Collaborative design of a multi-functioning building envelope

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ABSTRACT: This paper details the design evolution of a multi-functioning building envelope. The range of functions and performance achieved by the envelope were the result of close collaboration of faculty, students, and external consultants in architecture, electrical engineering, mechanical engineering, structural engineering, composite materials science, lighting design, and computer science.

The envelope was designed with particular attention to tropical climate conditions. Negative factors, such as high heat, humidity, material degradation (e.g., rot, termites, rust), floods, and hurricanes were considered. At the same time, the tropics typically provide high insolation levels and potential for energy harvesting. A main focus of the research was to investigate the unique conditions present in tropical climates and to evolve responsive building envelope design in order to increase human comfort and lower energy use in this large world region.

The envelope is comprised of: (a) semi-*monocoque* shell structure with tension bracing, (b) thermally-broken stressed FRP interior/exterior skins, (c) aerogel cavity granular insulation encapsulated in polycarbonate panels, (d) computer-controlled color-changeable LED light strips, (e) variable cavity ventilation system, and, (f) external photovoltaic computer-controlled louvers. These elements were designed to have the following attributes and functions: (a) lightweight structure for minimal material use, (b) watertight enclosure for flotation, (c) minimal thermal envelope gains/losses, (d) variable daylighting, (e) variable artificial lighting color, intensity, position, and pattern, and, (f) variable incident PV angle for optimal energy harvesting. The steps in discovering, understanding, and capitalizing on the various and synergistic relationships among materials, assemblies, and systems to achieve high-level performance design objectives are detailed.

The paper uses the specific case of a building envelope design to argue for the more general need to assemble collaborative relationships in order to provide multi-functionality and systems synergy and to thereby achieve higher levels of performance and materials/system efficiency.

KEYWORDS: multi-functioning, envelope, tropical, photovoltaic, daylighting

INTRODUCTION

Tropical regions comprise around 40% of the earth's surface, and hold approximately the same percentage of the world's population.[1] Due to rapid growth and infrastructure development in many of these nations, such as Brazil, India, and Vietnam, it has been projected that within the next 20 years, tropical and sub-tropical nations could be responsible for more than half of world carbon emissions from the burning of fossil fuels for electricity.[2] The pressure of increased population places additional pressure on energy infrastructure that in many areas may already be insufficient. To address the current and growing need for reduced energy usage to achieve more sustainable architectural solutions, tropical building design should seek to incorporate appropriate active and passive systems to minimize heat gain, decrease overall energy consumption, and harvest solar energy. Self-contained "off-grid" solutions may be appropriate in certain situations to ease the burden on developing new or improving existing infrastructure.

Tropical regions are characterized by having high temperature, solar radiation, and humidity throughout the year.[3] Such conditions present challenges to providing adequate human comfort while utilizing minimum energy resources. Other factors need also be considered when designing tropical buildings, such as high winds, heavy rainfall, and flooding. The combination of these factors presents particular challenges in the design of an envelope seeking to achieve high energy performance and structural integrity, while resisting material degradation.

This research project sought to address these multiple issues connected with tropical building design and pursued an extension of the pioneering mid-century bioclimatic tropical research by Maxwell Frey, Jane Drew, and Victor Olgyay. The research was conducted within the framework of a U.S. Department of Energy Solar Decathlon 2011 award.[4] The project team determined at the outset that in order to achieve high levels of performance a close collaboration of experts from different fields would be necessary. In the early stages of design the team was comprised of individuals representing architecture, electrical engineering, mechanical engineering, construction management, and composite materials science. In the latter stages, people from structural engineering, computer science, and tropical agriculture/aquaponics fields were added.

1.0 DESIGN CRITERIA

1.1. Foundational Principles

Initial formulation of the guiding ideas and technologies for the project were conducted in a class comprised of faculty and students from architecture, mechanical engineering, and electrical engineering. Students were formed into interdisciplinary teams, and were challenged to develop initial design proposals. From these proposals, key guiding principles were formulated. First, the design was to focus on climatically responsive building strategies for the tropics. Second, the design would utilize traditional/indigenous tropical building solutions and modify these as appropriate. Third, the design would be conceived as a flexible prototype that could be adapted to varied sites and microclimatic conditions.

1.2. Research Methodology

It was understood that the project would involve whole building design and construction, and that all work would need to follow the prescriptive path mandated by the grant. The work was initiated by a two-stage proposal. The first proposal stage laid out the main organizational, technological and financial factors. After approval from the organizers, the team prepared the second stage proposal, which involved a conceptual building and systems design. The prescriptive project trajectory following the proposal stage was divided into schematic design, design development, construction documents, construction, and event display. This phased approach follows A.I.A. contract language and is typical in architectural practice today. This approach generally promotes a method whereby general programming, space planning, and site response is considered first, and where integration of systems and detailing follow later on in the process. While the required deliverables followed this ‘general-to-specific’ mode, our actual process was much less linear. This was due to the team’s decision to allow climatic response and technological systems to be significant drivers in the overall building form.

The team decided that all primary collaborators would be involved at outset. This was thought to allow all disciplines to have “buy-in of the initial concepts, and to allow each discipline to inform the other. Since the overall project was to take the form of a house, architecture would need to be involved. Also, since the house needed to provide high-level energy performance, mechanical engineering would be added. And finally, since the house was designed to be “net-zero”, using only photovoltaic and solar hot water systems, electrical engineering was also included. A faculty from architecture (author of this paper) served as the PI for the project, and the two faculty from engineering served as the Co-PI’s. These three faculty played an active role throughout the project’s duration. Therefore, an interdisciplinary approach was taken throughout the project, and in this, the main disciplines were given equal weight. We wanted to avoid a typical architectural process where engineering fills in later in the process to make the architect’s aesthetic vision “work”. More importantly, it was felt this method would result in a higher level of research and application and ultimately yield a higher performance building.

Table 1: Team disciplines represented showing subjective impact on the final building envelope design

Discipline	High	Medium	Low
Architecture	X		
Mechanical Engineering	X		
Structural Engineering	X		
Electrical Engineering	X		
FRP Material-Construction	X		
Computer Science		X	
Construction Management	X		
Daylighting/Lighting	X		
Aquaponics			X
Marketing			X
Culinary Arts			X

The majority of building design adapts existing technology to specific project circumstances, and is therefore typically considered applied research. The team wanted to explore beyond the application of existing technologies given the understanding that these technologies may not always be optimal. Therefore, a degree of basic research was conducted which focused in areas pertaining to translucent shell envelope construction, double skin envelope (having the outer skin able to simultaneously control daylighting, shading, and solar energy harvesting), phase change material thermal storage systems, and building automation systems able to control unique variables.

Finally, the research sought not only to coordinate among various systems, but also to find particular synergies between them. For example, the translucent envelope simultaneously provides structure, rain protection, flotation capability, privacy, insulation, cavity venting, daylighting, and artificial lighting. The steps in arriving at these design objectives will be traced through the primary development stages of Conceptual Design through Design Development.

1.3. Design Criteria/Goals

The 2011 Solar Decathlon used the following ten contests for judging the completed houses: (1) Architecture, (2) Market Appeal, (3) Engineering, (4) Communications, (5) Affordability, (6) Comfort Zone, (7) Hot Water, (8) Appliances, (9) Home Entertainment, and (10) Energy Balance. Each contest was worth 100 points, for 1000 possible total points.[5]

The team had the objective to obtain the maximum points in each category. At the same time, however, other key criteria were deemed important in developing a prototype house for the tropics:

1. Human comfort: address principally using ventilation and shading, with mechanical system backup
2. Net-zero: minimize energy use and provide solar energy harvesting
3. Hurricane resistance: efficient, aerodynamic enclosure/structure
4. Flotation capability: lightweight envelope able to survive flood events
5. Sustainability: low-energy, recycled/recyclable, reusable/demountable parts
6. Material Integrity/Resistance: materials resistant to rot, corrosion, termites
7. Integrated adjustable daylighting and artificial lighting: automated controlled louvers with user override

2.0. CONCEPTUAL DESIGN

2.1. Lessons from Indigenous Tropical Buildings

The team’s study of indigenous tropical buildings turned up a number of typical and recurrent design features. The floor is typically raised above the ground, protecting the structure and occupants from ground moisture and floods, and helping to capture cooling breezes. Such benefits were determined to be advantageous, and the raised floor feature was incorporated in the conceptual design. Tropical houses also typically have a large overhanging roof that serves to shade and keep the house cool, and that directs rain away from the house. For the conceptual design, it was decided to use a double-skin enclosure. An outer porous layer comprised of vegetated and photovoltaic panels would provide shading, and a watertight shell envelope would protect against rain. Finally, indigenous tropical houses commonly use a narrow floor plate with an open plan to maximize natural ventilation. The team elected to incorporate these features for the benefit of passive ventilation.

2.2 Structural Strength and Efficiency

Shell structures are among the most efficient because they minimize the need to resist out of plane forces. Shell structures can also be shaped to minimize wind resistance. Given these benefits, the team developed a *monocoque* Fiber Reinforced Plastic (FRP) shell structure so as to provide a lightweight structure capable of resisting hurricane winds and moisture. Because the house would need to be shipped and constructed quickly at the exhibition site in Washington, D.C., the shell was designed as a series of post-tensioned barrel-like staves. Shell structures require complex analysis, and FRP is not commonly used for building structures. As such, the team needed specific expertise and elected to contact Arup Group, Ltd. Arup agreed to donate structural engineering consultation services for the project. Arup ran initial Finite Element Analysis (FEA) models to check the feasibility of the shell structure.

2.3 Flotation

A high percentage of people in the tropics live in areas subject to flooding, and such events are likely to continue or worsen due to climate change. Therefore, the team elected to incorporate flotation capability in the house envelope. FRP was chosen as the best material to provide a watertight enclosure. FRP is commonly used for boats due to its high strength-to-weight ratio, ductility, formability, and imperviousness to water. With the decision to use FRP, the team brought in a community college partner that has a boatbuilding program and facility. Though discussion with this new partner, it as decided that a foam sandwich *monocoque* shell would provide optimal structural strength and buoyancy.

2.4 Layered Envelope

The team first considered a Building Integrated Photovoltaic (BIPV) approach, and to imbed thin-film photovoltaic (PV) modules into the foam sandwich FRP panels. However, members from electrical engineering cautioned about the difficulty of wiring the modules through the FRP foam sandwich, and members from mechanical engineering expressed concern about heat conductance from the modules through the envelope. In an effort to reduce conductance and radiant effects, the team decided on a double skin strategy whereby the outermost skin would be comprised of PV and solar hot water panels in areas positioned optimally toward the sun, and vegetated panels positioned in the remaining locations. The double skin strategy provided a number of advantages. An air gap between the outer and inner skin would decrease conductance, allow air ventilation between the two skins, and provide a concealed space to run wires to the PV modules. The outer skin would also serve to shade the structure.

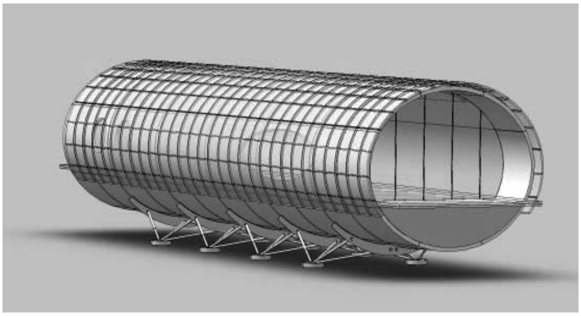

Figure 1: Exterior view of Conceptual Design phase design

2.5 Phase Change Material (PCM) Thermal Storage

The team determined that heating would not be required in most tropical locations, and that cooling and dehumidification—given proper shading and ventilation--would only be needed in more extreme conditions. However, the competition was scheduled for fall in Washington, D.C., and both mechanical cooling and heating were deemed necessary in order to score in the Comfort Zone and Energy Balance contests. Since the house was designed as a prototype for the tropics, space-conditioning systems would typically be unnecessary, however they would be needed for the competition. Therefore, the team elected to include a space conditioning system that could be installed only when circumstances warranted. The mechanical engineering members analyzed weather data in Washington, D.C. during the completion period and determined that 24-hour temperatures were likely to range between 78 – 45 degrees Fahrenheit. Also, the house would need to be closed during the competition, and using natural ventilation cooling would not be possible. Therefore, a highly efficient space conditioning system was needed to achieve a net-zero energy balance. Nighttime temperatures, if stored, could be used for daytime cooling. Similarly, daytime temperature could be captured for nighttime heating, and for preheating domestic hot water. To best capture the thermal energy, a system using separate hot and cold water tanks was designed. Phase Change Material (PCM) was to be used in each tank to decrease their volume. An all-water radiant heating and cooling system was designed so as to minimize water-to-air conversion losses.

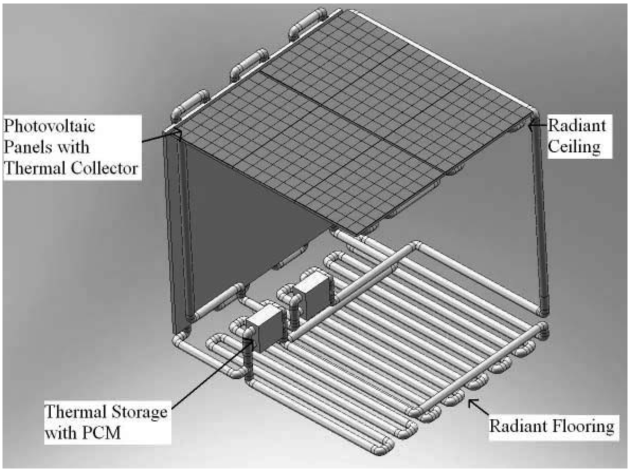

Figure 2: HVAC concept diagram, showing PCM storage, radiant ceiling/flooring and thermal collector.

2.6 Building Automation System

In order to achieve optimal energy balance and system efficiency, a building automation system (BAS) was proposed. The BAS included sensing, monitoring, reporting, and override functions. The space conditioning system was unique, and review of existing BAS systems and optimization algorithms were deemed to be a poor fit. Therefore, an additional partner from computer and information science was brought in to develop a custom software solution.

3.0. SCHEMATIC DESIGN

3.1 Semi-*Monocoque* Shell

Discussion with Arup, construction management members, and a composites researcher from the university, resulted in a decision to abandon the *monocoque* shell developed in the conceptual design phase. The project was subject to the International Residential Code which does not include provision for structural use of composite materials. As such, lengthy and expensive third party testing would be required to meet code. Given our cost and time constraints we shifted our thoughts toward development of a semi-*monocoque* shell. This shell type uses spaced-apart structural ribs with stressed skins. We quickly realized that we could use translucent FRP skins to have daylight filter between the ribs and allow the shell to be part of a daylighting solution. A first shell was developed as a round tube form to be built in sections and post-tensioned together on site. The round cross section was selected as it evenly distributes the compressive force exerted by the post-tensioning hoops.

3.2 Second Skin

In the conceptual design phase the *monocoque* shell was mostly opaque, and the second skin was comprised of fixed vegetated, PV, and solar hot water panels. The change to the semi-*monocoque* shell opened up the potential for daylighting. Numerous studies have shown that human subjects prefer daylighting over artificial illumination. Natural light has a dynamic quality and color temperature that cannot be reproduced with electric light. Cited benefits include increased health and productivity.[6] Daylighting would have to be balanced with shading in order to mitigate excessive heat gain. To provide this balance under different external conditions and times of day, an adjustable controlled louver solution was proposed.

The electrical and mechanical components for a controlled adjustable louver system are fairly complex and expensive, and the team therefore wanted to have further justification of their utility. The option of placing PV modules on the louvers provided this additional utility. Controlled PV louvers could be made to track the sun position, and thereby achieve greater energy harvesting efficiency.

Figure 3: Exterior view of Schematic Design phase design

3.3 Building Automation System Development

The team performed Autodesk Ecotect simulations to test PV tracking, daylighting, and shading/heat gain. Initial studies showed that each of these three functions could be made to perform well on an individual basis, but there were questions regarding the trade-offs that would be required between them in certain conditions. The computer science team initiated study of algorithms to help provide proper balancing of the three functions that would be integrated in the BAS. A variety of external, cavity, and interior sensors would be linked to the BAS.

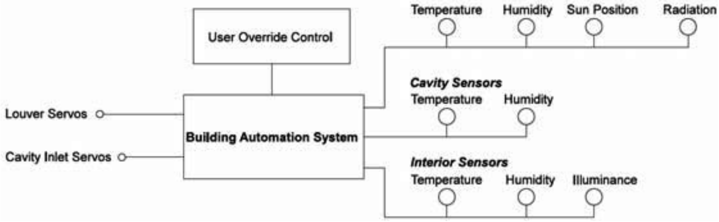

Figure 4: Building Automation System schematic diagram

4.0. DESIGN DEVELOPMENT

4.1 Shell Shape Optimization

The round cross section using post-tensioned connective structure was further studied and improvements made. First, Arup recommended replacing post-tensioning with simple bolting to simplify technical on-site assembly issues. Second, the shell was morphed into semi-oval cross section in order to decrease the interior volume of conditioned air. This had the added benefit of making the shell more aerodynamic and to lower wind pressure on the structure. Third, a small courtyard space was added, and the shell was bent into a doubly curved shape. This shell configuration offered a dynamic architectural expression and increased potential for natural ventilation. Unfortunately, this shell shape produced another series of challenges. It was difficult to stiffen the shell sufficiently in key areas, and a number of bracing schemes were tested until a viable, albeit complex, solution was found. Perhaps most importantly, the doubly curved shell required a high number of unique rib, bracing, and FRP skin components. The shell shape resulted in conflicts in accommodating the thermal storage tanks, and some other key below floor mechanical components. Feedback from the construction management team indicated that these factors would increase construction time and cost. As a result, the shell was changed back to a straight extrusion. The cross section was optimized for interior use and volume, servicing systems accommodation, structural strength, and aesthetics.

Figure 5: Exterior view of early Design Development phase multilayered envelope with doubly curved shell

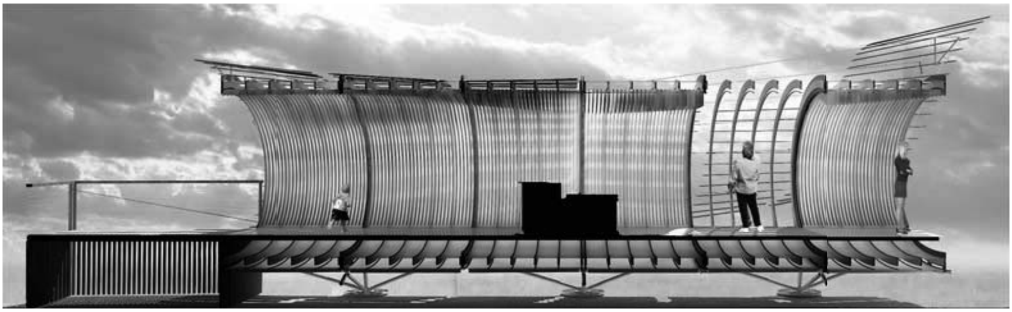

Figure 6: Longitudinal section view of Design Development phase multilayered envelope with straight extrusion shell

4.2 Shell Cavity Insulation and Ventilation

Of all known commercially produced insulating materials, only aerogel possesses relatively high light transmittance.[7] While aerogel is quite expensive, calculations determined that a thickness of around 2.5 cm was sufficient. At this thickness, the aerogel offers a U-value of 0.6W/m2K, and the overall shell assembly provides a U-value of 0.5W/m2K.[8] Keeping the aerogel relatively thin had the added benefit of maintaining a higher level of light transmission through the shell. Physical measurements indicated that the approximate average total visible light transmission though the shell assembly would be 0.35. This figure is dependent on exterior environmental conditions and shading factors produced by the second skin. Simulations and bench testing of physical prototypes were used to evaluate tradeoffs between cost, light transmittance, and thermal conductivity of the shell assembly. As part of this optimization process, cavity ventilation studies were conducted. Simulations indicated that significant benefits could be obtained by using a relatively simple passive system. This would be effective during the hotter days in the competition period; however, open ventilation would present a liability during the colder periods. Therefore, a variable controlled inlet was designed to adjust the airflow as desired under anticipated temperature and radiation conditions.

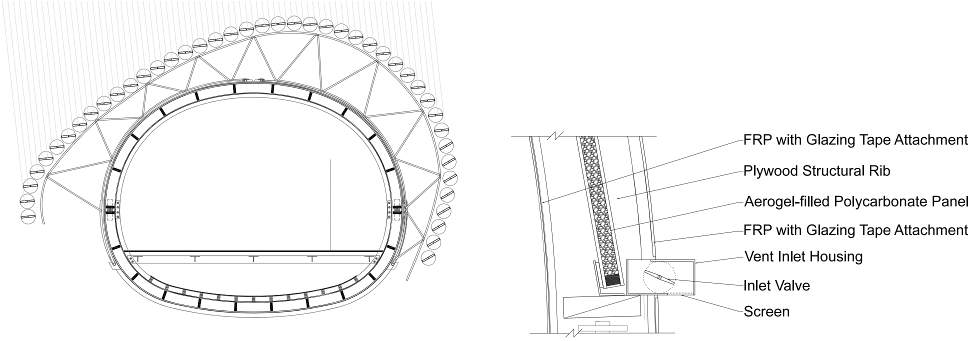

Figure 7: Cross section through Design Development phase design with detail of cavity inlet vent

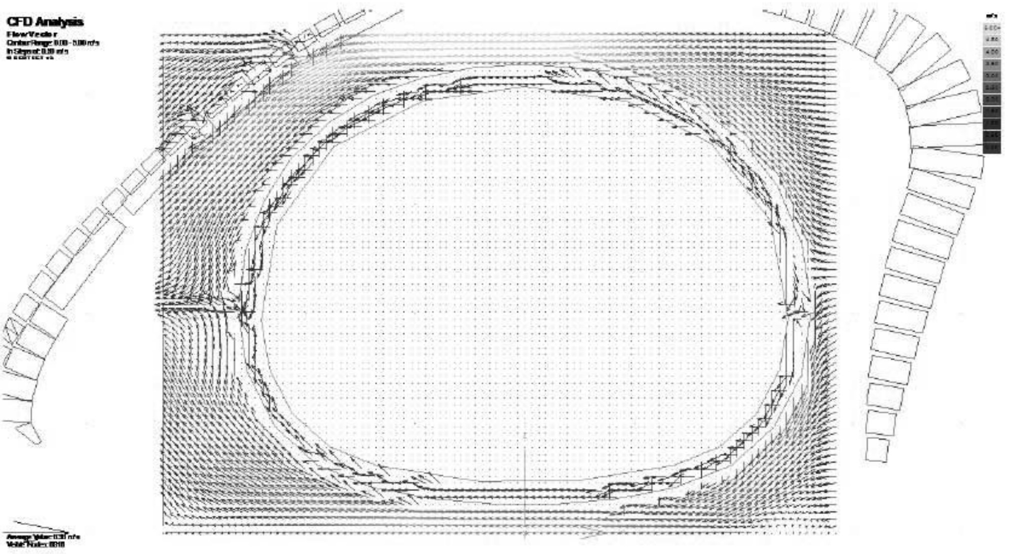

Figure 8: Computational Fluid Dynamics (CFD) analysis diagram showing airflow vector field

4.3 Photovoltaic Modules

The team secured an initial sponsorship agreement with Samsung Electronics Co., Ltd. to provide the photovoltaic modules for the project. Samsung had built a solar demonstration house using a narrow width thin film module. These PV modules had the proper width and properties to enable them to be incorporated into the controllable external louver second skin design. Toward the end of the Design Development phase however, it was found that these modules could not be supplied. As a result, changes were necessary in the second skin superstructure design to accommodate standard dimension panels. A bi-facial panel was selected as it provides light transmission, and can collect light energy reflected off the building shell.

CONCLUSION

The research aimed to find solutions to achieve comfort in interior spaces in the tropics while using a minimum of energy. A first strategy was to lower demand side energy use by capitalizing on traditional passive means to augment perceived comfort by minimizing solar heat energy transfer, and providing maximum ventilation and daylighting. At the same time, energy would need to be harvested from the sun to power modern conveniences (lights, appliances, hot water, etc.) and provide space conditioning to meet the competition contest criteria. The current research indicates the promise for a layered system approach where external shading devices, reflective building envelope surfaces, thermal breaks, cavity vents, and insulation panels work together to lower heat transfer. At the same time, selected elements in the system can be used to harvest solar energy, and to tailor interior daylighting levels. For conditions where high humidity causes discomfort that cannot be alleviated using shading and ventilation, a backup air conditioning system is provided that is coupled to a solar hot water and photovoltaic panel array, and a PCM thermal storage system. Simulations and calculations indicate that the system can be operated to maintain the net-zero goal under most tropical environmental conditions. A building automation system assists the occupants in maximizing the parameters of energy collection, daylighting, and shading, and to ultimately balance the needs of comfort with responsible energy use.

Each of the variety of systems incorporated in the design is relatively complex, and the development of each benefited from team experts in respective fields. In this research a high level of systems integration was sought, and was only able to be achieved via a tightly coupled interdisciplinary approach. The multi-functioning building envelope is shaped by a variety of conditions that necessitate responses to structural forces, sun path and radiant effects, wind flow, and energy management. The envelope takes the form of a shell to provide high strength with minimum material, an efficient use of living space, and flotation capability. The ribbed semi-*monocoque* construction allows for the passage of light into the interior, and the cavity to be vented to minimize thermal transfer. The under floor area provides an efficient means to house and route mechanical and electrical services. The bladder thermal storage tanks serve as ballast to minimize overturning. The second skin cooperates with the shell to provide shading and control daylighting levels while tracking the sun to optimize solar energy collection. Because the complete house was not built, full testing and monitoring of the total system was not possible. Evaluation of energy performance was limited to testing of selected prototype components, and calculation and simulation of other systems, such as ventilation and daylighting. Therefore, much additional research, testing, and evaluation of the individual components and total system function is a necessary area for future research.

In summary, the collaborative research model shows promise as a method to evolve new strategies for low energy building envelope design for tropical locations. A number of technologies were developed and integrated in order to develop multifunctioning and synergistic system behavior. This approach shows promise for future research into energy efficient design that can positively impact the significant populations inhabiting tropical regions.

ACKNOWLEDGEMENTS

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ENDNOTES

[1] Estimated from the CIA World Factbook, https://www.cia.gov/library/publications/the-world factbook/rankorder/2119rank.html.

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