Design-Build Within an Educational Context: Reflections on Experiences Gained from Two Experimental Net-Zero-Energy Housing Projects

Since 2009 students and faculty members have been involved with two Design-Build projects within the context of the US Department of Energy Solar Decathlon (SD) competitions for net-zero-energy housing. The competition climaxes with the construction of a house at an event site where houses are opened to the public and where student teams compete in a collegiate manner. Two consecutive projects have been completed for this competition.

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The first project resulted in the "E-Cube" entry for the 2011 US competition held in Washington DC (Ghent University). The second project resulted in the "Solatrium House" for the 2013 Solar Decathlon China competition held in Datong, China (Ghent University + Worcester Polytechnic Institute + NYU-Poly). The competition offered a challenging venue to further our students understanding of energy efficient design and prefabrication, while also offering opportunities to gain practical construction experience. In this paper we review the design strategies, team formation, logistical and fundraising efforts, as well as various challenges encoutered during these two projects. We conclude with making some overall observations and recommendations based on our experience with both projects. The paper concludes with a preliminary reflection on possible future efforts to embed a Design-Build curricular component in a newly established architectural engineering program at WPI.

E-CUBE 2009-2011

The E-Cube project was in large planned as a student driven Design-Build project whereby faculty members served as advisors to the project. The project started with a visit to the preceding solar decathlon competition in the early fall of 2009 (Washington DC) after which the team formulated an overall approach and the faculty member wrote and submitted a proposal.

E-Cube Design: During the project conceptualization phase the team adopted affordability as an important design criteria, a decision made in the midst of the financial crisis. A do-it-yourself building-Kit was envisioned that would allow prospective

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Figure 1: E-Cube prefabrication Ghent University, Belgium

builders/owners to realize cost savings. The DIY approach was extended to all components of house construction resulting in the development of guidelines for maximum component weight as well as the means and complexity by which components are to be connected. This "Ikea" approach aimed to provide an affordable house construction method that thrives on the energy that people are willing to invest in a home. Such onsite component based assembly process for the house was considered to be more challenging to students. The team used the Passive-House Standard as a guide to help meet the zero-energy target for the competition. A design charrette was organized with students working in alternating pairs and various conceptual design strategies were developed. A critical junction was reached when a decision was made to use a standard pallet rack system as the structural system for the house. From this point onwards, the structural frame became the guide and scaffold for every other design decision.

The house evolved into a compact cubical shape with a footprint of approximately 8 by 8 meter (64m²) and the E-Cube (Energy-Cube) name was coined. The overall design remained largely student driven, although some technical solutions, such as the use of standardized pallet rack system for the structural frame, was promoted by the faculty advisor. A steel pallet rack system was used in combination with structurally insulated panels with PIR insulation core and pre-finished marine-grade plywood facings. These panels were custom made by a sponsoring company and were used for the floor, roof, and external walls. High performance aluminum frames with triple glazing were used for the windows. All wall panels and fenestration components were designed to have the same dimensions and edge detail so that their position within the facade could be changed, a feature that offers some flexibility in the design of the house. The second story of the house was only partially filled with floor panels in order to comply with the maximum house size for the competition (1000SF or 93m²). Due to the openness of the second floor, the design contained many voids that allowed visual connections and passing of light and air between the first and second floor levels. The design was kept plain and simple. Wall and floor panels were pre-finished with a high quality factory applied varnish and were left as such. Kitchen cabinets were made from low cost shelves and none of the appliances were built in. Façades were clad with fiber cement boards that served as a rain screen. The team did not invest in elaborate exterior amenities such as decks and planters, in order to keep cost down and retain the visitor's focus on the house itself.

E-Cube Team: During the first year there was one faculty advisor and four primary

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students who worked on the E-cube project in the context of their thesis (senior architecture students in a 3+2 program). The first year started with a visit to the 2009 competition in the early fall (Washington DC), and with the team being selected for participation in early 2010. At this stage, the seed team was expanded with four more students who collaborated on the design development of the project in the framework of a required design development studio (4th year Architecture students). The studio was used to advance the architectural design while exploring technical solutions for the façade, mechanical installations, integration of techniques, and so on. Team dynamics changed during the project's second year. As the initial seed team of 4 students had graduated, a financial arrangement was made to retain one of them to stay involved with the project on a full time basis as the project leader. Two other graduates also stayed involved on a part-time basis. The project leader worked with the 4 students who had joined the team in the preceding year and who also continued to work on the project in the context of their senior thesis. The team was reinforced with one additional faculty member who provided substantial support to the team during the design development and construction phases of the project. This allowed the initial faculty advisor to focus on the many logistical and fundraising aspects of the project. Two elective course were developed that allowed more students to join the team, an arrangement that provided the workforce to construct the house.

E-Cube Challenges: One of the challenges of our participation in this competition had to do with the financial uncertainties. Besides a relative small budget provided by the DOE (100k), no funds were committed up-front by industry sponsors or the university. The team was also awaiting a final decision from the event organizers who had added a second stage to the competition with results due late in the first academic year. During the first year it was therefore difficult to galvanize contacts with industry, who were expected to be the main sponsors of the project. The search for technical solutions was tied to potential sponsorship, vice versa, and new sponsors were sought as technical preferences changed. Balancing the budget remained very challenging until the final stages of the project as it became increasingly difficult to have every aspect of the project sponsored in-kind. As a result, purchase decisions needed to be made before all funds were secured. In retrospect, up front financial commitments are much preferred.

Another challenge was managing the large number of students. The initial student team had gradually grown from a seed team of 4 students in the first semester,

Figure 2: E-Cube first full assembly in Ghent

expanded by a second group of 4 students during the second semester, to finally grow into a group of about 40 students during the second year. The faculty support group had also expanded from 1 faculty member to multiple faculty members being involved in one form or another near the project's end. Students from the seed team that had initially assumed design roles moved into more managerial roles, which caused some frustration. The large team expansion during the second year was also troublesome as many participants were expecting an opportunity to have some design input. As this was deemed impossible, selected students from the seed team continued to lead the architectural and technical design and worked with one faculty member who guided their design efforts. The remainder of the students were assigned to building tasks within the scope of special topics courses. In retrospect, this strategy turned out to be a reasonable formula for the competition although a better communication of roles would have streamlined the overall process.

E-Cube Logistics: The construction process was component based and many parts were custom fabricated by sponsoring companies, student tasks were therefore largely reduced to component preparation and assembly tasks. A large covered university workshop was partially dedicated to the project but there was insufficient room for staging of materials. Materials were prepared and half of the house was pre-assembled in this indoor workshop. Materials were then moved into 3 forty-foot shipping containers outdoors, staged next to a small university plaza in the city. The first full assembly of the house occurred in this outdoor location. Exterior cladding and weatherproofing, interior finishes, some of the system testing, and installation of PV systems occurred during this period. No professional contractors were used with the exception of some support from university technicians. The house was disassembled and packed for shipment in two days during the summer period with a skeleton crew. In retrospect, lacking a large indoor workspace dedicated to the project and with space for staging materials and assembly was a major constraint. In addition, all constructions tasks needed to be completed during semester terms and outside of the examination periods, which was also a major constraint. The assistance of some contractors would have provided more scheduling flexibility.

SOLATRIUM 2011-2013

The Solatrium project was conceived as a more faculty driven Design-Build project whereby students served in supporting roles to the project. A project team was formed consisting of faculty members of Ghent University, Worcester Polytechnic Institute, and NYU-Poly. The project started with a team of faculty members visiting the 2011 solar decathlon event in Washington DC.

Solatrium Design: The team was interested to use a performance based design strategy to accomplish the same end goals as the Passive House standard in terms of annual energy consumption and comfort. The project evolved into an open architecture that emphasized connectivity to the outdoors, the house measures 11.25 x 11.25 m and has a wall-to-glass ratio of about 66%. The architectural design can be seen as an adaptation of a traditional courtyard house and the project includes a large enclosed central atrium that draws in views and light from above ("Solatrium"). Similar to the previous competition the team opted for a panelized prefabrication and construction method to reduce transportation volume and costs.

A relative large format panel system was envisioned to reduce seams and increase the overall envelop airtightness. Fiber reinforced composite sandwich panels were used for the structural system of the house (floor, walls, and roof). The panelized system consisted of a sandwich system with FRP skins and a polymer foam core. The panels are manufactured with a custom pultrusion process using cross-foam

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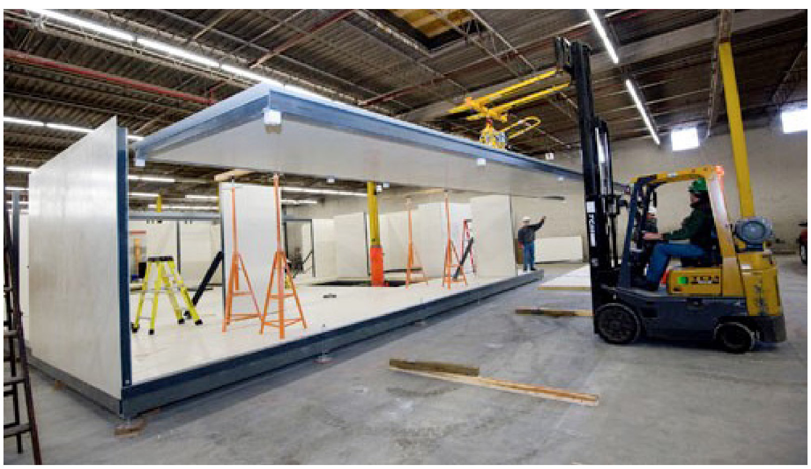
glass-fiber stitches that structurally connect both faces of the sandwich into a robust structural panel. The panels were precut to our specified dimensions, and were provided with structural FRP square tube inserts at their corners upon request. The edge inserts were part of the structural system and a custom connector system was developed for connecting the panels into a one structural system. The panels were waterproof and no interior or exterior finishes were needed, this feature resulted in a very minimal construction process. This was a new product and a large fraction of the effort was devoted towards the testing and development of a construction method for this material, which became a major research component.

A more classical solar design strategy was preferred for this project and the project included a substantial amount of glass. The large glass area in combination with lightweight composite materials made the project prone to overheating during



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sunny days, and overcooling during colder periods (winter, nights). The large amount of glass also offered potential for solar heat gain in winter. In order to make this work in conjunction with the use of a lightweight composite construction system, the team developed a new concrete paver system with phase change materials to increase the latent heat absorption performance. A custom concrete paver system with phase change materials was developed and fabricated by students. The floor pavers were about 1.5 inches thick and were important in optimizing the passive solar performance by increasing the latent heat absorption characteristics of the house. A total of 365 pavers measuring 60 x 60 cm were cast by the students. The development of the PCM enhanced paver system became another major research

Figure 3: Solatrium interior view, Datong China

Figure 4: Solatrium prefabrication, Worcester MA

task. The passive solar design and use of lightweight materials demanded a more careful analysis to accomplish the zero-energy and comfort targets. A whole building parametric study was undertaken using the DesignBuilder software, in order to specify optimal thermal and solar performance of the various building envelop components.

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Figure 5: Installation Concrete/PCM pavers

Solatrium Team: The first semester of the project was entirely faculty driven and no students were involved during the proposal submission stage, a student team gradually formed during the project's second semester. The final team included 4 students from Ghent University (civil engineering), 12 students from WPI (architectural engineering and other majors) and 6 students from NYU-poly (civil engineering), and about 6 faculty members. About 6 students worked on the project in the context of their final project or thesis. Many students volunteered or received credit for their contributions. At WPI, 4 students worked on the project to satisfy the institute-wide interactive qualifying project requirement. In addition to University students, the team also included about 10 high school students and various teachers from Worcester Technical High School, 6 of whom joined the team during the competition period in China. Students participated in all project development stages, however their design contribution was in large of a "consultancy" nature resolving selected design issues related to their majors, such as structural, electrical, mechanical, or architectural engineering. The architectural design was developed entirely by one faculty member and the student team did not include any architectural design majors, although many architectural engineering student were involved.

Solatrium fundraising: The project immediately followed the 2011 E-Cube project and it was therefore decided that a collaborative effort would make more financial sense. The E-cube project had placed a substantial burden on the faculty (Ghent university) and it also seemed unlikely that financial support could be attained within the short timeframe. Because of this, a multi-university team was formed consisting of faculty members of Ghent University, Worcester Polytechnic Institute, and NYU-Poly. Worcester Polytechnic Institute committed to become the lead institution carrying the bulk of the fundraising effort, and house construction activities. In return, a visiting faculty member from Ghent University committed to coordinate the project on behalf of the three universities. NYU-Poly's role consisted of developing and fabricating the custom concrete paving system with phase change materials, in addition to providing student support during construction. The team received substantial support from the WPI development office, which assigned a dedicated person to assist the team with fundraising. An advisory committee was set up that consisted of WPI alumni and local business people. The team reached out to various community partners for help. Faculty and students from the Worcester technical High school were engaged and helped the team with various practical fabrication tasks, with contributions made by students from the school's welding, machining, electrical, and plumbing departments. The team also reached out to the local carpenter union for help and a crew of about 4 highly skilled carpenters completed all the woodwork in the house. The advisory board and alumni were instrumental in securing contractor support for plumbing, HVAC, and electrical work. The overall cost of the project amounted to about US 500k. At the proposal development stage WPI had committed a cash contribution, Ghent University had committed a full time faculty member to the project, and NYU had committed to the fabrication of the custom tile system. Working with the advisory committee, the team secured about 350k in contributions, from which about half were in-kind material donations. The team also managed to sell the house to the Chinese government at the completion of the event. The fundraising remained a time demanding aspect of the project, the team ended up with a surplus of about 250k after selling the house.

Solatrium Logistics: The project was spread over a period of 2 years. Most components of the house were prefabricated by partner companies, the woodwork used in exterior sunshades, kitchen cabinets, partitions and interior ceilings were fabricated by volunteer carpenters. The team tasks were largely restricted to preparatory tasks and assembly. The foundation system was CNC fabricated out of FRP pultruded shapes, a feature that allowed for a very precise and fast assembly. A custom made steel truss system was fabricated by students from the technical high school. The team secured a large warehouse space off-campus, allowing work during the winter months and providing enough space for staging of materials. The first assembly tasks started the day before Christmas 2012, the house was disassembled and shipped in three 40 foot standard shipping containers in May 2013. The indoor workspace with limited headroom made it difficult to place the atrium structure on top of the house indoors beforehand. The topping-off occurred in China, and proceeded as planned without much difficulties. One faculty member was full-time dedicated to the project, this greatly facilitated project management, design, construction, and competition tasks.

CONCLUDING REMARKS

The E-cube project mostly relied on students to drive the design effort while faculty members assumed supporting roles. The E-Cube project involved mostly architecture students, only a small group of these students however engaged in design activities while the majority of students assumed more supporting roles. In contrast, the Solatrium project was entirely designed by a faculty member and students assumed mostly supporting roles. The majority of students in this project were enrolled in either architectural engineering or civil engineering programs. Both projects required substantial faculty guidance during design, design development, construction, and for event logistics. Both projects also proceeded under very compressed time schedules and entailed use of alternative construction methods. Both projects included rewarding moments and experiences that instilled a collegiate spirit among students and faculty.

Experience with both projects has shown that dedicated Design-Build faculty members are critical in bringing the design and construction aspects of the projects to a successful outcome. The E-cube and Solatrium projects were rather a-typical Design-Build projects that required much prefabrication and planning to accommodate fast assembly at the competition event sites. This prompted the development of innovative construction solutions, which added interesting research dimensions to the projects. Prefabrication of components and collaboration with industry was a practical route for both projects. In the aftermath of the competition, the E-Cube house was shipped back to Belgium were it currently serves as an experimental house for a university affiliated incubator center. The Solatrium house was sold to the municipal government in Datong China were it currently remains on display at the event site. The Solatrium project included more research components and resulted in 4 master thesis projects and several peer reviewed technical journal publications to date. We have deliberately included research components that overlap with faulty research interests and which offer potential for more traditional academic outputs. In Europe there is generally no university outreach to alumni for financial gain. Therefore, most of the E-Cube funding came from industry (in-kind) and the university (cash). In the US, a project advisory board strategically engaged alumni working at companies with expertise or products relevant to the project and funding was accomplished without cash invested by the university. Approximately half of funding was in-kind for both projects. The project advisory board and engagement of community partners has shown to be quite helpful in leveraging support. The sale of the house resulted in a US$ 250k surplus. Collaborations with a local technical high school and carpenter union was quite successful, these collaborations embedded the international project within a very local context. The scale of both projects demanded a dedicated fund-raising team that reaches out to industry and community partners, allowing the design and construction team to focus on their primary tasks.

The Solatrium project has offered great visibility to the newly established program in Architectural Engineering (AREN) at Worcester Polytechnic Institute. There currently exist two institute-wide project requirements at WPI, namely: the interdisciplinary qualifying project (IQP) and the major qualifying project (MQP). The institute is currently also experimenting with a first year Great Problem Seminar (GPS), a two-course elective that introduces university-level research and projects focusing on various themes. We are currently contemplating to embed Design-Build components into the AREN curriculum, however there is very little curricular space available and increasing concern that existing and emerging institute-wide project requirements (IQP, GPS) take away valuable curricular space to deliver major-specific content. Another concern relates to faculty work-loads and recognition for engaging in Design-Build activities, and how such activities require substantial departmental resources such as faculty time, project space, and funding. Our provisional conclusion is that, if we want to include Design-Build in a sustainable fashion, that the existing frameworks (IQP, MQP, GPS) are the most feasible places for doing so within the WPI context. The broad goals of these existing initiatives align well, for example, with the spirit of community based Design-Build projects and research based activities. Such embedment also increases the curricular space and resources for the AREN major provided that AREN faculty members can play active roles. This route also implies that Design-Build can offer institute wide opportunities and the potential creation of a dedicated AREN project center.