Reducing Carbon and Improving Thermal Comfort for an Orphan Village in Rural Liberia

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Liberia experienced two devastating civil wars during the 1990s and early 2000s that resulted in hundreds of thousands of deaths and nearly total destruction of its electrical and water infrastructure systems. The loss of these systems has been especially acute and persistent in rural areas where power is generally provided by small, inefficient, gas-powered generators to power lighting and electric fans. Thus, it is imperative that buildings in Liberia reduce their carbon footprint while improving thermal comfort by employing a variety of passive strategies.

The project presented in this paper tested a variety of strategies and adapted them to the specific program, climate, society, materials, and methods of construction currently available in rural Liberia. The team used a series of computational fluid dynamic (CFD) simulations to assess the best combination of ventilation strategies for thermal comfort. Based on the previous research these simulations were focused on increasing air speeds to improve thermal comfort in this hot and humid climate. A comparison of the baseline design against interventions such as wind funnels and angles of the slats in jalousie windows show the way the wind speeds and patterns of wind movement thereby enabling informed decision making. These recommendations were then constructed and tested in the first built prototype, a communal home for orphans on a new eco-village near Buchanan City. This made it possible to calibrate subsequent simulation models with the actual ventilation metrics and air flow patterns onsite as the campus expands. An iterative process of simulations and physical site measurements has led to a number of important insights for this development and those in the surrounding area as elements of this work are already being copied in the area, creating a new, more sustainable, lower carbon vernacular for rural Liberia.

INTRODUCTION

Liberia is located on the West Coast of Africa and the project is located in a rural area outside of Buchanan City, a two-hour drive south of Monrovia, the capital city. The client, Psalm 82:3, is a small non-profit established to build a self-sustaining village for the care of orphans and the elderly.

Before colonization, the area was, and remains, home to the Bassa, one of 16 indigenous peoples found within its borders. Liberia was founded in 1847 as an independent nation but began as an American colony in 1820 by The Society for the Colonization of Free People of Color of America, more commonly known as the American Colonization Society (ACS). This “benevolent” organization was created to encourage and support the voluntary migration of freed African Americans to the continent of Africa. However, membership in the ACS was primarily comprised of Southern slave holders and excluded blacks from membership. According to most historical interpretations, ACS intentionally reduced the number of formerly enslaved people in the United States so they would not interfere with the dominance of white society. This also created a lasting tension between indigenous groups and the descendants of formerly enslaved people that settled in Liberia and ruled the country since its founding.[1]

This sordid history came back to haunt Liberia during two devastating civil wars during the 1990s and early 2000s fueled by tensions between indigenous groups and politically powerful descendents of colonizers. This was followed in 2014 by the Ebola outbreak that together resulted in hundreds of thousands of deaths and nearly total destruction of Liberia’s tourism industry and centralized electrical and water infrastructure systems. The loss of these systems has been especially acute and persistent in rural areas. Power, for those lucky enough to afford it, is generally provided by small, inefficient, and noisy gas-powered generators to power lighting and electric fans. Rural Liberians also commonly use charcoal for almost all cooking and heating needs.

However, Liberia is on the rebound and is currently among the top 20 countries in the world for population growth rate and has recently begun to aggressively rebuild its power system. It currently has an installed capacity of 126 MW with a 2030 target of 300 MW.[2] Unfortunately, most of this electricity is currently generated using diesel and heavy fuel, which produces large quantities of black carbon. Therefore, it is imperative that buildings in Liberia reduce their carbon footprint while improving thermal comfort by employing a variety of passive means. However, passive design strategies are not commonly practiced in Liberia for a number of social and economic factors.

Psalm 82:3 was founded in 2014 to “defend the weak and the fatherless, uphold the cause of the poor and the oppressed,” based on the founders’ personal experience leading several service trips to a struggling orphanage in Monrovia. In 2017, the organization purchased a 50-acre, P-shaped parcel that adjoins the abandoned remains of the largest chicken farm in Grand Bassa County.[3] After the purchase was complete, the team learned that the previous owner had sold the rights for a high-voltage power easement that divides the land in half and also discovered that much of the site is saturated during the wet season.

In 2018, our team was asked to provide fundraising images of buildings, which later led to the development of a resilient prototype designed to maximize natural ventilation and daylight with an easily adaptable floor plan to accommodate a wide range of programs that could quickly transition from orphan housing, elder housing, or staff housing to an administration building, clinic, school, or other as-yet-unknown uses. To develop the prototype, we looked into a range of strategies documented in the literature discussed in the following section.

LITERATURE REVIEW

Guided by the World Map of the Köppen-Geiger Climate Classification,[4] the team collected lessons from vernacular examples and research in similar climates in adjacent African nations, southern India, Southeast Asia, the Southeastern United States, the Caribbean, Central America, the northern portion of South America, and northern Australia. Makaremi et al.[5] found that people in Malaysia felt that an increase in wind speeds might improve their thermal comfort, but also found many locals found the weather to be acceptable. In a similar study in Ghana, a country near Liberia, Appah-Dankyi et al.[6] suggested that people in tropical countries may have a higher heat tolerance that exceeds the 26°C to 28°C ASHRAE standard by 1°C to 5°C. The study also found that elevated humidity levels in the range of 60 to 80% resulted in a satisfaction level of 81%. These findings led the team to reconsider our initial assumptions about comfort based on typical US standards.

Studies by Dili et al.[7] and Nguyen et al.[8] showed that vernacular dwellings in hot humid climates effectively used courtyards to create a convective wind flow and improve ventilation. Roof studies by Ibrahim et al.,[9] Jayasinghe et al.,[10] and Roslan et al.[11] found that low-pitched roofs resulted in higher indoor temperatures and recommended higher-pitched roofs with increased air movement to reduce heat gain indoors. These studies also found that roof orientation did not have an impact in this study, but the addition of insulation improved the thermal conditions indoors.

A study by Zhai et al.[12] found a significant difference in thermal comfort when air movement was present. They also found that the speed of the wind did not make much of a difference to the comfort. Ismail et al.[13] studied strategies such as wind catchers and fans that create a stack effect in buildings and found that they result in lower indoor temperatures.

One particularly helpful reference for the team was the 1978 Regional Guidelines for Building Passive Energy Conserving Homes.[14] Liberia is quite similar to Zone 13 typified by Miami and the guide provides several design priorities, including taking advantage of the comfortable climate by avoiding overheated microclimates; using large open lots with open, elongated plans; providing outdoor living space; connecting inside and outside; isolating heat producing areas like kitchens, minimizing solar exposure by surrounding the buildings with large shade trees and green lawns; orienting the building with the long façade facing south; using courtyard plans; utilizing overhangs, louvers, and large roofs; maximizing natural ventilation by allowing breezes to go over and under the building; using a vented attic, operable partitions that can be adjusted to allow breezes through the building; bug screens, and high exhaust windows, and other ventilation inducing techniques. With these many lessons in mind the team set out to design the initial prototype.

DESIGN STRATEGY

The prototype concept for the housing duplex shown in Figure 1 is one half of a mirrored plan designed to maximize solar shading and natural ventilation through the building by orienting it with a long east-west plan. The 45-degree wind scops are located on the predominant windward side of the building to reduce eddies near the windows and thus increase wind speed. The planned expansion will also share the open-air kitchen. The plan is also designed to be easily adjusted via moveable partitions to serve a variety of functions since the building will serve sequentially as a staff office, then staff housing, then initial orphan home, and ultimately as a health clinic.

The team worked with a local architect and contractor to choose materials and techniques appropriate to the local building industry in Buchanan City. Low cost, low maintenance, resilience, and repairability were primary concerns due to the area’s heavy rains that last several months. Therefore site-cast CMU, wood rafters, metal roofing provide, and jalousie windows provide the basic material palette for the prototype.

As the project quickly progressed, the team learned that the culture of building is far more informal and fluid than the US. Acquiring an accurate site survey has proved particularly problematic and effective communication has been difficult despite the fact that Liberia’s official language is English. As the walls went up the design team received construction photos and learned that the building had been relocated from the north to the south part of the site and the plan had been rotated

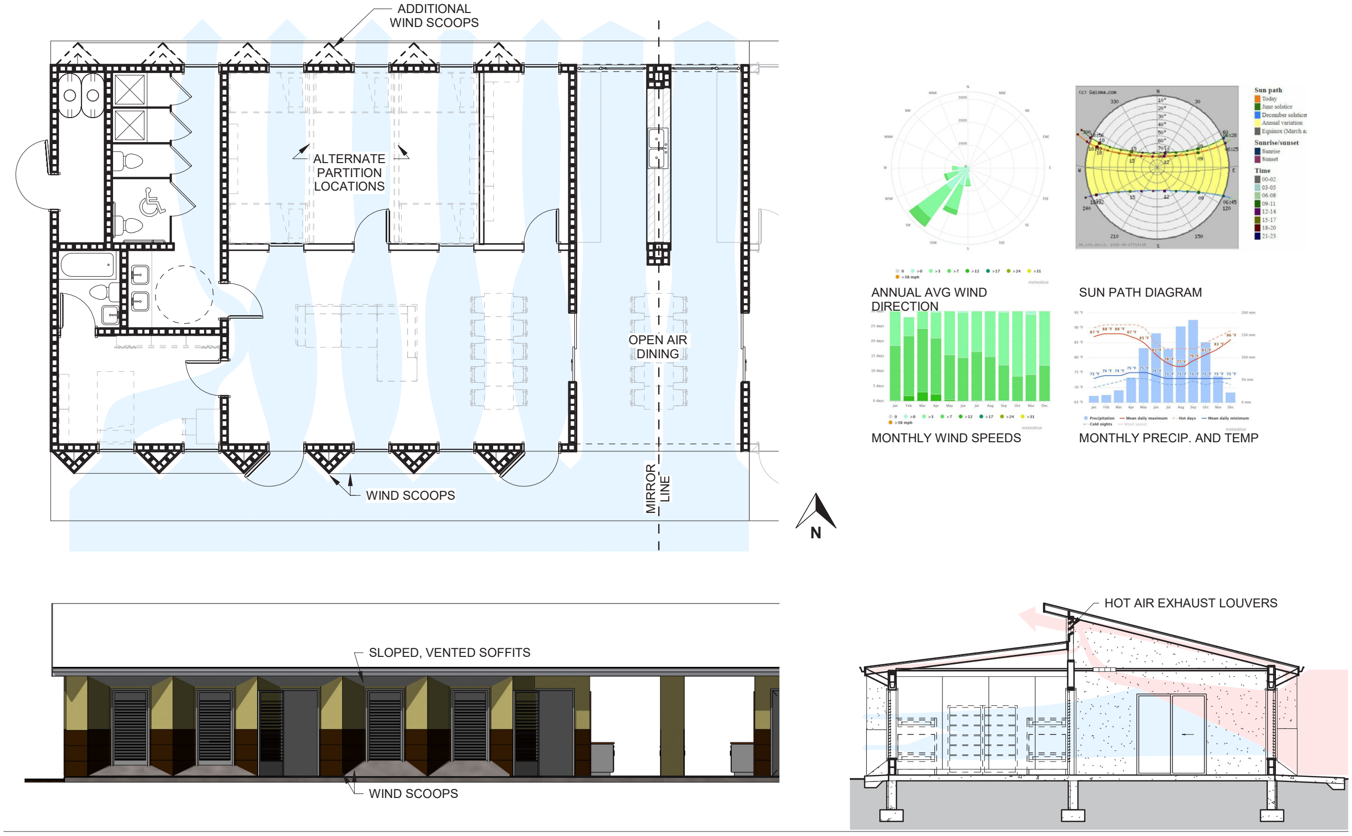

Figure 1. Plan, South Elevation, and Section.

Figure 2. Prototype on Opening Day. Photo by Tamme Dillon.

180 degrees. Rafters and the sloped ceiling were replaced by trusses and a flat ceiling. These changes had major implications for the effectiveness of the passive natural ventilation and stack effect scheme. Fortunately, a few alterations were possible, including adding wind scoops to the other side of the building, rotating the trusses, and adding ceiling exhaust vents. The monsoon season halted construction activities for several months, but the prototype building is substantially complete with a number of outstanding punch list items to complete. Staff working and living in the prototype reported that the building is generally working as planned and that the natural breezes that flow through the building provide a comfortable indoor environment. In fact, the addition of the wind scoops on both sides proved fortuitous since the initial assumption based on the prevailing wind direction was later found to be an insufficient assumption when an EPW file was located during our CFD analysis described in the following section.

Since the prototype is the first of several buildings to be built, a number of questions remained that required a series of investigations using computational fluid dynamics (CFD) and physical tests to judge the effectiveness of the decisions made on the prototype.

METHODS

The team used a series of computational fluid dynamic simulations to assess the best combination of ventilation strategies for thermal comfort. Based on the previous research these simulations were focused on increasing air speeds to improve thermal comfort in this hot and humid climate.

Since understanding the climate is one of the first steps towards creating a simulation, it was important to identify appropriate weather data. Climate data from Gaisma[15] and Meteoblue[16] were used at first to get a broad understanding of the climate. Detailed, site-specific EPW data was not available, so the EPW weather file for Monrovia was used as a reasonable substitute. Climate Consultant software was used to examine the weather data in greater detail and to identify potential design solutions that could help improve thermal comfort.

After identifying and examining the climate data, the next step involved identifying the software to use for the CFD simulation. Since CFD simulation is highly complex, the simulation software itself was likely to have an impact on the results. A matrix, as shown in Table 1, was used to rank various software (Ansys fluent, Autodesk CFD, Open Foam, Rhino CFD, MatLab CFD , and SimFlow) against four parameters (cost and access to software, ease of modelling for architects, ability to compute natural ventilation in buildings, and the ability to handle complexities). Autodesk CFD was found to be the most favorable.

Table 1. CFD Software Comparison

Software	**Cost and access to software**	**Ease of modeling for architects**	**Ability to handle natural ventilation for buildings**	**Ability to handle complexities**
Ansys Fluent	●●●	●●○	●●○	●●●
Autodesk CFD	●●●	●●●	●●●	●●○
Open foam	●●●	●○○	●●○	●●○
Rhino CFD	●○○	●●●	●○○	●●○
MatLabCFD	●●●	●○○	●○○	●●●
SimFlow	●●○	●●○	●●●	●○○

The first step to conduct the simulation involved creating a simplified geometry for the baseline. Complex geometries and details burden the CFD software but does not provide better results.[17] The design drawings were simplified so that the crucial proportions in the building geometry were retained while unimpactful computationally complex features were removed. The construction assemblies were identified, and their thermal properties (emissivity and U-values) were used as inputs in the CFD model (film coefficient and material emissivity).[18] The air volume around the geometry was modelled per the instructions for Autodesk CFD natural ventilation in order to ensure that the surrounding air volume resulted in accurate results.

The weather data showed that the weather does not fluctuate significantly over the course of a year (average monthly dry bulb temperature varies between 24°C to 26°C). The focus of the study was on providing thermal comfort in hot and humid weather and December had the highest average monthly temperature (31.1°C), so the December Solstice was selected as the test day. The CFD simulation is conducted at a point in time and 3 pm was selected since it has the highest solar radiation and air temperature. Weather parameters such as wind speed, ground temperature and dry bulb temperature were extracted from the EPW weather file and used as inputs in the model.[19] The latitude and longitude for the site were used in the model in order to ensure that the appropriate solar radiation was considered. In order to ensure that the buoyancy driven wind flow was considered, the gravitational field was turned on in the model. Heat transfer, radiation and solar heating were turned on for the simulation.

The average wind speed for the month (3.1 m/s) was provided as a boundary condition on one surface of the air volume at the hourly dry bulb temperature (31.1°C). The opposite surface was given a boundary condition of zero pressure (0 psi) to mimic the wind flow. The ground temperature was assigned as per the EPW ground temperature 0.5 m below the surface for the month (25.4°C). The simulation was then run with the default iterations (750) and the result was visualized by slicing planes, both as plans and sections, to view the wind velocities in different portions. The geometry was modified one portion at a time and the simulation procedure was carried out in steps to view the impact of changes in the design.

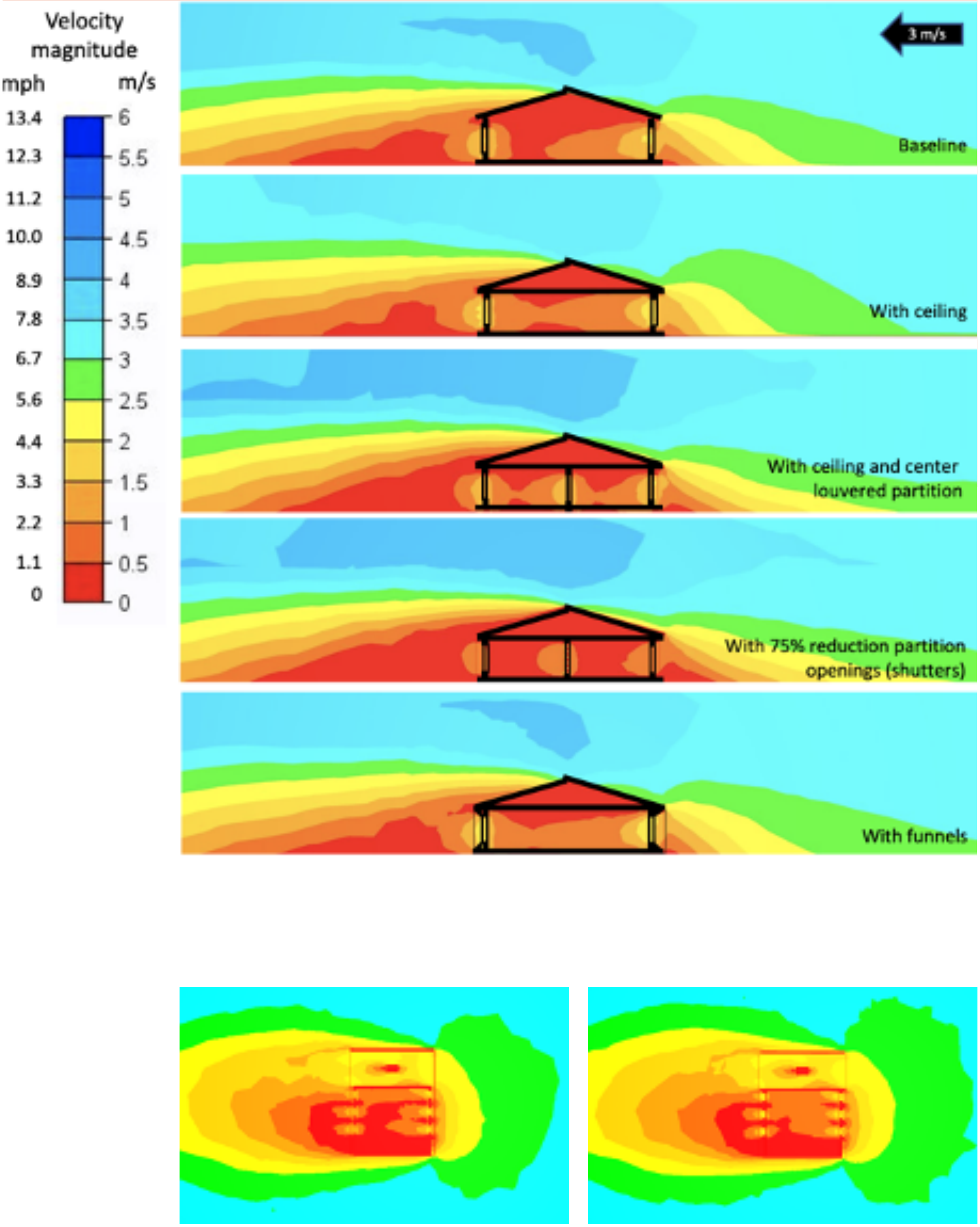

Figure 3. Computational Fluid Dynamic (CFD) Comparisons in Section and Plan (without wind scoops on left and with wind scoops on right).

Figure 4. Soda Can Smoke Test. Photos by Author.

FINDINGS

A comparison of the baseline design (open ceiling) against several interventions (flat ceiling,center partition with jalousies in different positions, and wind scoops) as shown in Figure 3, illustrate the wind speeds and patterns of wind movement within and around the prototype.

The baseline condition shows an open interior and sloped ceiling designed to maximize natural ventilation and take advantage of induced draw from the negative pressure created on the back side of the roof offset intended to create cooler breezes below via the stack effect. This was the initial design for an open plan program such as a school or open office. The induced draw and cross-breeze did not seem to work as expected as indicated by low wind speed represented by the color red near the middle of the building. As noted earlier, the prototype was not built this way for a number of reasons. Most important was the addition of a flat ceiling.

Fortunately, the addition of a flat ceiling provided a compressed section, which helped to maintain a consistent wind speed above 1.1 mph (0.5 m/s) through the building as well as elevated wind speeds near the windward and leeward windows. The current use required an intermediate partition near the center of the space. As seen in the third panel, a jalousie window similar to those used on the exterior was used to allow breezes. As shown, this counterintuitively provided additional areas near the intermediate partition with elevated wind speeds over 2.2 mph (1 m/s). However, the contractor installed standard interior shutters instead of the jalousie window. To illustrate the impact of this decision, the fourth panel shows a nearly stagnant wind speed. This image helped convince the team in Liberia to replace the interior shutters with jalousie windows. The final panel shows the effect of the wind scoops added to the exterior intended to reduce turbulence and thereby increase wind speed through the building. The effect was not dramatically different from the open plan simulation, although it did seem to provide more consistent air flow near the floor. However, in plan it is observed to improve the air speed throughout the building.

Informal smoke tests were conducted on site using a soda can technique commonly used in Africa to ward off mosquitos. This simple, but effective demonstration proved quite informative for the team as we noted how quickly the wind seemed to sink towards the floor. The team also used a pair of Holdpeak HP-866B digital anemometers to compare the CFD simulations to the conditions onsite. One anemometer was placed 40 feet in front of the windward side of the building, the other was placed on the outside of the leeward side window. Readings were taken every five seconds for five minutes. Based on the simulations, the team expected lower wind speeds on the leeward side but found that the wind speed readings were almost identical. This result was quite encouraging and will be used to calibrate future CFD research.

Carbon Calculations

Based on our Climate Consultant model, it is quite possible that electric fans would be used for enclosed spaces most of the year due to Liberia's relatively high temperatures and humidity. In fact, using ASHRAE 55's PMV (Predicted Mean Vote) model there is only one hour per year considered "comfortable." However, as we noted in the literature review portion, Liberians are likely to have an expanded thermal comfort range by as much as 1°C to 5°C and are also likely to be more tolerant of elevated levels of humidity. The Adaptive Comfort Model in ASHRAE Standard 55-2010, suggested that ventilation could provide comfort in the 80% range, 80.8% or 7,080 hours per year. Assuming the design provides sufficient interior daylighting during the day and laptops can be charged while lights are needed for two hours on the generator each evening, our team estimated that effective natural ventilation could be used 6,350 hours per year. Using this number our team estimated the potential carbon savings by reducing the use of electric fans powered by a 5-kVA diesel generator that consumes 0.75 gallons per hour or 4,764.5 gallons annually. This amounts to a potential carbon savings of 45.80 metric tons of CO_2e for each building per year.[20] When the 10-building campus is complete that number would grow to 458 metric tons of CO_2e per year. According to the EPA, that is equal to 63.3 acres for each building or 633 acres total of US forest that would be required to sequester this amount of CO_2 annually.[21]

DISCUSSION AND FUTURE WORK

The prototype has already served as a staff office and community center for classes that outreach to the surrounding villages. It is currently being adapted to serve as a full-time orphan home and the area around the building is being used to test the viability of wide variety of crops to be grown on the land.

Based on the relative success and lessons of the prototype building, the organization is planning to add 10 more buildings, including a clinic, staff and guest home, administration building, a school, additional children's homes, and a church. The site plan for these buildings is arranged in a checkerboard pattern to allow the southwestern and northeastern winds to flow over the upwind buildings and recover before reaching the next building with approximately 100 feet between. The CFD models were particularly helpful in making this determination.

The iterative process of simulations and physical site measurements has led to a number of important insights for this development and those in the surrounding area as elements of this work are already being copied in the area, creating a new, more sustainable, lower carbon vernacular for rural Liberia.

The team is preparing a series of additional CFD studies to test further hypotheses, including the effectiveness of stack ventilation, alternate roof albedo and emissivity, the addition of solar and wind powered roof exhaust turbines, landscaping strategies (softscape and hardscape) for thermal comfort and ventilated attics. If these simulated results indicate potential substantial benefits, the team has been granted permission to conduct additional physical tests on the buildings.

The team is also investigating the feasibility of using compressed earth blocks above grade instead of the site cast concrete masonry units currently used. This would dramatically reduce our overall CO_2 production by reducing the number of CMUs used on the project. The team is partnering with Kingdom Earth Builders (KEB), a non-profit sustainable building organization, that owns a BP-714 Compressed Earth Machine and is currently building single story structures around Liberia. Unfortunately, the samples the team received were too brittle and therefore rejected. Alternative mixtures are being investigated with KEB for use on the subsequent buildings.

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18. Material properties used: Air (ε=0.8), CMU (12" thick, U-value=4.42 W/m^2-K), Conc. Slab (90 lb/ ft^3; 6" thick, U-value=3.63 W/m^2-K), Metal Roof (uninsulated, basic cool roof, ε=0.85, U-value=6.81 W/m^2-K).
19. Weather input parameters for simulation: Date (Dec 21), Time (2:00-3:00), Avg Hourly Temp DBT°C (31.1), Avg Hourly Wind Speed m/s (3.2), Wind Direction (189), Ground Temperature at 0.5m (25.4).
20. This calculation was completed using "heating fuel" in the Carbon Footprint Calculator available at: https://www.carbonfootprint.com/calculator.aspx.
21. This calculation was completed using the EPA's Greenhouse Gas Equivalencies Calculator available at: https://www.epa.gov/energy/greenhouse-gas-equivalencies-calculator. 4,762 gallons of diesel fuel is equivalent to 5,455 gallons of gasoline, which is the fuel option available in the calculator.