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Parametric Carbon-Neutral 3D-DesignWithClimatic Tropism For Better Building Energy Performance

Thomas Spiegelhalter[1] and Andrew Lee[2]

[1] Florida International University, Miami, U.S.A., Prof. Architect, Engineer, LEED A.P.
[2] LEED A.P.

Abstract. The natural world has provided ideal models of resource balance that have evolved over millions of years. Native ecosystems are composed of abundant examples of life forms that utilize local resources in an efficient way that is synergistically aligned with dynamic environmental conditions. Worldwide, numerous architects seek to capture and translate practical solutions from the relationships observed in biological systems into carbon-neutral buildings. This paper presents two examples of distilling climate-specific parametric design approaches from the adaptive qualities of native plant communities. Climate analyses were conducted to select plant community and species that were most applicable to the design of an energy-efficient structure. The first example is a research project that applied the metabolic and respiratory cycles of Southern California desert plants to reduce cooling loads in a solar powered building. The second example is a built mixed-used project in Southwest Germany that applied the phototropic nature of regional plant life to the design of heat gain, heat mitigation and energy harvesting systems. In both case studies, the basis for selecting the resource efficient natural cycle, the application to architectural design, and the impacts to energy performance are explained.

Keywords: Net-Zero-Energy Building, Plus-Energy-Building, Carbon-Neutrality, Energy Efficiency, Life-Cycle, Native-Biological-Systems

1. Introduction

As evidence of climate change and global resource depletion grows, architects are increasingly challenged to design buildings that consume less energy. Buildings have already been attributed to over 40% of the total energy use that contributes to greenhouse gases in the United States, showing the alarming consequence of building design that relies heavily on fossil fuels. [1] In 2009 the European Parliament agreed on a mandatory measure for all new buildings to achieve net zero energy by 2020, as part of the Energy Performance of Building Directive (EPBD). [2] In the United States the American Institute of Architects (AIA) adopted the 2030 Challenge as a voluntary program where participating buildings aim to achieve a 90% fossil fuel reduction for buildings by 2025, and carbon-neutrality by 2030. [1]

To accomplish these energy goals, designers must strive to best utilize the resources available on a site. When buildings are sited to best absorb light or control heat, or enclosure systems are designed to mitigate temperature variances, less energy is used by mechanical and electrical systems to artificially balance the interior conditions. This is the core concept of shifting energy use from active to passive systems, where architects must better design buildings to naturally function with their immediate site. While architectural examples from recent and ancient history exist that exemplify this approach, the best models of site adaptive structures are those from biology. Native plants, showing a great diversity of scale and function, exist as physical manifestations of response to site and climate properties. Variation in plant species are evolutionary indicators of regional variances in solar resource availability, temperature ranges, precipitation, and other factors that are commonly evaluated when designing the passive strategies for a building. Thus, by translating what is known about biological adaptation to building design, architects have the opportunity to create more climate specific solutions.

The following two case studies are used to demonstrate how biological precedents can inform the optimization of building systems. In the first case study – a net-zero-energy building design project for Los Angeles, California – the photosynthetic cycle of a desert plant was used to inform the envelope design and means of passive ventilation. This example focuses on the selection of endemic plants as critical criteria for the biological application; the design process highlights the benefits of optimized passive systems for the site conditions.

The second case study is a plus-energy building that was built in Freiburg, Germany. This project exemplifies a uniquely adaptive structure that was inspired by the diurnal cycle of an alpine flower. Movement is an important aspect of this project; as such, the metaphor from biological precedent is that of adaptive active and adaptive passive systems.

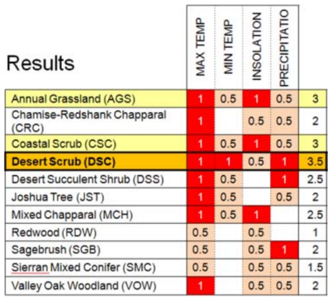
2. Case Study: Net-Zero-Energy-Building Los Angeles, USA

2.1. Project Introduction

The first case study is a Net-Zero-Energy building that was designed as a graduate student research project of the University of Southern California (USC) School of Architecture. The project was a 1,400 square foot live-work building on a site in the urban Los Angeles basin, designed with the goal of achieving net zero annual energy use. The design started with conventional passive design strategies such as a highly efficient envelope system, high performance glazing, and shading systems that would mitigate heat gain. Once loads were reduced, all supplemental energy needs were to be provided solely through solar photovoltaic (electric) and solar thermal (heat) collectors. However, in order to meet the ambitious energy goals of the project, the student team investigated biological precedents from native plants as a means to further tune the passive design to its microclimate

2.2. Biological Precedent Selection

The site, a landscaped area within an urban university campus, lacked the native flora and fauna for direct surveying. For this reason, selection of a relevant plant community was completed through a comparison of climate factors between the urban site and undeveloped zones throughout California. Geographic Information System (GIS) software was used to map temperature, solar insolation, precipitation, and wind power data overtop land areas bounded by known plant communities. [3] Microclimate profiles were cataloged from this data and compared to conditions of the project site using a weighting system (Fig.1). From this analysis, it was found that the desert scrub plant community was most applicable.



Results	MAX TEMP	MIN TEMP	INSOLATION	PRECIPITATIO	
Annual Grassland (AGS)	1	0.5	1	0.5	3
Chamise-Redshank Chapparal (CRC)	1		0.5	0.5	2
Coastal Scrub (CSC)	1	0.5	1	0.5	3
Desert Scrub (DSC)	1	1	0.5	1	3.5
Desert Succulent Shrub (DSS)	1	0.5		1	2.5
Joshua Tree (JST)	1	0.5		0.5	2
Mixed Chapparal (MCH)	1	0.5	1		2.5
Redwood (RDW)	0.5		0.5		1
Sagebrush (SGB)	0.5		0.5	1	2
Sierran Mixed Conifer (SMC)	0.5		0.5	0.5	1.5
Valley Oak Woodland (VOW)	1		0.5	0.5	2

Fig. 1: (left): Weighted comparison of plant community microclimates to Los Angeles site. Diagram: Author

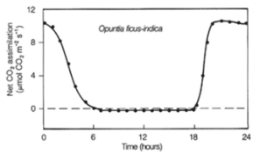


Fig. 2: (right), Figure 2. Hourly CO2 respiration cycle of representative CAM plant. Image: Author

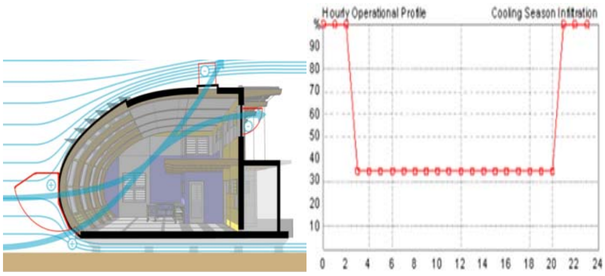
2.3. Biological Precedent Selection:CAM Photosynthesis

In reviewing prominent species of the desert scrub community, a prevalent trait was observed: succulence, or the physiological traits that support the storage of water. This trait was a direct response to the high temperatures and low precipitation that is characteristic of areas that host the desert scrub plant community. Thus, many of the form-based adaptations supported overheating prevention, while many of the metabolic adaptations supported moisture capture and retention. Chief among these adaptations was a metabolic cycle known as Crassulacean Acid Metabolic (CAM) photosynthesis. CAM is a modified version of the traditional Calvin Cycle of photosynthesis that is unique to succulent plants. Non-succulent plants respirate CO2 simultaneously with the absorption of solar radiation and water; this occurs during the daytime hours when sunlight is available. However, CAM plants have a time-shifted respiration cycle that allows CO2 intake at night, when temperatures are lower and relative humidity is higher. CO2 captured during the night time is then synthesized into a malic acid and stored within the plant structure. (Fig. 2) This stored chemical is later released during the day, when sunlight is available for the metabolic cycles to proceed. This metabolic adaptation provided a compelling inspiration for building application due to adaptations in the structure and energy cycles. Two key adaptations were highlighted: night-time respiration and converted energy storage.

2.4. Application: Passive Systems

The adaptive benefits of the CAM cycle was applied to the building as a means of tuning the passive and active systems. First, a modified envelope strategy was established to admit night-time ventilation. Prefabricated wall systems and fenestration products were designed to minimize uncontrolled infiltration, similar in function to the waxy skin surfaces of succulent plants. This strategy allowed controlled day-time ventilation that was limited to the lowest rate allowable by California Title-24 code. [4] The building form was also designed with a curved form oriented to the prevailing winds to minimize exposed surface area as well as induce pressure variations on opposing sides of the structure.

Variable passive ventilation was accommodated during night hours through the addition of operable inlets and outlets to the envelope, sized to support passive cross-ventilation using only the average summer wind speed of the site. The ventilation schedule for openings was tuned to increase night ventilation during hours that were consistent with the respiration cycle of a desert plant utilizing CAM photosynthesis. Additional passive alterations included the proposed addition of thermal mass to the interior surface of the enclosure system. By exposing this surface to cooler night-time breezes, "free" cooling energy could be stored in the slabs as rejected heat. This strategy paralleled the energy storage strategy of malic acid conversion in the walls of the CAM plant, thus completing the biological metaphor. (Fig. 3)



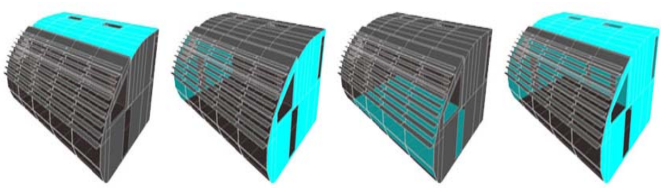


Fig. 4:Diagrams showing the four simulated thermal mass configurations.

Fig. 3: Sectional diagram of passive ventilation (top) and graph of relative hourly ventilation rates (bottom).

Diagrams: Authors

2.5. Parametric Simulation

A psychrometric analysis of using night ventilation and thermal mass revealed that the occupant comfort zone could be expanded to include over 47% of the annual hours – a 35% increase. With this validation of the potential benefits, additional evaluation of the applied design strategy was conducted using parametric Ecotect energy simulation software. (Fig. 4) Interior concrete slabs were tested as thermal mass capacity in four configurations; a 10 cm ceiling layer, 10 cm wall layer, 10 cm floor layer, and 5 cm layers on the walls and ceiling. In all four configurations of the thermal mass, cooling demand was found to be reduced during the summer months. The most effective placement option – a 5 cm concrete layer on the ceiling and walls – yielded a 76% reduction of overall cooling hours. When the night purge ventilation scheme was included – to reflect the ventilation cycle of CAM plants – cooling hours were reduced by up to 82.3%. (Table 1) These results demonstrated that the biologically inspired design strategy had the potential to nearly eliminate the hours required to provide active cooling , thus making the net-zero energy balance possible.

Table 1. Results from the simulation of thermal mass with night ventilation, Table: Author

Design Model	Thermal Mass Configuration	Mass Area	Mass Volume	Cooling Degree Hours Reduced
Design A	10cm concrete panels on ceiling	92.4m^2	9.34m^3	300 degree hours (-52.7%)
Design B	10 cm concrete panels on east&west walls	109.6m^2	11.19m^3	447 degree hours (-78.5%)
Design C	10 cm concrete floor slab	136.6m^2	13.88m^3	364 degree hours (-63.9%)
Design D	5 cm concrete panels on walls & ceiling	289.9m^2	14.72m^3	469 degree hours (-82.3%)

3. Case Study: Plus-Energy-Heliotrope, Freiburg, Germany

3.1. Project introduction

The second case study is the Heliotrope; a live-work building designed by architect Rolf Disch and built in 1994. The project is located in Freiburg, Germany, latitude 48°, longitude 7.5°, annual total irradiation about 1.100 kWh/m^2. The project is located on a 512 m^2 suburban property that has direct solar access to the north, east, and south. This 357m^2 building includes 180 m^2 spaces for living and working, a 60 m^2 roof garden, a 40m^2 technical room, as well as a 77m^2 seminar, exhibition and office space in the basement. The 14m high Heliotrope was built in compliance with the German Passive House standard, which requires a high level of thermal and energy efficiency. The building utilizes triple-paned insulated glass with krypton (U-value 0.5) and high thermally insulated walls with average of 30 cm of insulation (U-value of 0.10 - 0.12). The building is also designed with a cylindrical form that benefits from a low surface-to-volume ratio, thus minimizing the exposed surface for heat loss. This highly efficient envelope system is combined with additional energy saving systems that include a heat recovery ventilation system, a thermally active mass with low temperature heating, and a cogeneration heat and power unit. [5]

3.2. Biological Precedent: Heliotropism

What makes the Heliotrope unique is the adaptive form that was inspired by the diurnal movement of a native plant. Heliotropism, or motion related to the tracking of the sun, is a trait observed in plants such as the alpine buttercup (*RanunculusAdoneus*) that grow in the subalpine mountainous region near Freiburg. Heliotropism is important to these plants due to the short growing seasons, where optimization of sun angle exposure is critical to capturing enough energy for photosynthesis. (Fig. 5).

Fig. 5: Alpine Buttercup Flower orientation to the sun and sun-tracking Heliotrope PV-system comparison.

Photos: Author, 2010

The mechanics of this specific motion is based in the cell structure of a joint-like thickened part of the stem called the pulvinus. Motor cells within this section expand and contract based on turgor pressure, which is a water-induced pressure that is exerted against cell walls. This cycle of pressure increases on one side while decreasing on the other creates a rotational motion in the stem that turns the head of the flower over the course of the day. Using these movements the plant can exhibit behavior for tracking the sun (diaheliotropism) or avoiding the sun (paraheliotropism).

3.3. Application: Passive Systems

To allow the rotational motion of heliotropism, the building structure was designed as a cantilevered volume around a central pillar made of glue-laminated spruce timber. The 18-edged cylindrical spiral concept continuously connects the spaces through successive living and working levels over a height of 14 m. This configuration yields a floor plan that can be left open or segmented with internal partitions. All main rooms are accessible by winding steps, so no transition rooms or hallways are necessary.

The benefits of rotation are realized through the opposing configuration of glazing and opaque walls on either side of the 10,5 m diameter cylindrical space. During the cooler days when heating is required, the glazed portion is positioned towards the direct sun for optimized solar gain and daylight penetration. Conversely, on warmer days when solar gain is not desired, the building turns the insulated portion towards the sun to reject the sun. Using a 120-watt electric motor with an average annual consumption of only 20 kilowatt-hours, the building can rotate around the central axis for up to 15 degrees per hour to follow the sun. A programmable timer with weather sensors (temperature, humidity, solar radiation, precipitation, etc.) is utilized to control the Heliotrope's movement, allowing up to 180 degrees of rotation to either capture the maximum sunlight or avoid the sun completely. This adaptive passive pattern yields a unique condition where the envelope is continuously tuned to the climate conditions, thus outperforms static designs. (Fig. 7)

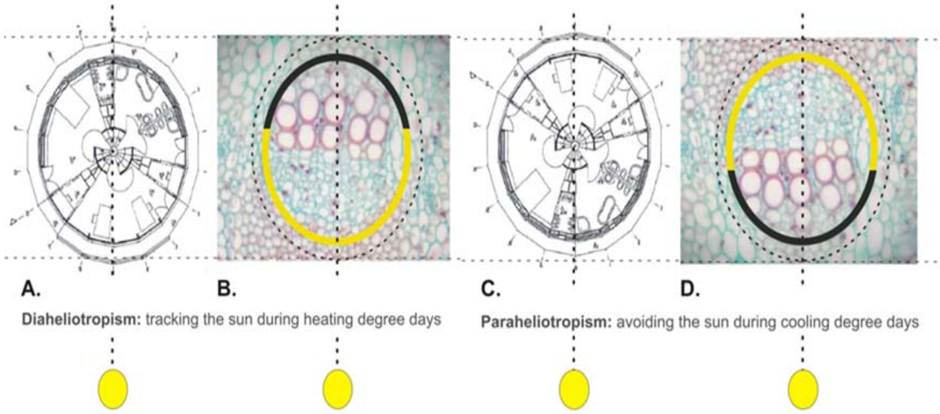


Fig. 7: Comparable tropism cycles between the rotation of the Heliotrope and plants. Diagram: Author

3.4. Application: Active Systems

In a similar parallel to the heliotropism of a flower head, the energy harvesting solar systems of the building were designed to rotate and track the sun. On the roof of the Heliotrope building there is a 54 m2 sun tracking photovoltaic wing of 60 monocrystalline modules, rated at 6.6 kilowatts at peak output. This active system rotates independently from the building structure. A two-axis mount allows the array to rotate 180 degrees and orient modules to the most optimal angle perpendicular to the sun. By using computer-controlled tracking sequences, this solar system achieves approximately 30-40% higher energy output than a conventional, fixed PV array. Based on these adaptive performance benefits, the solar system generates five times the building's annual electric power demand. [5]

3.5. Heliotrope Energy Performance Measuring

In 2012, an energy assessment showed that the 180m^2 living area consumed an annual average 20 kWh/m^2 and the 77m^2 office basement with high internal loads (computers, printer, etc.) consumed 40 kWh/m^2 for heating. In total, both areas consumed an average 6,800 kWh annually for heating and 2,160 kWh for domestic hot water. The 54 m^2 PV-System generates 9,000 kWh annual end energy with a total of 23,400 kWh primary energy. The annual surplus or "Plus-Energy" of the Heliotrope is 4,048 kWh for the end energy and 17,155 kWh for the primary energy is then sold under the German Feed-In-Tariff to the public grid. [5]

4. Conclusion

In the two examples shown, the applied biological concepts yielded benefits in energy efficient design. The benefits of these concepts stemmed from their inherent link to the site. Native biological systems respond solely to the resources available locally, and thus exist as clear indicators of appropriate architectural responses to climate. Given the attention to this information, architects and engineers hold an opportunity to gain key insight into the microclimate conditions at play, and the most prevalent resources available for their design. In order for biological precedents to find application in building design, architects and engineers need access to the information. By collaborating with professionals with biological expertise, designers can incorporate new strategies for investigation that go beyond direct site survey and climate analysis towards a greater balance of resource use that we need in the future to achieve carbon neutral buildings.

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