The Solar Decathlon 2015
Jury Narratives for
As-Built Deliverable

Published 8/17/15

Architecture Narrative

Indigo Pine. Drawn from the traditions of southern living while simultaneously integrated with today's cutting-edge technologies, our "techno-local" house is comfortable *and* innovative, familiar *and* forward-thinking, with roots buried deep in the south. Designed for a family of four residing in South Carolina, the concept of family living was a priority that we have maintained from the start. Likewise, Team Clemson began with and has carried forward a commitment to using and advancing wood construction methods, which account for much of the built forms in our region. Although this house is showcased in Irvine, California, its heritage remains in South Carolina. Hence the name, Indigo Pine – two important cash crops in the state's history, whose defining characteristics of vibrancy (Indigo) and utility (Pine) parallel our aspirations for this house. From the start, our mission has remained unchanged:

> *"The Clemson University Solar Decathlon team is collaborating on the design, construction, and promotion of a three-bedroom, 1000 sq.ft., low environmental impact, net-zero energy, solar house that is cost-efficient in today's market and comfortable in South Carolina and comparable climate zones. Our concept focuses on stitching together innovative building methods, southern charm and local products in a home for a southern family."*

The design of Indigo Pine has been governed, first and foremost, by a central idea. Conceptually, the house leverages front-end ingenuity and fabrication technology in service of smarter, easier, and safer construction that is likewise more accurate, more affordable, and more sustainable. Looking beyond the house itself, we aimed to design a *system* and a new way of thinking about building.

Building Indigo Pine

The floor, walls, and roof of the Indigo Pine house exist as a series of digital cut files. Using a CNC (Computer Numerical Control) machine allows us to transmit our digital drawings to a router that cuts our components out of typical sheet goods that can be found at any home improvement or construction supply store. Because Indigo Pine is intended to suit a typical family, all aspects of the construction system are designed to fit into the nation-wide network of locally available materials and CNC fabricators.

Figure 1 – Near completion of Sim[PLY] frame at Indigo Pine East

Designing a system which consists of digital files allows the home to be emailed to the nearest fabricator, cut out, and shipped as flat-packed pieces to the construction site. This ability to email the home not only cuts down on shipping costs and carbon emissions (versus shipping larger modules), but also creates a ready-to-build home that is relevant and adaptable to nearly any location.

The Sim[PLY] Framing System

The Sim[PLY] system was developed by Clemson University students and faculty and has been utilized within

Indigo Pine as an alternative method to traditional lumber framing. The system sends digital cut files to a CNC machine which cuts out the structural components of the house from typical 4' x 8' plywood sheets. Each CNC-cut piece has been "nested" for material optimization. That is, the files are digitally arranged such that the pieces can be cut using the minimum number of plywood sheets, incurring very little waste. The waste that is produced is confined to the fabrication factory and easily recyclable into other wood products. Every completed plywood component, no matter how large or small, has its very own identification number etched onto it during the cutting process, so each piece can be easily identified and its location in the home known. Once the plywood pieces have been cut, they are flat-packed and transported to the construction site for assembly.

On site, the entire house is assembled using a method that is reminiscent of putting together a 3D puzzle.

The plywood pieces interlock to create a highly intelligent structure where wooden mortise and tenon joints form the primary connection, and stainless-steel zip ties are used as a secondary fastener. No nails or nail guns are used in the construction, eliminating a significant safety hazard and saving energy. Because each component is pre-cut with the precision of digital machinery, every plywood piece is accurate and precise. On the construction site, there are no tape measures, pencils, or blades needed.

Figure 2 – Details of mortise and tenon joints, zip ties

Although the Sim[PLY] assembly method is unique, it draws from traditional framing techniques like tilt-up walls.

Similar to traditional platform framing with lumber, each of the walls of Indigo Pine are constructed flat on the ground, then tilted up into place. However, unlike conventional techniques which rely on nails to secure the wall into its standing position, Sim[PLY] has a built in "hook" joint at the base of each stud which allows it to be rocked into place and lock into the floor joist system below. The result is a resilient wall system with some inherent lateral and uplift resistance.

Figure 3 – South wall ready to tilt into place.

The subfloor, sheathing, and weather-resistant barriers required in any house have also been incorporated into Indigo Pine. A common 4' x 8' sheet product has been selected that acts as both sheathing and weather barrier, while a standard subfloor material is also being used. Similar to the plywood structure, these subfloor and sheathing panels are also CNC cut to create small "register holes" which allow the panels to be slid onto tabs in the structure to create a perfectly "square" home with added shear strength. These tabs act as the primary connection to the structure, while screws are also added as secondary fasteners using electric screwdrivers.

The result is a rapid and safe onsite construction method using plywood pieces that are small and light enough for an average person to lift and carry. The size of the pieces as well as the primary tools, hand-powered zip-tie

guns and electric screwdrivers, eliminate the need for large, unsafe machinery. Much of the construction can be performed by non-skilled labor, even the owners themselves, who will follow a simple, easy-to-read assembly manual. With the help of friends and family over a series of weekends, the house can be dried-in without expensive, skilled workers.

The Sim[PLY] system has even provided a long span box girder enabling a "free plan," an open and flexible space without the need for interior bearing walls. For 80% of the construction, the house is a large, empty box that doesn't have the obstacles of interior walls to impede work. The details of the interior wall partitions will be outlined in the next section. Useful for the competition, but equally important for the inevitable renovations and additions that occur during the life of a home, is the ability for Indigo Pine to be easily disassembled and reassembled in a non-destructive fashion. The same way the home is assembled like a 3D puzzle, it can be safely disassembled. Simply remove the screws, snip the stainless-steel zip ties, and flat-pack the pieces again. The only waste materials will be the easily recyclable steel zip-ties.

The Siding

Figure 4 – Assembling siding panels.

Imagine you are in South Carolina. The houses you see are bright and welcoming in appearance, with a clean, light colored siding to protect the home and to reflect heat from the Carolina sun. Now, take a look at the clean, white, lap siding of Indigo Pine.

The panels, when applied to the house, are roughly 14" tall and vary in length, with two friendly, yellow, button-like rivets peeking out at each of the lower corners.

The siding is another ingenious example of utilizing CNC technology in Indigo Pine. A sheet of ACM (aluminum composite material) is cut and etched in such a way that it can be folded by hand on two sides. This creates a strong edge that also acts as a built-in furring strip, with pre-cut holes for cavity ventilation, allowing heat from the sun to escape before it hits the house. The panels sit about 2" from the sheathing, creating a nice air barrier that further insulates the home The folds are secured in place using a rivet from a hand-powered rivet gun, another sustainable alternative to power tools, and then the entire panel is attached directly to the structural members through the sheathing, creating an incredibly strong and durable system. Like the Sim[PLY] components, each of the siding panels are also etched with their own identification code. In addition to enhancing energy efficiency, the siding is virtually maintenance free. The finish will never fade and the material is very easy to clean. Finally, the siding system also features its own solar shades of the same material. Rather than being foreign elements, as is typically the case, these important shading devices are seamlessly integrated into Indigo Pine's skin.

Living in Indigo Pine

Indigo Pine is a three bedroom home, which is unusual for a 1000 square foot residence in the United States.

However, it was important that this home could accommodate the target family of four. The bedrooms in this house are probably smaller than the ones typically found in American homes, but this supports our belief that bedrooms should be reserved for sleeping, dressing, and quiet activities like reading or studying, while the actual living in the home takes place in the large main room or porch, where the whole family can interact with one another. This is a smarter and more judicious use of space and resources.

The Cabinet Walls

Indigo Pine has a very unique system of interior walls. Instead of typical interior stud walls attached at the floor and ceiling, our interior partitions consist entirely of large, free-standing cabinets. This is possible, as alluded to in the previous section, because Indigo Pine's free spanning roof structure does not require interior supports. Similar to Sim[PLY], the cabinets are assembled from CNC-cut plywood, although they consist of a finish grade plywood. Although the joints are still exposed and the unique assembly method left in plain sight, the cabinets are fastened with screws instead of zip-ties for a more refined aesthetic.

The cabinets are made up of a series of modular boxes. Once the house is entirely dried-in, and the finished floors installed, these boxes are simply walked through the front door one at a time and set in place.

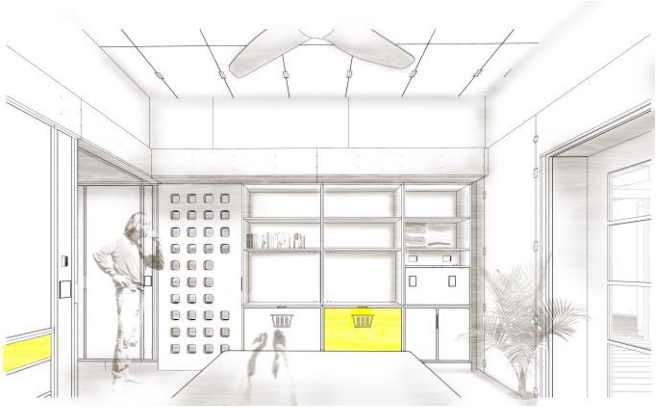


Figure 5 – Cabinet wall in the master bedroom

Each side of the cabinets serve a different room. For example, on one side you'll find the entertainment system, while on the other, storage for one of the two smaller bedrooms. All of the functions of the home are integrated into the cabinets, including kitchen appliances, HVAC return, bedroom closets and drawers, laundry hampers, entertainment systems, coves for up-lighting, and even interior doors. The advantages of cabinet walls over traditional stud walls include keeping the interior space open and obstacle-free during the dry-in process, providing ample storage and other functions so that no interior space is wasted, the ability to reconfigure the entire floorplan just by moving cabinet elements, and, like all other aspects of Indigo Pine, they can be moved easily and assembled using man power, with no heavy machinery.

The Porch

South Carolina enjoys a mild climate for much of the year, so what better way to spend time with the family than drinking a glass of sweet tea on the porch? One of the defining features of any South Carolina home is a front porch, which not only serves a functional purpose in providing shade and ventilation to the home, but also serves an important cultural purpose as a social, gathering space. The tradition of *front* porches in Southern communities involves their role as a transition zone, a mediator between the privacy of the home and the public street. Indigo Pine's porch is meant to serve those same climatic and cultural functions.

The largest living room of the house is actually the spacious front porch, drawing families out into its shade and breeze.

The Indigo Pine porch is structurally independent from the house; it is the element in the overall scheme that is intended to fully adapt to its site and context (including the building materials). The Indigo Pine porch is built from pre-sized and pre-cut lumber to facilitate quick and easy construction.

Figure 6 – Porch living at its finest (CNC fabricated rocking chair).

Other Features

Entering the front door of Indigo Pine, one of the first things that draws attention is the series of windows facing the south side of the house. These large double-hung windows, a traditional feature of South Carolina homes, not only fill the room with warm, southern light, but they also can be opened to provide cool breezes during the mild spring and fall, as well as help passively heat the home during the winter.

Continuing through the house and into the small bedrooms on the east side, a special feature has been added to maximize the livability and adaptability of the home. The two rooms have a shared closet that can be left open to create one big room, or it can be closed off to separate the space into private rooms. This adaptability also allows for the program of the rooms to change depending on the needs of the owner (children's bedroom, guest, bedroom, office, study, etc.).

With four people sharing one bathroom, as would typically be found in a 1000 sq. ft. home, arguments over bathroom use are commonplace. To mitigate those situations, we've split the single bathroom into two, and added a second sink. One bathroom has a toilet and sink, while the other has a shower and sink, allowing different people to perform lots of different tasks at the same time. Note that both bathrooms are served by integrated cabinet walls as well.

Summary

Indigo Pine is a house *and* an idea. Team Clemson's innovative design approach raises the bar for sustainable architectural and engineering design standards. From inside to outside Indigo Pine offers a warm and inviting home for our target families, while also providing a wide variety of energy saving measures, both high-tech and low-tech which will enable them to save money and reduce their carbon footprint.

Market Appeal Narrative

Figure 7 – Indigo Pine's kitchen, dining, and living rooms intermingle to provide ample common space.

Indigo Pine was conceived as an innovative approach to contemporary southern living from the inside out. The house delivers the essential elements to take advantage of South Carolina's temperate climate and remain familiar and inviting to its target market. However, it also challenges the way homes are built and occupied while providing enhanced economy, flexibility, and resiliency. The Indigo Pine house is Livable, Marketable, and Buildable.

Livability

The target client for Indigo Pine is a family of four in the southeastern United States. The three-bedroom home provides a large central living space to promote interaction between family and friends, as well as an expansive covered front porch that serves as an outdoor extension of the interior living space. The home also features a flexible one and one-quarter bath arrangement, making it easier for a family to get ready in the morning. Each of these aspects combine to allow this 1,000 square foot home to comfortably and efficiently serve a family of four, while also equipping them be active and hospitable participants in the life of their neighborhood.

CHARACTERISTIC	DETAILS
LOCATION OF PERMANENT SITE	SOUTH CAROLINA
HOUSING TYPE	SINGLE FAMILY
# OF OCCUPANTS	4
CLIENT DEMOGRAPHIC	COUPLE WITH 2 CHILDREN
CLIENT ANNUAL INCOME	$45,000
# OF BEDROOMS	3

Table 1 – Indigo Pine Target Client Chart

The Porch

The front porch is a quintessential element for homes in South Carolina, and the Indigo Pine house draws on both the social and performative dimensions of this history. The weather in our region is temperate and inviting for 6 months out of the year. The generous front porch serves to extend the living space, making the house feel much larger and providing a welcoming gathering place. The porch also provides ample shading of the house throughout the morning, thereby reducing glare and heat gain.

Functional & Adaptable Interiors

In lieu of standard interior walls, Indigo Pine utilizes integrated cabinetry to provide functionality while also dividing rooms from one another. Whether playing host to the kitchen appliances, or to closet storage in the bedrooms, the cabinets maximize every square inch of floor space in the Indigo Pine house.

The entertainment systems are likewise built into the cabinetry wall systems, providing space to conceal wires, cords, and other unsightly elements. Finally, much of the house's MEP systems are contained within Indigo Pine's cabinetry, whose removable panels offer greater accessibility than one typically encounters.

> *"This gives a family of modest income the opportunity to begin with a basic Indigo Pine model and slowly enhance it through the addition of advanced components."*

Because the structural framework of Indigo Pine was designed to span the entire house, there is no need for interior load-bearing elements. For this reason, the cabinetry walls are free and flexible to be moved, rearranged, or replaced. This is important for a family of four, whose needs evolve over time. Our target homebuyers value functionality, flexibility, and the potential for customization. Indigo Pine's unique cabinet wall system provides each of these qualities.

Flexible Lighting

The home's lighting system consists of two primary fixture types, which provide flexibility for various light levels and scenarios. Ceiling-mounted light fixtures throughout the house provide a simple and reliable solution for down-lighting. Additionally, Indigo Pine utilizes alcove lighting around the perimeter of its rooms. This up-lighting solution provides a softer, indirect light for times when overhead light is unnecessary.

The lighting fixtures are complemented by the natural light transmitted through Indigo Pine's double-hung windows, which are particularly sizeable on the southern, sun-receiving side of the house. Through the use of top-up bottom-down blinds, the windows also deliver ventilation without sacrificing privacy.

Occupant Comfort

The Indigo Pine house utilizes simple but effective solutions for its heating and air conditioning system. The system consists of a highly efficient mini split unit and a heat recovery ventilator (HRV). In addition to the central thermostat, enhanced thermal control is provided through custom dampers, which allow occupants to direct more or less conditioned air into certain zones of the house. Finally, the unique concrete masonry plinth acts as both a foundation for the house and as a unique thermal mass system. Outside air is circulated through this plinth where it is cooled during the summer and warmed during the winter. The precooled or preheated air is then delivered to the mini split helping it to run more efficiently and thereby reducing utility costs for the occupants.

Marketability

The contemporary look of Indigo Pine is composed of cool grays, bright whites, and warm wood textures. Together, this palette forms a clean, welcoming, and appealing aesthetic for our target clients. The expanse of living spaces in both the interior and exterior spaces of the home provides open spaces for entertaining groups large and small. You could say that it is a small house that lives big. In addition to these first impressions, there are a number of areas in which the Indigo Pine house is particularly marketable.

Affordability

The median household income in South Carolina is a little less $45,000. Thus, affordability is key when it comes to housing, and it is important to remember both the up-front costs as well as long-term utility and maintenance costs.

One of the most important features of the Indigo Pine house is the combination of high-tech and low-tech solutions, which can be taken together or applied separately and remain effective. This gives a family of modest income the opportunity to begin with a basic Indigo Pine model and slowly enhance it through the addition of advanced components such as the solar panel array, which, at $18,000 (approx. $14,500 after South Carolina tax rebate) represents 11.25% of Indigo Pine's material cost.

> *"One of the most important features of the Indigo Pine house is the combination of high-tech and low-tech solutions, which can be taken together or applied separately and remain effective."*

Low-tech innovations, on the other hand, like the CMU plinth or rainwater harvesting system offer both front-end affordability and long-term utility savings. In every case, an emphasis was placed on selecting reliable and durable materials for Indigo Pine in order to reduce maintenance costs over time.

Finally, as described below, the unique methods of prefabrication and construction serve to dramatically reduce on-site construction time and costs. In fact, the framing of an Indigo Pine house is so easy that homeowners could reasonably entertain assembling it themselves, further saving on labor costs.

Materials & Equipment

Indigo Pine leverages front-end fabrication technologies to deliver a house with superior energy performance and which is also easier, faster, and safer to build. The innovative Sim[PLY] framing system, developed at Clemson, is comprised of CNC-cut plywood components. These elements can be produced wherever a CNC-machine is available. In many areas, homebuyers could even shop around to select an ideal fabrication partner from among their local network of CNC operators.

The Sim[PLY] system has been engineered and tested to perform in high wind and seismic zones. Its joinery and fasteners make it ductile and resilient. The plywood itself is produced to exacting standards and is offers high consistency in quality. Homeowners can trust the quality and stability of an Indigo Pine house.

The exterior siding on the Indigo Pine house is also cut using CNC machines. It is made of aluminum composite panels that are folded, riveted, and fastened to the sheathing. The folding of the panels allows the siding to act as an all-in-one ventilated rain screen system, eliminating the need for additional furring elements.

The panels come in a wide range of colors, they are remarkably easy to clean, and the finish is permanent, meaning there is no fading or repainting. The particular panel product used for Indigo Pine comes with a 30-year warranty and

is even able to be touched up if it ever gets scratched.

Not only is the siding durable and maintenance free, it also carries a high solar reflectance rating (SRI = 82), which combines with the integrated ventilation space to keep the house cool, thereby lowering the need for air conditioning. This siding system was devised for Indigo Pine but could also be applied to existing structures in renovation or energy-retrofit scenarios.

Interior finishes include attractive Corian countertops and durable laminate flooring. The wall and ceiling surfaces are painted plywood panels, but could be drywall if the homeowner elected. A panel option is particularly easy to install, though, and offers increased flexibility, as the panels are easy to remove and replace.

In terms of equipment, the appliances are stylish and offer excellent energy performance. The hot water system utilizes a hybrid solar electric water heater, which has two electrical supplies, one AC and one DC. This allows the system to be powered by the grid or directly by the house's PV panels.

Unique Sustainability Features

Today's homebuyers are becoming increasingly conscientious and eco-savvy. A more sustainable home is more marketable, so long as the up-front premium is not too steep. Indigo Pine offers an array of passive strategies for heating, cooling, and ventilation, thereby improving the base-level energy efficiency with simple, affordable measures. This includes the house's shading elements, its vented siding, and its thermal mass foundation system.

Additionally, the Indigo Pine house offers an impressive degree of insulation to limit heat transfer through the envelope, thereby lowering monthly power bills for the occupants. The Sim[PLY] framing system is designed to provide a 12" wall cavity depth and even greater ceiling cavity depth, allowing for more insulation than standard wood framing. The resulting R30 insulating value comes from cavity insulation alone and does not require expensive rigid insulation outside the structure. The Sim[PLY] studs are also spaced at every 24" rather than the more typical 16". This serves to increase the percentage of insulation and reduce heat transfer through thermal bridging. The triple pane windows also provide a high insulating value compared to other standard window products.

Low energy consumption notwithstanding, arguably the most important sustainable features of the Indigo Pine house are linked to the materials and methods of its construction. The plywood in the Sim[PLY] framing comes from sustainably managed forests and has a low embodied energy with respect to non-wood-based structural materials such as concrete, masonry, and steel. Consumers can feel confident that building with wood products represents a sustainable choice with documented life-cycle benefits. The Sim[PLY] system is also very easy to disassemble meaning that it is easy and non-destructive to make modifications. This, again, represents a tangible life-cycle benefit to Indigo Pine owners.

Buildability

The real beauty of Indigo Pine's Sim[PLY] framing system, described above, is the ease with which it can be assembled. Utilizing mortise and tenon joints and steel zip ties, the system simply snaps together. The pieces are individually numbered, there is no need for heavy, specialized equipment, and the construction sequence would be conveyed through a series of easy-to-follow assembly diagrams. This all serves to speed up construction and limit the need for skilled labor, saving the homeowner money.

Particularly motivated homeowners might even elect to complete the framing themselves with the help of family and

friends. While our target buyers may have modest incomes, they can elect to contribute their own time and labor. The Sim[PLY] system makes this a viable choice. This would not only save money, but also instill an intimate knowledge of the house itself as well as the satisfaction of having built it.

Not only can the home be built quickly with unskilled labor, but all of the elements of the home can be sourced locally, often from the local hardware store, reducing transportation emissions and allowing for easy access to materials. Furthermore, without any need for power saws, nail guns, or powerful lifting equipment, an Indigo Pine building site is safer and easier to manage.

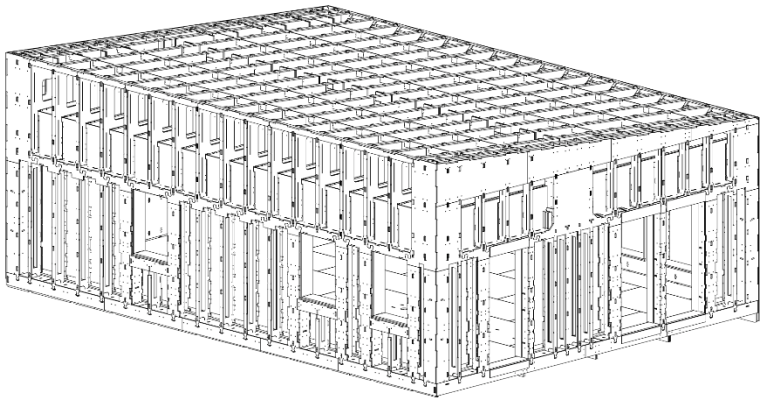


Figure 8 – Completed Sim[PLY] structural system.

"Not only can the home be built quickly with unskilled labor, but all of the elements of the home can be sourced locally, often from the local hardware store, reducing transportation emissions and allowing for easy access to materials."

Indigo Pine's construction drawings and specifications are clear and well-organized, enabling a contractor to easily derive a cost estimate due to the specificity of the material sizes, connections, and finishes. Moreover, the fabrication costs for CNC operations would be easily calculated given the precise cataloguing of all components as well as the pre-prepared and optimized cut files. As mentioned previously, an assembly manual would also be provided in order to effectively walk contractors (or owners themselves) through the construction sequence. This would ensure quality control and also serve as a tutorial for builders who may be unfamiliar with the Sim[PLY] system and other unique elements of the Indigo Pine house.

Summary

In summary, Indigo Pine represents an innovative, sustainable, and cost-effective approach to contemporary housing for today's demanding consumers. Our target families in South Carolina, as well as families across the country will find the Indigo Pine house to be an exciting and appealing option to call home. Taken together, the various features of the Indigo Pine house provide for spacious, light-filled, functional and adaptable space, capable of enhancing the lives of its occupants.

Engineering Narrative

Approach

Indigo Pine is designed for a family of four residing in South Carolina. With this client in mind, the engineering systems aim to deliver the following: strong, reliable and sustainable *performance* within South Carolina's demanding climate; widely *accessible* materials and technologies; *affordability* over the life-cycle of the house; *simplicity* of installation and operation; and *adaptability* over time.

Moreover, the innovative engineering solutions described below are synergistic in the context of the Indigo Pine house, but were also carefully developed such that each could stand on its own and be applied independently to benefit other sorts of new and existing houses.

Conceptually, Indigo Pine leverages front-end fabrication technologies to deliver a house with smart components and easier, faster, and safer construction. An Indigo Pine house arrives to the site as a unique kit-of-parts with easy-to-follow assembly instructions. While some elements, such as plumbing and electrical, must be installed by a licensed contractor, Indigo Pine's structural and MEP systems are designed to be assembled rapidly with unskilled labor. This serves to lower construction costs and even gives Indigo Pine owners the opportunity to participate in building their new home if they desire.

Note that the calculated values found in the descriptions and appendices below reflect values for Clemson, SC, the location of the first constructed Indigo Pine house, "Indigo Pine East." Due to the learning curve in the construction of this highly innovative first house, team Clemson has not been able to fully test the actual performance of all engineering systems. Some values noted below (noted as "estimated") indicate Team Clemson's estimates based on its most recent calculations and predictive modeling.

Sim[PLY] Structural System

The Sim[PLY] structural framing system is one of the most unique engineering innovations that Indigo Pine has to offer. Sim[PLY] revolutionizes and democratizes the construction process by providing lightweight, prefabricated components which are easy to assemble by the average person. The Sim[PLY] system utilizes CNC-cut plywood components in lieu of traditional dimension lumber. The prefabricated nature of this system maximizes quality control, while minimizing on-site construction time and waste by relegating all measuring and cutting to the factory. The use of CNC processing also allows for various forms of customization including MEP integration and component labeling, among others. Each component of the system is individually numbered, packed, and shipped directly to the building site to be assembled in a three-dimensional structural puzzle.

The framing components of the Sim[PLY] system are cut from standard 4ft x 8ft sheets of 23/32"-thick plywood sheathing, an industrial product that is highly standardized. The Douglas Fir-Larch plywood in the Indigo Pine competition house comes from sustainably managed forests (SFI certified) and has a low embodied energy with respect to non-wood-based structural materials such as concrete, masonry, and steel. The regularity of structural plywood stems from its engineered physical properties and the quality-control standards governing its manufacture. With respect to traditional graded lumber, plywood offers enhanced dimensional stability because of the alternating grain direction of its layers.

The Indigo Pine application of the Sim[PLY] system is designed to mimic a 24" on-center, double-stud, "advanced" platform framing scenario. The roof framing utilizes Sim[PLY] rafters, which consist of spliced double-layered webs. The rafters are supported by the Sim[PLY] box girder, which spans the entire house in the east-west direction. This free spanning system eliminates the need for interior bearing walls, thereby providing totally flexible interior spaces.

Harkening back to mortise-and-tenon construction, our structural system locks itself together with a simple tab and slot connection. Each piece is self-aligning, making our process highly intuitive and user-friendly. As a means of safer construction, Indigo Pine utilizes stainless steel cable ties (rather than nails and nail guns) to secure the joined members in place. Additionally, the cable tie connections are easily reversible by clipping the ties. This means that any renovations made to a house like Indigo Pine are easy and non-destructive when compared to houses with traditional framing.

The Sim[PLY] system is not just a good idea, though. It has been engineered and tested to perform in high wind and seismic zones. Its joinery and fasteners make it ductile and resilient. For a listing of structural tests and results, please refer to Project Manual section "Structural Testing" and "Appendix A: Structural Calculations."

HVAC System

Heat pumps are traditionally used in Southeastern states, which are home to considerable cooling loads in the warmer months and significant heating loads in the colder months. The main disadvantage of heat pumps, however, is that they do not perform well in the extreme heat and humidity found in some areas of South Carolina. In order to improve performance, Team Clemson has designed a base of simple, lay-in concrete masonry units beneath the house. This serves as a dually functional element – the CMU not only acts as an integral part of the structural foundation, but also serves as a thermal mass system. As such it supplements our use of a high efficiency mini-split heat pump system by passively pre-conditioning the air before entering the outdoor heat exchanger unit.

As explained in Figure E1, unconditioned air is drawn into the thermal mass system through openings on the east and west sides of the house. The air then moves through the CMU system, which stays cool in the shade beneath the house. In this setting the air temperature will be reduced by an estimated 10°F before being circulated to the outdoor heat exchanger (see calculations in Appendix B). The standard masonry units can be purchased inexpensively at any retail home improvement store (thereby adhering to the concept of accessible materials). They also have a high compressive strength necessary for foundation requirements (approx. 1,900 psi, net), and are widely versatile, boasting a high volumetric heat capacity in comparison to other traditional building materials (2,112 kJ/m^3-°C, see Appendix B). CMU's high volumetric heat makes it an ideal thermal storage material for the purposes of transferring the regulated ground temperature to the air circulating through the system (via conductance).

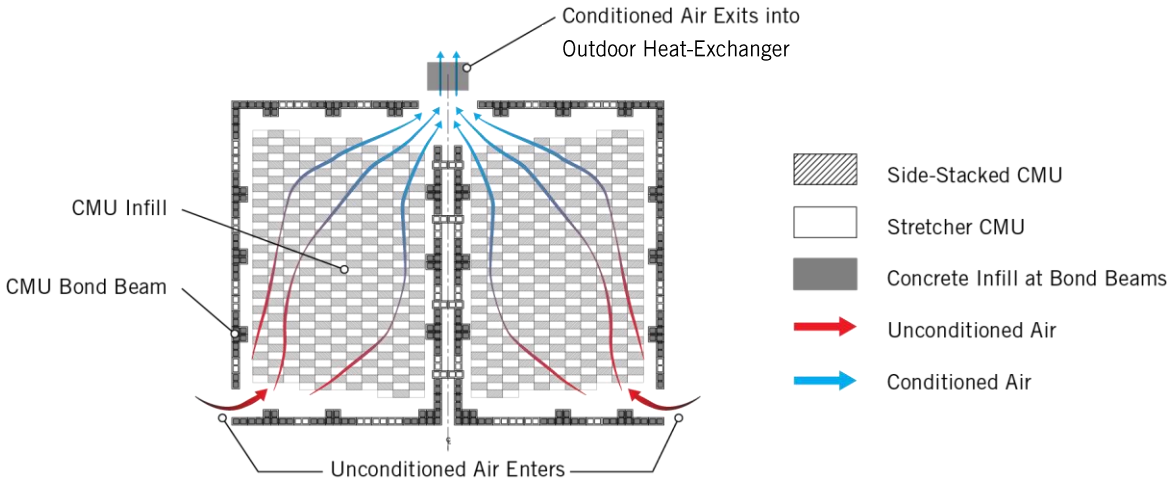


Figure 9 – CMU Thermal Mass System Diagram

The regulated air intake temperature at the outdoor air exchanger reduces the negative impact of extreme temperature days. These extreme temperature days represent 14.4% of the calendar for the Clemson location, where 8.1% of the heating season is below 32°F and 6.3% of the cooling season is above 86°F. The net effects of this thermal mass pre-conditioning is estimated at 10-20% reduction in the energy required to operate the outdoor air unit, a reduction in the maintenance cost over the lifetime of the unit, and, most importantly, an increase in occupant thermal comfort during extreme temperature days.

Additionally, this unique system is not strictly dependent on the footprint of Indigo Pine or on its mini-split mechanical unit for enhancing system performance. Team Clemson's utilization of an inexpensive wholesale material (CMU) allows this simple system to be implemented beneath any new home or any existing home with a crawl-space, provided that the home has a sufficiently insulated floor (R-30) or additional insulation included with the installation of the system.

Once inside the home, a heat recovery ventilator (HRV) is used to provide the desired fresh air for indoor air quality. This unit recycles an estimated 70% of the sensible energy of the indoor air (otherwise exhausted as waste) and blends it with the fresh air taken in from outside. Additionally, an integrated control system and manually operated dampers allow occupants to monitor temperatures and control air distribution between the different zones of the house. This serves to concentrate conditioned air where it is needed throughout the day, maximizing thermal comfort while minimizing wasted energy.

Heat Ventilation and Mitigation Systems

Like its thermal mass foundation, Indigo Pine's innovative lap siding system acts as a dually functional element for the home. Team Clemson's solution for the home's exterior cladding utilizes aluminum composite material (ACM) panels that act both as the exterior finish and as a heat ventilating rain screen system. Rather than attaching the ACM to the structure with external panel clips, as is the industry standard, Indigo Pine's siding is an all-in-one solution. It is CNC routed, then folded by hand into three-dimensional modules before being quickly and easily installed onto the home using a combination of rivets and screws. The design of the folds provides a fully integrated spacer and ensures that the siding stands off from the sheathing beneath it, allowing for proper ventilation.

The siding modules are designed to include a 2"air-space between the panel and the sheathing behind it. Ventilation holes are pre-routed into the folded spacer of each module. This ventilated cavity ensures that the house will stay dry, and also provides a cooling effect during the warmer months of the year. The cooling effect of the siding begins with its high reflectance of solar heat energy. See below for the reflectance ratings of ACM panels selected for Indigo Pine. Solar radiation providing 1) additional thermal protection and 2) a continuous plenum for heat to escape from the exterior wall enclosure. ACM panels have the following properties that make them ideal for use in the heat ventilation system:

Color: Bone White
Light Reflectance Value (LRV): 78.50
Solar Reflectance Indicator (SRI): 82
Emissivity: .67

Any heat that does make its way through the siding and into the air space behind is evacuated passively through the integrated ventilating capabilities described above. Ventilated air spaces are the norm for rain screen systems, but the all-in-one nature of the Indigo Pine siding, paired with its high reflectance, make it particularly intuitive and effective at preventing heat gain. Team Clemson continues to monitor the performance of this system with various temperature readings and infrared analyses.

Included within the siding system is a series of folded ACM window shrouds along the southern side of the home. These shrouds are designed to passively optimize the home's solar heat gain, blocking sun in the summer and admitting sun in the winter. The depth of the shrouds can be easily adapted in the CNC cut-files to the solar altitudes of any particular site (see Appendix A for Clemson, SC solar altitude data).

Like the thermal mass foundation, the overall effect of Indigo Pine's ACM siding system (siding modules + window shrouds) is to improve the house's energy performance and further reduce the electrical load required to operate the home's HVAC system during days of extreme temperatures. The siding system also has market validity beyond the scope of the Indigo Pine home. Virtually any homeowner who is interested in a durable, low-maintenance option for increasing the energy performance of their house could purchase the siding system. The panels would arrive flat-packed, and the easy assembly and installation of the system would follow instructions provided with the product.

Solar Water Heater

Instead of using solar collectors as means of hot water generation, which often require significant maintenance during their use, Team Clemson has implemented a new DC-powered water heater with a 50 gallon tank, called Thermalux. A set of five dedicated PV panels are installed on the roof to generate the DC power used to directly heat the water during the day.

Our team's water heater is one of the first of its kind. Rather than plugging the water heater (one of the largest energy consumers) to the home AC circuit, our unique system powers the water heater directly with five solar panels, vastly reducing the energy loss through conversion and increasing our energy efficiency as a whole.

The DC power generated by the PV array is provided to the Intellement™ control system in the water heater. The Intellement™ system constantly senses the amount of electrical energy coming from the PV array and optimizes the energy delivery to the water in the tank. The water heated during the day is stored in the tank for use.

In days of low or no sun and at night, the house's standard AC power provides electricity to an auxiliary backup if hot water is needed, which is the only disadvantage of the system. The Thermalux water heater has the lowest maintenance cost of all water heaters due to having no moving parts.

The system is designed such that the water heating section of the PV array is completely separate from the AC grid so all the energy goes to the water heater. Using DC power, the water heater is not affected by the grid going down for a period of time. This is generally not an issue, given the high reliability of the US electrical grid. However, it is an advantage that the other systems cannot claim unless they have a dedicated inverter for the water heater that is not grid tied.

Photovoltaic system

Simple enough to be installed by anyone, Indigo Pine's Photovoltaic system utilizes monocrystalline solar panels and micro-inverters. This system is used to power all electrical devices of the house, including lighting, hot water heater, appliances and entertainment systems, as well as the electric vehicle charging station. The system is designed to provide both DC and AC power with optimal efficiency, and has the ability to supply additional energy back to the electrical grid, saving utility costs through net metering.

In total, the electricity generating photovoltaic system contains 34 solar panels of 285W, among which 29 panels are equipped with 29 micro-inverters for AC power and 5 panels for generating DC power used by the water heater. The total system produces 8.4kW to cover the electrical load of the home.

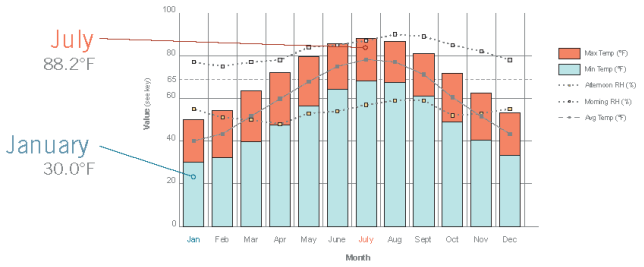
In order to meet the three-foot buffer requirement imposed by the upcoming 2015 building code (requiring a 3-ft wide walkable area around the solar array) and fit all panels onto the remaining surface area of the roof, Indigo Pine's solar array utilizes panels with an efficiency of 17%, one of the highest currently available on the market. For the purposes of the competition, Team Clemson chose to oversize the solar array in order to retain a true net zero performance while competing during all hours of the day and late into the night. In practical application, however, Team Clemson suggests the implementation of a battery backup system to effectively maintain the net zero performance of the home. During the day, while the family is likely away and power usage is at a minimum, the batteries would charge to allow the family to have access to their electrical systems at night. Team Clemson expects the system payoff to be less than 10 years when factoring in the Federal and state (SC) tax credits. See the calculation below.

Approx cost of electricity generating solar panel system:	$	25,000.00	
SC State Tax Credit:	$	(3,500.00)	
Federal Tax Credit (30%):	$	(7,500.00)	
System Cost After Tax Credit:	**$**	**14,000.00**	
Avg. Cost per kWh in SC:	$	0.11	
Avg. Household kWH / Yr in SC:		13,428.00	kWh
Avg. Yearly Electricity Bill in SC:	**$**	**1,477.08**	
Expected System Payoff:		**9.48**	**years**

Appendix A: South Carolina Climate Data

The following data is a representation of the climate data found in Clemson, SC; the location of Team Clemson's first home, Indigo Pine East. This information is provided as a means of understanding the typical climate found in South Carolina, the area that Team Clemson has identified as the target market for Indigo Pine.

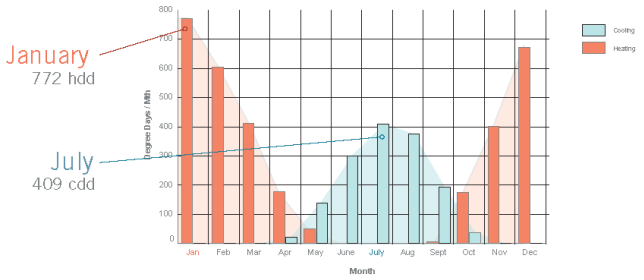
Temperature + Relative Humidity:



Average Max: 70.7°F
Average Min: 49.2°F
Average Total: 60.0°F

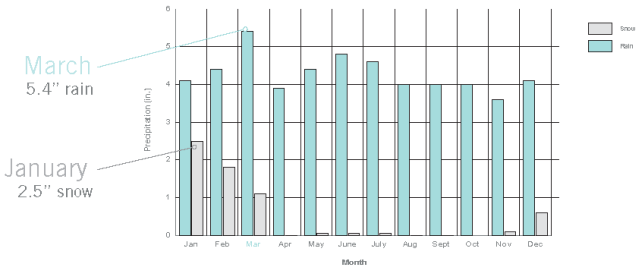
Average Morning RH: 82%
Average Afternoon RH: 54%
Average Yearly RH: 68.5%

Degree Days:



Yearly Heating: 3272
Yearly Cooling: 1473

Precipitation:



Yearly Rainfall: 51.3"
Yearly Snowfall: 6.1"
Rainfall Days / Yr: 119

http://www.climate-zone.com/climate/united-states/south-carolina/greenville-spartanburg/

Solar Altitudes: Summer - 78° Winter - 32°

Appendix B: Supplemental Calculations

CMU Thermal Mass System

The analysis below if provided as a comparison between the thermal storage capacity of the CMU thermal mass system (approx. 40,698 kJ) and the total thermal energy to be withdrawn from the air passing through the system (approx. 27,354 kJ). As the thermal capacity of the CMU system is greater than the energy being extracted from the air passing through the system, Team Clemson estimates that the temperature of the CMU system will not increase to its max – the system will perform consistently throughout the day and throughout the seasons. Of note, the calculations below utilize Team Clemson's estimates of temperature differential values. Ideally, a transient computational fluid dynamics analysis is necessary to show that the air flow, the heat flow, and the temperature distributions of the CMU and the air are non-uniform in space and time.

Thermal Mass System Estimates:

Item	Volume of Conc (m^3)	Qty.	Total Volume (m^3)	Volumetric Heat Capacity (kJ/m^3-°C)	Total Volumetric Heat Capacity (kJ/°C)	
Side Stacked CMU	0.0068	360.00	2.45	2,112.00	5,170.18	
Stretcher CMU	0.0029	364.00	1.06	2,112.00	2,229.43	
			Total Heat Capacity of System:		**7,399.60**	**kJ/°C**

Estimated CMU Temperature Differential:	5.5	°C
Total Thermal Energy Storage Capacity:	**40,697.82**	**kJ**

Thermal Energy Withdrawn from Air Estimates:

Heat Pump Capacity	600.00	CFM
Estimated Run Time	4.00	Hrs / Day
Total HVAC Air Intake:	**4,076.64**	**m^3**
Volumetric Heat Capacity of Air	1.22	kJ/m^3-°C
Total Heat Stored in Air	**4,973.50**	**kJ/°C**
Estimated Temperature Differential of Air	5.5	°C
Total Thermal Energy to be Withdrawn from Air	**27,354.25**	**kJ**

Energy Analysis Results and Discussion

Numerical simulation was used to determine the impact of specific aspects of Indigo Pine and, in some instances, help make design decisions. EnergyPlus [1], version 7.2, was used. EnergyPlus is an energy analysis and thermal load simulation program that calculates heating and cooling loads necessary to maintain thermal control set points and the energy consumption of buildings. The house was analyzed for two locations of interest, Clemson SC and Irvine CA, defined by their respective weather files. Two separate run periods were considered, full year (January 1st to December 31st) to simulate the overall behavior of the house and predict payback periods, and the duration of the competition in October (October 8th to October 18th) to predict the behavior of the house during the Solar Decathlon competition in Irvine, CA.

Reference Design

The house was modeled as a simple rectangular box with appropriate fenestration on each façade and shading devices on the West and South facades (See Figure 10). The volume is considered as a single zone. The roof is modeled as a flat roof, which does not vary significantly from Indigo Pine's actual 1 in 12 pitch.

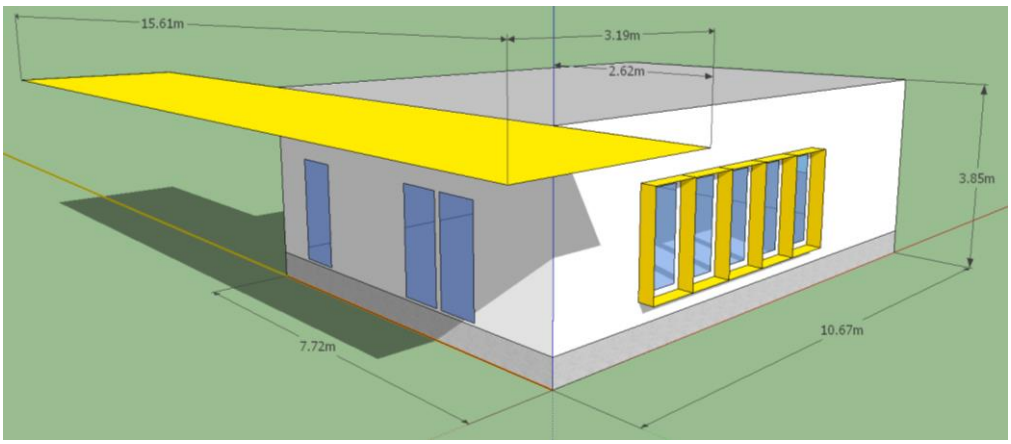


Figure 10 - Shading devices on West and South facades

The wall, floor and roof constructions are defined using the properties of each layer material of the envelope. The corresponding R-values are 25.3, 23.3, and 42.4 respectively. We used the ideal load air system in EnergyPlus to model the behavior of the HVAC system. As a result, the energy loads are calculated to meet the desired set point temperatures, which we defined as 22.2°C for heating and 24.4°C for cooling.

The ductwork includes three dampers that divide the house into four independently controlled zones. The purpose of this feature is not to reduce the energy consumption of the house but mainly to provide additional control to the users and increase thermal comfort. In particular, it allows the user to adapt the supply of conditioned air to the zones based on user occupancy, hourly solar heat gain, and/or specific internal heat generation. As a result, the user is able to specifically define a more uniform temperature throughout the house, or, inversely, a more non-uniform temperature distribution according to her/his desire. However, the effect of this feature on energy consumption is not easily evaluated on such a small building with a single return. Therefore, we consider the building as a single zone and neglect, in our modeling, the potential energy benefits of this feature.

Results of reference design

The main results shown below are the monthly energy consumption under the weather of Clemson SC without and with the heat recovery ventilator. The most compelling conclusions include:

- Heating and cooling energy consumptions are 56.4% and 43.6% of the total energy consumption, respectively.
- The hourly energy consumption peaks at 5 MJ/h. This value is on target with the typical energy consumption of high efficiency homes [2] and corresponds to 26% of the cooling capacity of the 1.5 ton HVAC system.

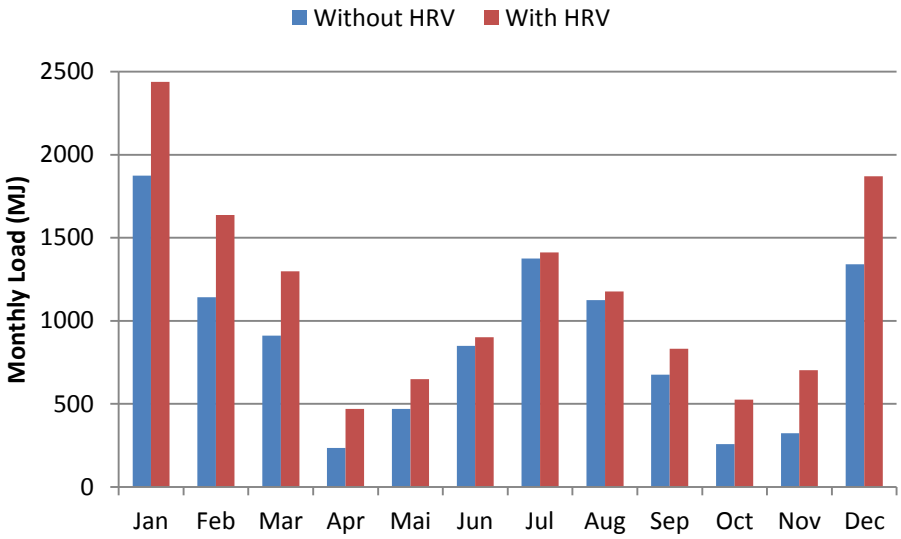


Figure 11 - Monthly heating and cooling load with and without HRV

Expected results during competition

Using the weather file of the competition site (Santa-Ana, CA), the behavior of the house during the competition (October 8th to 18th) can be evaluated. As expected, the weather in Irvine CA in October is expected to be ideal and the HVAC system will not be solicited. The total energy load is expected to be about 10% of maximum load encountered during the year.

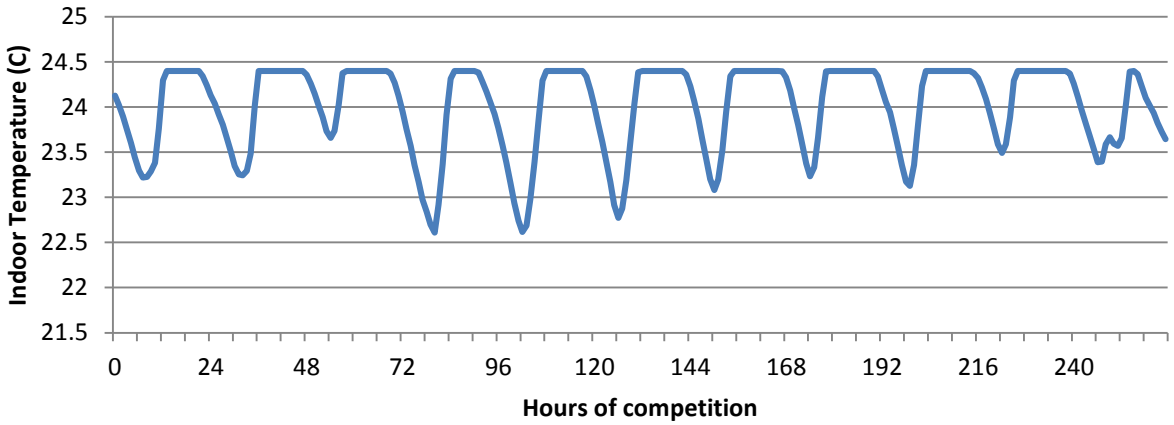


Figure 13 - Estimated indoor temperature

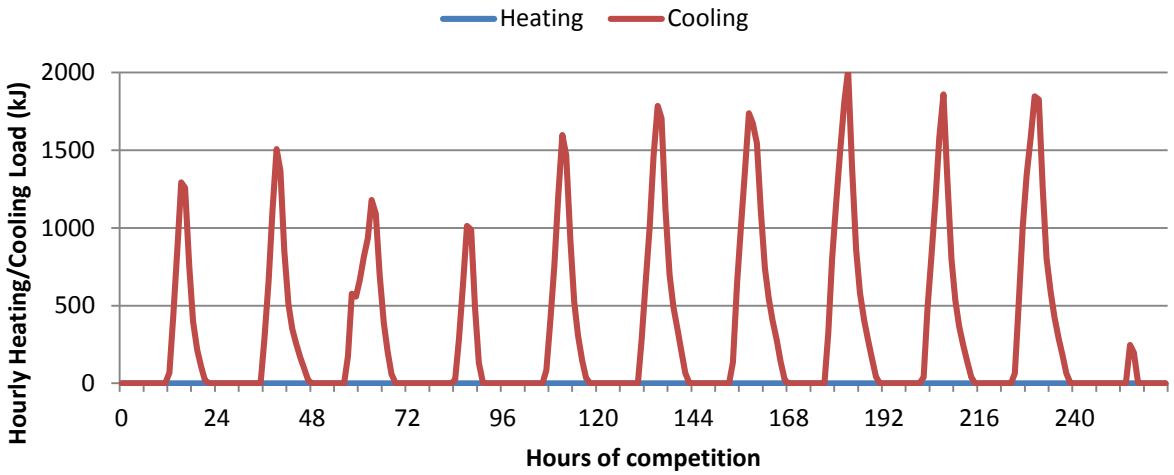


Figure 14 - Hourly heating/cooling load during competition in Irvine CA

A complete description of the energy analysis can be found in the project manual.

References

[1] http://apps1.eere.energy.gov/buildings/energyplus/energyplus_about.cfm

[2] U.S. Energy Information Administration, www.eia.gov

Communications Narrative

Figure 10 – Indigo Pine East construction underway.

Goals and Objectives

Indigo Pine strives to utilize a multitude of outreach outlets to creatively share our ideas and interactively promote our home. Our goal is to share the passion and excitement we have for Indigo Pine in hopes that others will join us in our journey to change typical home design and construction.

Knowledge

We aim to share the *knowledge* of our technologies with others in the hope that efficient, affordable housing that is easy and safe to construct by the average person can become a reality. Conveying the concept that Indigo Pine is accessible and uniquely buildable and adaptable requires simple, graphic, and clear communication of the key ideas surrounding the home. Those key messages are: *Accessible Innovation* and *Southern, with a Twist!*

> *Whether through interaction with family and friends, time spent outdoors, or drinking a cold glass of sweet tea, we hope to share the southern lifestyle with our audience.*

Outreach

The *outreach* of Indigo Pine extends from the local to the national level. By constructing two separate versions of Indigo Pine on both the East and West coast, rather than moving our home away from campus, Team Clemson will mirror the competition events and share our experience with our local community in a unique way. Additionally, leading up to the competition, the Indigo Pine team has communicated its message through local and worldwide media coverage, news and journal articles, and events at numerous locations.

Strategies for Target Audiences

Utilizing campus displays, local events, and digital projection, Team Clemson is continually spreading the ideas of Indigo Pine. Through Facebook, Twitter, and Instagram, in addition to Indigo Pine's website, Team Clemson's online presence is well known. Several videos have been created and posted online through all of our outlets in order to quickly educate the public about our project. Another great way for us to spread the word about the project and attract publicity has been through hosting and attending events.

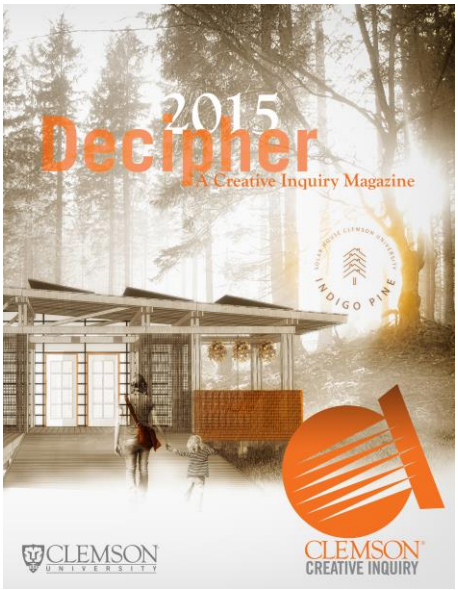


Figure 11 – Indigo Pine cover feature

Press Coverage

Publications include: Clemson's Decipher Magazine, Archinect, The Huffington Post, FOX Business, Houston Chronicle, San Francisco Chronicle, The State, Washington Times, Charlotte Observer, Seattle Post-Intelligencer, Yahoo! News The Post and Courier, and The Island Packet, among many others.

Events on Campus

- Indigo Pine Unveiled **(and video)** - The project was officially unveiled during a ceremony in the Clemson School of Architecture which attracted university figures, sponsors, and media. Full-scale mockups of the structural system and interior cabinetry, models, and drawings were on display.
- **"Valenpine's Day"** - Students were encouraged to snap photos in the photo booth set up in the mock-up of our structural system on campus. Fun hashtags (#willyoubemyvalenpine) encouraged participation and sharing.
- Indigo Pine East Ribbon Cutting **(and video)** - To celebrate the construction of IPE, our prototype of the competition home which will stay on Clemson's campus, a large, well-publicized ribbon cutting was held and attracted many important visitors from the university, our sponsors, and the media, as well as students, faculty, family, and friends.

Building a home that will stay on Clemson's campus through the competition has created a buzz that will be sustained through the months following the Solar Decathlon, and allow for many events to be held in Clemson in the coming weeks.

Events Across the State

- **iMAGINE Upstate and Artisphere** - Indigo Pine had booths at *iMAGINE Upstate*, a technology innovation festival, as well as *Artisphere*, one of the top art festivals in the country. Both were held in downtown Greenville, SC.
- **AIA (American Institute of Architects)** - Members of Team Clemson presented Indigo Pine at both the AIA Greenville and AIA Columbia section meetings, in addition to having a popular booth at the AIASC annual conference.
- **Local schools** - Several team members have made visits to local high schools to present the Indigo Pine project and educate students about sustainable and innovative design.

Figure 12 – Indigo Pine events

Metrics for Success

We will never be finished sharing Indigo Pine with the public. In recent months, the team has been especially encouraged by media outlets who have approached *us* about covering our project. As word continues to spread leading up to the competition, our communications strategies will remain a top priority. For those who support the project as sponsors and partners, Team Clemson recognizes them on all of published materials, including printed signage, brochures, and posters, as well as digital media such as our website, newsletters, social media, etc. Plans are also in the works for a permanent display of thanks to be located in the architecture building on Clemson's campus.