabrication techniques[27] and deeply committed to learning through making and testing. Each of the systems was less the product of asking, "What can we do with CNC machines?" and more the product of asking, "How can we leverage available production technologies to accomplish a better building system and a more sensitive and humane building site."

After cycles of prototyping, testing, and refining, the Sim[PLY] system, as utilized in the IPW house, represents a viable alternative to traditional platform framing with lumber. Structural tests demonstrated rigorous code compliance plus strength and stiffness that are comparable to conventional methods. Easy governance of cavity thickness and thermal bridging provides for very high insulating values, matched only by comparatively complex double-stud or Larsen truss construction. Moreover, the culminating IPW build provided observational evidence of rapid, safe, and intuitive assembly by hand with unskilled labor, as well as nondestructive disassembly, a profound advantage over standard wood framing.

Built prototypes also provided a detailed understanding of the processes and costs of production. The total cost of CNC fabrication for structural plywood components in the IPW house was estimated by the fabrication partner to be $6,815, translating to approximately $7 per square foot of house. This includes an estimated $1,290 for CAD/CAM file preparation, a fee that would be spread across multiple houses in larger production. Adjusting for ten houses, and assuming the fabricator streamlines production with increased experience, the prefabrication costs quickly approach $5.75/sf. However, research indicates that the cost of framing for an average house in the United States represents only 18 percent of the overall construction cost.[28] Therefore, it is unclear whether a system like Sim[PLY], with its advantages for fast assembly, can overcome its front-end fabrication costs. A more appropriate comparison, however, would include projected life-cycle

energy savings stemming from superior thermal performance over conventional framing.

In addition to deeper economic analysis, there is much room for other future research. There is the need for further optimization, including reductions in complexity and unique parts, as well as integrative geometric optimization across multiple variables, such as structural capacity, waste minimization, length of CNC routing path, and packaging and shipping efficiencies. In conjunction, there is a need for parameterization in the design files to address this complex set of variables, and others. These developments will demand further structural analysis, including additional predictive modeling. Finally, there is the need for new and diverse applications, including multistory applications, whose path has been paved by the platform nature of the Sim[PLY] system, but they remain untested. These future applications should aim to again involve outside fabricators, as well as outside builders and MEP subcontractors, in order to provide a more complete feedback loop from industry.

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Notes

1. Barry Bergdoll, "Home Delivery: Viscidities of a Modernist Dream from Taylorized Serial Production to Digital Customization," in *Home Delivery: Fabricating the Modern Dwelling*, ed. Barry Bergdoll and Peter Christensen (New York: Museum of Modern Art, 2008), 12–26.
2. A 2015 U.S. housing census report shows 93 percent of new houses utilized light wood construction methods. United States Census Bureau, "Characteristics of New Single-Family Housing Completed," http://www.census.gov/construction/chars/pdf/framing.pdf (accessed July 31, 2016).
3. This biannual event, sponsored by the US Department of Energy, invites university teams to design, construct, and operate solar-powered houses, which are judged on a range of quantitative and qualitative metrics. More information at http://www.solardecathlon.gov.
4. Richard Sennett's *The Craftsman* is a core text within our Community Design/Build sequence. He describes the human hand and its linkages to cognitive processes and cites ethnologist Mary Martzke, who herself studied grip functions essential to the hand's work. See Sennett, *The Craftsman* (New Haven, CT: Yale University Press, 2008), 149–53; and

Martzke, "Precision Grips, Hand Morphology, and Tools," *American Journal of Physical Anthropology* 102 (1997): 91–110.

5. See Building America Solution Center, "Advanced Framing: Minimal Wall Studs," https://basc.pnnl.gov/resource-guides/advanced-framing-minimum-wall-studs (accessed August 9, 2016).
6. Recent research indicates net savings in transportation energy for controlled off-site construction versus on-site construction. See J. Quale, M. J. Eckelman, K. W. Williams, G. Sloditskie, and J. B. Zimmerman, "Construction Matters," *Journal of Industrial Ecology* 16, no. 2 (2012): 243–253. These findings assume a reasonably short distance between point of prefabrication and point of final assembly. Moreover, rapid and ordered assembly for digitally fabricated systems will disrupt such comparisons.
7. See Howard Cook, "Seismic Retrofit for Cripple Walls: A Good Job Addresses the Building's Weakest Link—Where the Foundation Attached to the First Floor," *Journal of Light Construction* 24, no. 7 (2006): 93–101.
8. See South Pole Group, "Calculate and Offset Now," https://shop.southpolecarbon.com/en/category/freight (accessed August 9, 2016).
9. The U.S. Environmental Protection Agency estimates the average household emits 14,920 pounds (6,768 kg) of CO2 from annual electricity use. (See US EPA, "Household Emissions Calculator Assumptions and References," https://www.epa.gov/ghgemissions/household-emissions-calculator-assumptions-and-references (accessed August 9, 2016).
10. See Marcel Botha and Lawrence Sass, "Instant House: A Model of Design Production with Digital Fabrication," *International Journal of Architectural Computing* 4, no. 4 (2006): 109–23 and Bergdoll and Christensen, *Home Delivery* (note 1), 196–203.
11. Alastair Parvin and Nick Ierodiaconou, "WikiHouse," http://www.wikihouse.cc/WikiHouse_Partners_2016_v1.7.1.pdf (accessed July 31, 2016).
12. See Jeremy Edmiston and Douglas Gauthier, "Burst*008," in Bergdoll and Christensen, *Home Delivery* (note 1), 204–13; and Facit Homes, http://facit-homes.com/made-with-intelligence/precision-manufacturing (accessed August 10, 2016).
13. APA, "Environmental Product Declaration: North American Softwood Plywood," http://www.awc.org/pdf/greenbuilding/epd/AWC-EPD-SoftwoodPlywood-1307.pdf (accessed August 26, 2016).
14. See Philip Crowther, "Design for Disassembly: Themes and Principles," in *RAIA/BDP Environment Design Guide*, White paper, no. DES 31 (Melbourne: RAIA, 2005).
15. Using nesting operations, the overall plywood sheet utilization efficiency for the house was 70.89 percent. This included all structural framing elements as well as finish ceiling panels.
16. A floor live load of 50 psf (2.394 kN/m2) was provided by the competition organizers. Roof live load was 20 psf (0.958 kN/m2).
17. International Code Council, *2012 International Residential Code* (Country Club Hills, IL: Author, 2012).
18. ASTM Standard D1761-12, "Standard Test Methods for Mechanical Fasteners in Wood," ASTM International, West Conshohocken, PA, 2012, DOI: 10.1520/D1761-12, www.astm.org.
19. American Wood Council, *2012 National Design Specification for Wood Construction* (Washington, DC: Author, 2012).
20. ASTM Standard D4761-13, "Standard Test Methods for Mechanical Properties of Lumber and Wood-Base Structural Material," ASTM International, West Conshohocken, PA, 2012, DOI: 10.1520/D4761-13, www.astm.org.
21. ASTM Standard E564-06, "Standard Practice for Static Load Test for Shear Resistance of Framed Walls for Buildings," ASTM International, West Conshohocken, PA, 2012, DOI: 10.1520/E0564-06R12, www.astm.org.
22. Based on testing, an HD5A hold-down from USP (or similar), spaced at approximately 8 ft is sufficient for seismic D2 settings.
23. For more information on structural testing, see D. Albright, M. Stoner, V. Blouin, D. Harding, U. Heine, and D. Pastre, "Sim[PLY]: Innovative Platform Framing with CNC-Fabricated Plywood Componentry," in *Proceedings of WCTE 2016, World Conference on Timber Engineering* (Vienna, Austria: WCTE, 2016), 5582–5589.
24. At the time, this shop utilized four 3-axis CNC routers with 48"×96" (1.22 m × 2.44 m) bed capacity and one 3-axis router with 60"×120" (1.52 m × 3.05 m) bed capacity.
25. Some off-site preassembly of individual studs and rafters had preceded this step.
26. The assembly team worked in two shifts, each with thirteen students and two faculty. The first shift ran from 7 a.m. to 5 p.m., and the second shift ran from 4 p.m. to 2 a.m.
27. Bergdoll, "Home Delivery" (note 1).
28. See Heather Taylor, "Cost of Constructing a Home," NAHB Economics and Housing Policy Group, 2015, and HousingEconomics.com.