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A framework for multi-disciplinary student teams participating in a design-build competition of a sustainable and affordable housing

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A Framework for Multidisciplinary Student Teams Participating in a Large-Scale Design-Build Competition

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Abstract

California State Polytechnic University (Cal Poly Pomona, CPP) was selected as one of the fourteen university teams to compete in a design-build of a sustainable and affordable house at the inaugural Orange County Sustainability Decathlon. This was a new, state-funded, international juried competition that challenged university teams to design-build net-zero homes in response to climate change and the California housing crisis. Cal Poly Pomona's Roots House was a culmination of three semesters of work by approximately one hundred students across eleven majors, competing against teams from as far away as China. In this paper, a multidisciplinary team of faculty provide an overview of the design approach and the topics that were covered to prepare our students for the 10 contests of the decathlon. The topics included architecture and interior design, sustainability and resilience, engineering and construction, communications and marketing, market potential, innovation, energy efficiency, water use and conservation, health and comfort, and lighting and appliances. Our students gained hands-on experience in the emerging industries such as sustainability, technological innovation, and climate change; provided tours to educate the public; and learned to work with industry professionals and various contractors on an accelerated construction schedule. This resulted in the construction of a 1008 sq ft, net-zero house that was built in a factory in six weeks and installed on site in two weeks. This project was a unique learning opportunity for our students. This paper summarizes the positive student learning outcomes.

Introduction

To meet the Orange County Sustainability Decathlon 2023 (OCSD23) challenge, the Cal Poly Pomona team began with a collaborative assignment to develop a schematic design of the house. We formed eight design groups; each group included three students from architecture and three students from civil engineering. These competing design groups brainstormed ideas and submitted eight different schematic designs. Of the eight designs, students, faculty, and industry mentors voted on the best design and floor plan. The students submitted names for the final house design and chose “Roots” by popular vote. Our logo, submitted as an extra credit assignment, was designed to align with our narrative, mission, and school colors.

The final submission was the Roots House, which is an energy efficient, resilient, sustainable, and affordable single-family residence for the California housing market. It is a design-build of a prototype house that responds to two major challenges of OCSD23: (1) global warming with its devastating effects, increasing extreme weather events such as wildfires, flooding, and drought that are displacing millions of people; and (2) California’s rising cost of housing that, compared to the national affordability index of 2.7 (ratio of the median home price to median income), is 6 to 10+, making California the epicenter for lack of affordable housing.

Background

Cal Poly Pomona: Our campus is located 30 miles east of Los Angeles in California, offering an affordable education in a vibrant and diverse community. CPP’s student enrollment is about 53% Hispanic, 22% Asian, 3% African American, 14% White, with the balance composed of other ethnic minorities. Additionally, 46% of the students are female, 57% are first-generation college students, and approximately 40% of the total undergraduate population are transfer students. CPP’s educational philosophy is “learn-by-doing,” engaging students in hands-on research, scholarship, and creative activities; our design-build project embodied this aspect of CPP’s educational philosophy. CPP has a high percentage of STEM majors at 41%.

CPP ranks highly as a top performer in upward social mobility, ranking at #6 in the West, propelling low-income students to financial success by graduating them into rewarding careers.

Student Participants: During this design-build project of a sustainable and affordable house approximately one hundred students, representing eleven majors, participated in our team over three semesters. Participants included the following number of students in each of the majors: 25 architecture, two regenerative studies, five landscape architecture, 40 civil engineering (including environmental engineering and construction management), one chemical engineering, two mechanical engineering, six electrical engineering, one computer science, one math, one business, and one gender and ethnic studies.

Faculty and Mentors: We had commitment from five full-time faculty advisors, one part-time faculty advisor, one energy consultant (with a partnering university), two sustainability consultants (industry), and four industry mentors who specialized in mechanical electrical and plumbing (MEP), sustainability, and energy efficiency. The roles of the advisors, consultants, and mentors were to guide students in their initial designs, check their work, and provide constructive feedback towards multiple iterations of design optimizations.

Methodology

Although each of the 10 contests of the decathlon deserves its own section, the following sections are concisely highlighted for the design framework utilized by Team Roots: (1) architecture and interior design, (2) landscape architecture, (3) engineering and construction, and (4) sustainability and resiliency.

(1) Architecture and Interior Design

The architectural and interior design of the Roots House is a result of consideration of various design goals and project constraints, aligning closely with the American Institute of Architects (AIA) Framework for Design Excellence and the design framework utilized by Green Builder Media's Housing 2.0. The AIA Framework for Design Excellence framework articulates 10 principles aimed at fostering progress "toward a zero-carbon, equitable, resilient, and healthy built environment." Although all 10 principles were addressed during the project, this paper concisely delves into the a few principles below. Once the house was designed, the design was iterated multiple times for optimization.

Design for Equitable Communities

The Roots House addresses the pressing housing crisis in California by providing affordable options for first-time homebuyers, including millennials, and the elderly looking to downsize. The community design incorporates a 10-house site centered around an organic vegetable garden, a recreational area, and a community center to foster a sense of belonging for the multi-generational community. See Figure 1.

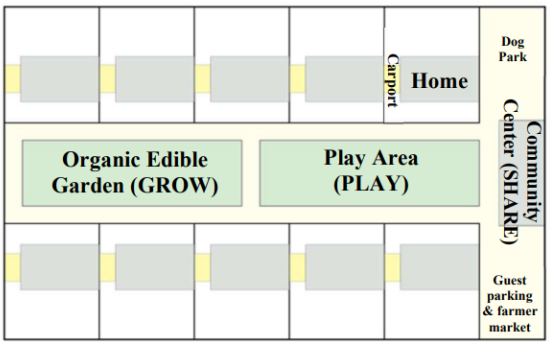

Figure 1. Community Design

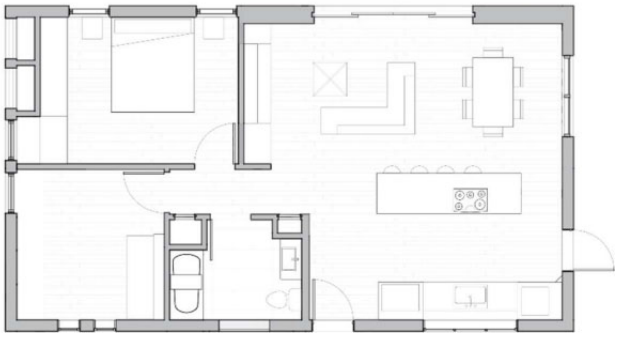
Figure 2. Floor Plan of the Roots House

To provide flexibility, the house can also be a standalone design (rather than part of a community), as an Accessory Dwelling Unit (ADU). This design caters to homeowners. With its affordability and modern open-concept design, the house accommodates work-from-home environments and families with children. The design promotes graceful aging in place, ensuring visual and thermal comfort and compliance with American Disability Act (ADA) standards. See Figure 2.

Design for Well-Being and Natural Comfort
Two components of nature were utilized for the home's natural comfort: sun and wind. Team Roots worked to design a home that would enhance the natural heating, cooling, lighting, and fresh air inside of our home. In addition to daylight and natural ventilation, the Roots House prioritizes access to views for psychological well-being. The use of Living Building Challenge's Red List approved or free products, such as hemp insulation, enhances indoor air quality. The insulation, made from natural plant fibers, is recyclable and compostable.

Design for Change (Adaptability)
Conceived as a prototype, the Roots House is adaptable for various conditions. It can be reduced in length by omitting ADA requirements, offering flexibility for different site constraints, including ADU configurations and compliance with legislative conditions. In conclusion, the Roots House design embodies principles of sustainability, equity, and adaptability, and it contributes to a progressive and resilient built environment.

(2) Landscape Architecture

For the Roots House, the site design's focus was on assimilating architecture/engineering to outdoor spaces for relaxation. To enhance indoor-outdoor linkages, both eco-revelatory and biophilic designs were utilized. Eco-revelatory is a design strategy to enhance site ecosystems while engaging users by revealing ecological systems and processes. Biophilic design emphasizes our instinctive bond with nature and its natural systems. To create an inviting site design, multiple useable outdoor spaces were created. Site drainage, water harvesting, and bioswales were integrated with native plants and landscaping.

Site Water Capture
Our team coordinated overlapping sustainable practices with the civil engineers by integrating graywater systems into a fruit orchard, harvesting rainwater from the roof for irrigation, and including fog harps and pervious paving for site water capture. The team utilized native plants and rock mulch to conserve and reduce water use. A lawn substitute was utilized (instead of turf or synthetic turf) with mulch to reduce water use by 75%. Overall, the landscape architecture team adopted a holistic view of the site to integrate the various sustainable methods and features from all the disciplines into a seamless whole.

Regional Characteristics of the Site
The landscaping plants were selected using mainly native trees and plants, including California oaks and sycamores, coastal sage, and local Toyon Rhamnus and Baccharis.

Community Design
The Design for Equitable Communities was previously mentioned in architecture and interior design. This community design has organic vegetable gardens, recreation, and a community center for shared uses. It incorporates the concepts of growing your own food with vegetable and herb farms fruit trees, and composting produced from the food scraps.

At the end of the design work, students were engaged in a two-week site-build construction period. Students collaborated with fellow students from other disciplines to a common goal of bringing their design to life. The crossover of disciplines allowed for a practical learning laboratory understanding of multiple disciplines and an understanding of how to approach site design as an integrated, interdisciplinary whole. This process fostered team camaraderie and focused on achieving an understanding of the construction

process with real-life parameters. This project and its process provided students with a real-life experience of working with multiple disciplines to execute a successful project.

(3) Engineering and Construction

The engineering and construction portion of the competition provided vast opportunities for the students to implement their design knowledge into practice, research new design methods to reduce waste, and collaborate with other engineers to integrate their designs.

Water Conservation

Considering the scarcity of water in California, the Roots House maximizes water collection through a (1) greywater system, rainwater collection, and fog harps. The greywater recycling system collects wastewater from bathroom sink, shower, and clothes washer and cleans it to be used for toilet flushing and plant irrigation. Rainwater is collected from the roof and redirected for landscape irrigation, complemented by a fog harp to collect atmospheric water. Furthermore, the floor plan centralized the bathroom, kitchen, and laundry facilities into one module to reduce plumbing lengths. Similarly, the hot water heater was placed strategically to also reduce the plumbing lengths. To minimize water usage, low-flow fixtures that meet United States Environmental Protection Agency's (EPA) WaterSense criteria were installed throughout the house.

Design for Economy

The Roots House was designed to be built in a factory and transported to the site. The optimal width for transportation was determined to be 12'. The house consists of two modules of 12' x 42', resulting in a 1,008 sf. and with construction completed in six weeks at the factory. The site work was performed concurrently with fabrication, greatly reducing construction timing. The efficient floor plan minimizes circulation, and the modern design adds value to homeowners and the larger community.

Natural Comfort

The design prioritizes passive strategies, optimizing natural ventilation and daylighting. Window and door placements considered prevailing winds for cross and stack ventilation. Ample fenestrations on all sides provide abundant daylight, with flexibility to adjust openings based on site conditions.

Energy Efficiency

Energy efficiency was initially conducted as a senior design project and part of master's project for students in the electrical and computer engineering department. The students collected and analyzed data, designed systems, selected appliances, and created an itemized list of electrical equipment. The electrical activities were divided into six main areas that included (1) solar panels design, (2) appliances power consumption calculations, (3) Home Energy Rating System (HERS) rating calculations, (4) electrical panel and lighting design, (5) smart home network design and integration, and (6) security systems design.

The energy efficiency design was conducted several times to compare the results of a stand-alone house versus a grid-tied, net-zero house. Upon this comparison, the team chose to move forward with a grid-tied, net-zero house, and the design was optimized once again.

Energy Modeling and Computational Fluid Dynamics

Mechanical engineering undergraduate students with a heating, ventilation, and air conditioning (HVAC) emphasis were engaged to conduct the Roots House's energy modeling with the load calculation principle and to simulate natural air ventilation with computational fluid dynamics (CFD). The Carrier Hourly Analysis Program was employed for modeling the heating and cooling coil loads of Roots House. A design

in Pomona, California including hourly and monthly design dry and wet-bulb temperatures and design day maximum solar heat gains (Btu/hr/ft^2) was chosen as the site of the Roots House. Roots House was partitioned into bathroom, bedroom 1, bedroom 2, hallway, kitchen, and living room spaces with each space's corresponding square footage and space height. Overhead lighting and occupancy were included in the building energy modeling. The R-values specified from the design team were utilized. In addition, different window design and shading/overhang configuration were selected for the Roots House. The annual total heating and cooling coil loads (kBtu), given a variety of building design conditions, were simulated for comparison (Figure 3).

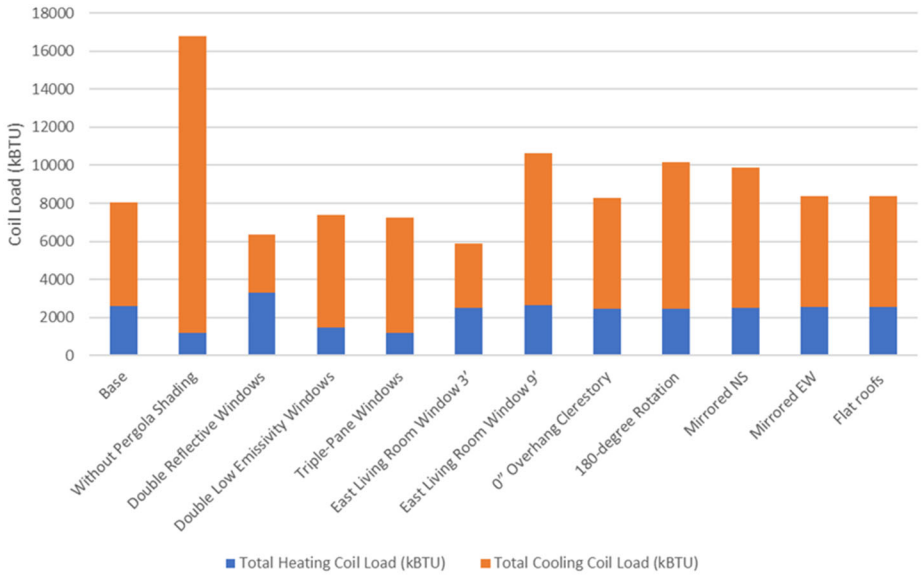

Figure 3. Annual total heating and cooling coil loads

The mechanical engineering team simulated active and passive ventilation conditions for the Roots House using the CFD approach. Semi-implicit method for pressure-linked equations (SIMPLE) algorithm was employed in ANSYS Fluent software to solve the ventilation dynamics inside the Roots House. Adiabatic wall boundary conditions and appropriate air conditioner's wind speed (active) or natural wind speed (passive) condition were employed in the CFD simulations. Figure 3 shows the active ventilation streaming down from the air conditioner inside the living room of the Roots House. Figure 5 presents the passive ventilation streamlines while all of the bedroom and kitchen windows, as well as the living room door, are open, assuming that natural air flows through the living room door to the indoor space of the Roots House.

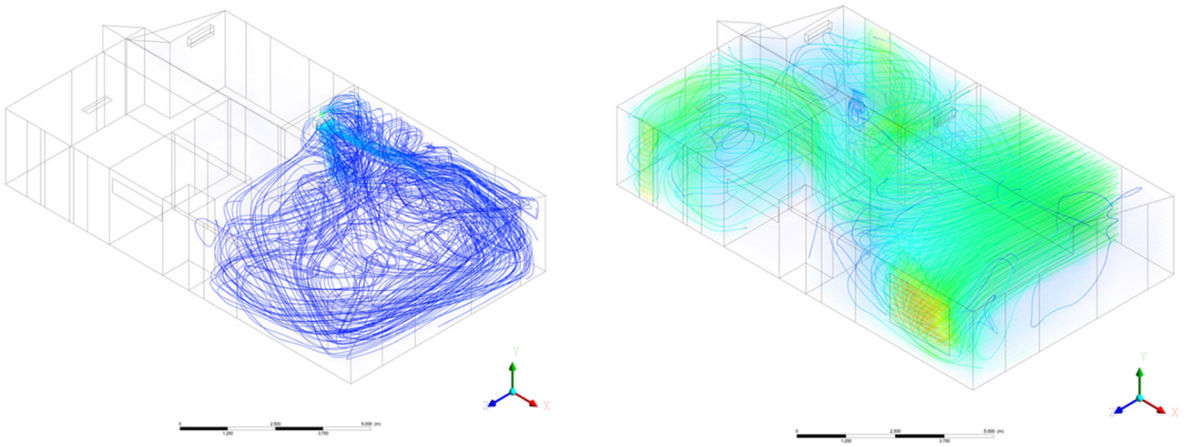

Figure 4. Active ventilation streamlines inside the living room of the Roots House

Figure 5. Passive ventilation streamlines while all bedroom and kitchen windows and the living room door are open, allowing natural airflow through doors and windows into the Roots House

(4) Sustainability and Resilience

Design for Resources

To understand the environmental impacts of the Roots House, a Life Cycle Analysis (LCA) from the (1) Production, (2) Construction, (3) Use, to (4) End of Life stages was conducted. A material takeoff conducted allowed for accurate accounts of the construction materials; also, construction methods and sourcing locations were captured for the analysis. This data was input into EarthSmart to determine the amount of embodied carbon in the four stages of the LCA. The project prioritized carbon-neutral or negative materials.

Design for Resilience

Resilient housing involves constructing a home to withstand the natural environment and survive extreme natural disasters. The students aimed to protect the house from natural disasters in California such as wildfires, earthquakes, and frequent periods of drought with a resilient design.

Student Learning Outcomes

Fifteen civil engineering students involved in construction administration stages of the competition were surveyed on their overall experience. Their reflections were tallied and analyzed. There were limitations in data collection, as by the time the competition occurred in October 2023, the bulk of the original design students had graduated.

Overall Experience

Participating in the OCSD competition was an enriching and enjoyable experience for most of the student participants. They appreciated the hands-on experience and enjoyed giving tours. They learned to appreciate the importance of multidisciplinary collaboration and they built lasting friendships. They grew, both personally and professionally. Many talked about enduring long hours and long commutes together with their teammates, but they also gained leadership experience, technical and soft skills, and felt they had improved their career paths. Some students have already incorporated the project on their resumes to discuss with employers. In general, the student feedback was overwhelmingly positive. Students gained a better understanding of sustainability and enjoyed the hands-on nature of the construction process. Suggestions for improvement include detailed construction schedules and the involvement of additional students and faculty. The overall sentiment is that the OCSD competition was a valuable and unmatched learning experience. Their direct quotes are included below.

> "The Orange County sustainability decathlon was an unexpectedly major undertaking of an event to say the very least. I will admit the event was a lot, from both a construction and tour guiding perspective, but it was easily the most valuable learning experience in my time in Pomona and the 10 weeks I have been part of the team easily outweighs any other class I have taken thus far…. The time spent as part of the Roots Team is time I would never want to replace, and I am glad I was able to play a small part in such a huge undertaking. I think the Roots Team did well in not only making the most out of what was possible, but also setting the standard for what competing schools should do within the competition."

> "The biggest success for our team was how everyone in our team was willing to help as much as they could and willing to learn. It was such a pleasure working with everyone and I'm very thankful everyone tried their best to help me out."

> "Overall, participating in this competition was a very fun and enriching experience. I am glad I chose this project over the other options because it had hands-on components rather than only hypothetical design…. It was a literal project that our team did together, both in pride and distress. We won together, we lost together, and we had a blast together. From early 4 AM mornings to midnight work, we stayed to make sure we did as much as we could and grew in progress of the home as well as growth in friendships…. I am extremely grateful for having the opportunity to work with my professor and fellow classmates on what I consider a successful and memorable project that will continue for years to come."

Team and Individual Experiences

The students reflected on various aspects of the team's experience in the competition. They were somewhat disappointed to have finished in Third Place. One student called the experience "a test of grit and perseverance." Successful relationships with sponsors, such as AMCO Structures, Arcadia, and AJ Madison, are noted as significant achievements. In addition, the students appreciated being recognized by the University. Many responses indicated how much students enjoyed working with their team members. In many cases, they mentioned a handful of students that went above and beyond to make the project a success. On the other hand, many felt that the time commitment was excessive. They highlighted the need for better construction scheduling. They suggested that more student leads could disperse the workload more effectively. Overall, the students were very grateful to their team members, faculty, and industry partners. Their direct quotes are included below.

> "One of our biggest successes was our relationship with sponsors such as AMCO Structures, Arcadia, AJ Madison, and others, all of whom helped produce some of the key aspects of this house."

> "My favorite day of the event was the kids' day with all the schools there because it was cool seeing the youth excited about possibly taking a future career in engineering or construction. My favorite moment of the entire event was when I spoke to a school program with a group of students who were all females with an interest in engineering."

> "The learning value is immense and it certainly is a huge boost to employability."

> "The competition was a very interesting event and I was happy to be a part of it. I came out of this project with a much greater understanding of sustainability, marketing, and construction management…. I was also very impressed by my classmates that joined alongside me this semester. Many, if not all of them, went above and beyond what I would have expected them to do…. The Roots House was beautiful. You could tell that so much passion was put into every aspect of its design. It was not only aesthetically pleasing, but also extremely practical. As a proponent of sustainable design, I hope that future developments use designs like the Roots House. I felt that the project involved many different disciplines and was happy to get the experience. I think that the project taught me a lot about the design and construction process and it was very cool to see the project go from design to fully built. My background as an engineer is primarily dealing with design, so it was nice to be able to learn something new. Aside from learning about and observing the entire construction process, I felt that there were many lessons that could be applied to all types of work and management. The importance of scheduling tasks, delegating responsibilities, and providing open and consistent communication are my main takeaways from this experience. I aspire to be a

leader in the field of engineering and being able to work effectively with a team is a necessity to reach that goal."

Conclusion

Overall, the student feedback strongly supports Cal Poly Pomona's participation in the OCSD competition, with students almost unanimously voting to compete again. Fourteen out of fifteen students voted that the university should participate again, and only one student noted reservations that the judging criteria should be improved by the team organizers. Students gave many reasons for wanting to compete again, including learning about sustainability, building comradery with classmates, enjoying the multidisciplinary work, gaining hands-on experience, and recognition from the public for their work. Other motivations, along with the immense learning value and enhanced employability associated with participation, included their desire to *win first place.* This competition serves as an excellent showcase project for CPP, demonstrating the university's talented community and its dedication to interdisciplinary collaboration.