

INTEGRATION OF ENVIRONMENTAL SIMULATION TO PARAMETRIC DESIGN WORKFLOW: THERMAL COMFORT AND DAYLIGHT

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ABSTRACT

This paper suggests a parametric design workflow of an institution building in New Orleans, Louisiana based on parametric, climate-based analysis. This workflow is aimed to support the early design process with passive strategies to enhance occupant thermal comfort and daylight conditions of the building as well as its energy-efficiency. By analyzing the hot and humid climate of New Orleans and the needs of multiple spatial programs, including open spaces, workplaces, and residential units, parametric models were generated to simulate the annual thermal comfort and daylight conditions, which provides grounds for comparison among parametric models. In response to the climate analysis and bioclimatic strategies, three design steps were implemented: self-shading, façade components, and multi-functional screens.

INTRODUCTION

In many practices, environmental simulation on building performance is conducted at the very last phase of design process as a means of validating the feasibility of building designs. When conducted late in the process, the environmental analysis can suggest only a limited range of improvements because most building elements have already been determined and interrelated to each other. However, considering environmental factors from the earliest phase of design can significantly enhance the timeliness of environmental analysis and the overall quality of building performance. Moreover, it can accelerate the design process by providing concrete evidence at each step of design decision-making.

This paper proposes a design workflow that utilized environmental simulation results to support the architectural design decisions, particularly in the early design phase. This workflow enhanced the thermal comfort, daylight quality and energy performance of the

building design. However, it is challenging to consider multiple environmental simulation results while the main parts of the buildings are not determined yet.

PROJECT DESCRIPTION

Purpose

The significance of this workflow is to maximize annual comfort hours indoor and outdoor mainly with passive strategies. This workflow can help designers accomplish minimizing energy load early in the design process before adopting building systems. Energy load refers to the amount of energy required to maintain a comfortable environment in a building. Reducing the load is essential for reducing energy consumption and augmenting the building's resilience (Samuelson 2015).

The purpose focuses on achieving 3 goals: (1) thermal comfort, (2) daylight, and (3) energy efficiency. Unlike common expectation, outdoor thermal comfort was given higher priority for this project to harmonize the outdoor music festivals and other outdoor activities with the hot and humid climate in New Orleans, where people enjoy the modest condition of outdoor balconies that protect them from the direct sunlight.

Site and Program Analysis

New Orleans, Louisiana is located in Climate Zone 2A, which is associated with relatively hot temperature and high humidity, according to the International Energy Conservation Code (IECC) climate zone map.

The site is located at the edge of the French Quarter, from which the city evolved in the nineteenth century. As New Orleans is regarded as a birthplace of jazz, the district is full of music bars and music festivals. The majority of buildings in this district are low-rise and of Creole and Greek revival styles, which create shaded areas with galleries and heavy lintel balconies, respectively. These styles reflect both the city's history and the climate.

The institution building is required to accommodate both office and residential spaces. In addition, based on site analysis, it was suggested to provide an outdoor open space on the ground level and the fourth floor and balconies attached to the residential area on the upper levels. The longer border of the site is facing to the Northwest direction with 220 ft. width and 120 ft. depth. On Northeast and Southeast sides, the site is surrounded with adjacent buildings.

BACKGROUND

Bioclimatic Design

Bioclimatic design was introduced as a concept that actively operates renewable sources such as the sun, water, and air flow (Olgyay & Olgyay 1953). Bioclimatic design became important again when the first oil crisis in 1973 highlighted the seriousness of energy shortages, specifically with regard to fossil fuels. Afterwards, climate change and environmental pollution again reminded us of the importance of passive design strategies, which do not require great amount of fossil fuels. Although the installation of efficient HVAC can decrease energy consumption, the minimization of a building's energy load during the early design process should be preceded to reduce the eventual reliance on fossil fuels and to save energy cost.

Thermal Comfort Models

The thermal comfort models included in American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE) Standard 55, "Thermal Environmental Conditions for Human Occupancy," are pivotal criteria for calculating energy loads, the energy quantities required for retaining acceptable thermal conditions for a built environment's occupants (ASHRAE 2010). Early comfort models for indoor environments were based on the empirical approach of Fanger (1970), who developed the Predicted Mean Vote (PMV) and Predicted Percentage Dissatisfied (PPD) models. These values display expected thermal satisfaction rates that can be applied universally regardless of local climate and cultural backgrounds.

Later, in the 1970s, Humphreys and Nicol developed the adaptive comfort model originally by accommodating the concept of adaptation, the gradual diminution of human response to reoccurring environmental conditions. Adaptive comfort represents sensational thermal satisfaction calibrated by adaptation and categorized into behavioral (personal, technological, and cultural responses), physiological (generic adaptation and acclimatization), and psychological adaptation (relaxation of expectation) (de Dear and Brager 1998). After adaptive comfort was included in the 2004 edition of Standard 55, for reasons

of practicality, it was further simplified by excluding the impact of humidity.

For outdoor comfort assessment, the Universal Thermal Climate Index (UTCI)¹ indicates how people will perceive thermal conditions, the human physiological response to the environment. UTCI is an equivalent ambient temperature recalculated from dry bulb temperature, coupled with relative humidity, radiation, and wind speed.

This paper used adaptive comfort and UTCI as indicators of indoor and outdoor thermal comfort, respectively.

Daylight Metrics

Daylight is another challenge of bioclimatic design. Affordable electric lighting disengaged the building structure from the duty of distributing natural light to the deepest part of the indoor floor. Nevertheless, many studies emphasized the importance of daylight because of its positive impact on occupant health and performance (Heschong 2002; Crowley 2014).

Daylight quality can be evaluated in terms of daylight availability. Daylight availability can be assessed using the metrics; Daylight Autonomy (DA), Spatial Daylight Autonomy (sDA), and Useful Daylight Illuminance (UDI). DA indicates climate-based daylight availability during the occupied hours when the daylight level on the working plane (the hypothetical plane, elevated 2' 6", 0.762 m, from floor level) satisfies the target illuminance at a certain point in time in a given space. If the illuminance is not less than the target (e.g., 300 lux at a workplace), it will be considered as a daylit condition. The value of sDA is the percentage of the floor area of daylit space where the illuminance value reaches at least 300 lux for 50% of the occupied hours without artificial lights, as recommended by the Illuminating Engineering Society of North America (IESNA 2012). As this metric shows only whether the light is sufficient or not, Reinhart (2001) found that this metric appeared similar at different locations in North America. To examine the probability of visual discomfort or overheating, Nabil and Mardaljevic (2000) suggested UDI as an alternative. Useful daylight ranges from 100 lux to 2000 lux for a typical workplace. Visual discomfort and excessive solar heat gain can be also assessed with Annual Sunlight Exposure (ASE) and Daylight Glare Probability (DGP). ASE and DGP are more useful for detailed design of façade than for the early phase of design because they

¹ Developed by the World Meteorological Organization and International Society of Biometeorology for application in all outdoor

are local-specific indicators depending on the occupant seats and facing directions.

In this paper, sDA and UDI were adopted because they can reflect the comprehensive qualities of daylight conditions effectively, especially for the early design phase.

METHODOLOGY

Climate-base Analysis

The environmental simulation is based on the weather database, EnergyPlus Weather (EPW)². These Comma Separated Values (CSV) data consist of hourly values of weather data for the 8760 hours of a year, which represent the annual typical weather. Among the weather data files available for the New Orleans area, the TMY3 file recorded at New Orleans International Airport was used due to the geographically proximity and similarity.

Ladybug and Honeybee

Ladybug and Honeybee are open source plugins for Rhinoceros3D/Grasshopper3D, developed to resolve the discontinuity of existing simulation platforms and integrate the overall process of environmental-analysis-related design (Roudsari 2013). The plugins allow users to associate the parametric geometry with climate-based simulation engines such as EnergyPlus (US Department of Energy), RADIANCE (Ward 2004) and Daysim (Reinhart and Walkenhorst 2001).

Ladybug is recommended for visualizing weather data for climate analysis and integrating weather data as design parameters. Honeybee allows designers to build energy models and run daylight analysis by linking Rhinoceros3D and Grasshopper3D with simulation engines (EnergyPlus and Radiance). The most profitable aspect of these plugins is that it can integrate environmental simulation with complicated geometries.

Design Explorer

When designers face tens or hundreds of optional geometries, making a clear decision is challenging because it can be often subjective. If multiple aspects of options must be considered simultaneously, decision-making becomes quite complicated. DesignExplorer³ is a web-based application for comparing possible options handy and visualizing comparison results effectively. It requires users to upload recorded values from the series of iterations as a CSV file.

² The files can be downloaded from the website of EnergyPlus or Epwmap: <https://energyplus.net/weather> or <http://www.ladybug.tools/epwmap/>

³ DesignExplorer is developed by the CORE studio at Thornton Tomasetti. (<http://tt-acm.github.io/DesignExplorer/>)

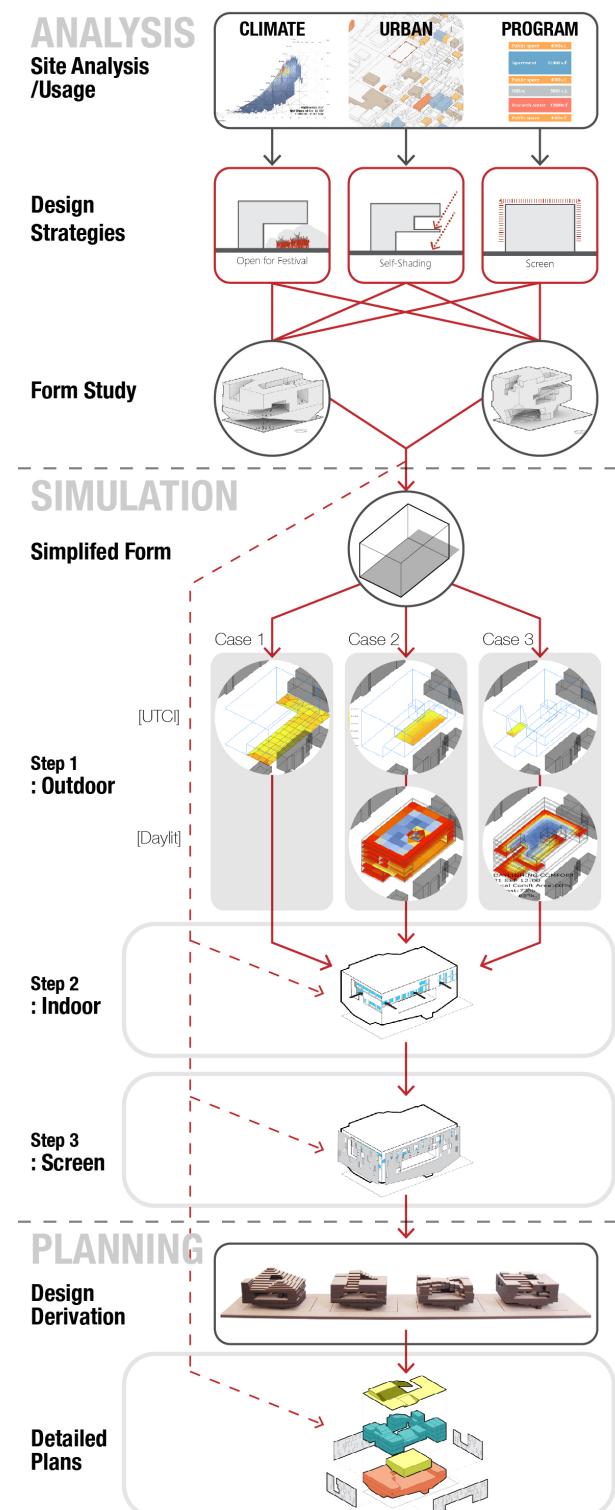


Figure 1 Design Workflow Diagram

Design Process

The design process is depicted in Figure 1. After the analysis of climate, urban context, and program, design strategies were established and first form study was conducted. The setting and assumptions for simulation are determined on the basis of the earlier analysis. Because the form has been simplified for simulation efficiency, the form needs further modification and adjustment based on the lessons learned through simulation process. According to the design strategies, the simulation process was divided into three steps, from larger scale to smaller scale: design for self-shading (Step 1), design for façade components (Step 2), and adding the multi-functional screen (Step 3).

The design workflow was integrated with advanced energy and daylight simulation engines (EnergyPlus and Radiance) and integrative platforms and plugins (Rhinoceros3D, Grasshopper3D, Ladybug, and Honeybee). After testing parametric geometries, the input parameters and output data were compared at DesignExplorer to select the appropriate option to adopt. Specifying the ranges of input or output data narrowed down the range of its possible options.

SIMULATION - STEP1: SELF-SHADING

Climate Analysis

As the Psychrometric chart (Figure 2) shows, a substantial hours are outside of the comfort range (the red color means the highest frequency in a year), the range demarcated by the thick line. Directing the most frequent hours of discomfort into the comfort zone can effectively increase the annual thermal comfort hours.

Purpose

This design step extends the thermally comfortable period of outdoor space to promote music festivals year-round on the ground level. Outdoor space is not able to be conditioned but has potential to obtain thermal comfort by shaping building mass strategically. Comfortable open space during the summer can encourage more outdoor events because the majority of the festivals occur during the spring (Figure 3).

Strategy

New Orleans's heat and humidity may prevent people from enjoying outdoor activities in the summer. Because annual comfort hours vary from 47% to 57% depending on the presence of direct solar radiation, it is expected that self-shading of the building itself increases comfort hours, encourage outdoor events, and provide a welcoming atmosphere for visitors. The variance makes a big difference, since 10% of a year equals to 12 weeks of work hours.

Simulation Settings

To produce useful analysis, simulations should be set up with awareness of climate conditions, required spatial programs, and urban contexts. Three cases were tested here: (1) the outdoor space on the ground level to accommodate musical performance events, which are a prominent feature of New Orleans life; (2) the outdoor space that serves city views to visitors and distributes daylight into the residential space; and (3) a small, communal open space for intimate relaxation.

Case 1: Ground level

The open space on the ground level is planned to accommodate music festival events. By creating a shaded area with its own mass, the outdoor comfort hours could be increased by a maximum of 10% from 47% (unshaded condition) to 57% (shaded condition).

Thermal comfort analysis was conducted with 81 geometries generated with variations of width (W_1 : 140, 180, 220 ft.) and depth (D_1 : 80, 100, 120 ft.) of the building mass and the width (w_1 : 50, 75, 100 %) and depth (d_1 : 50, 75, 100 %) of the void space. Selection criteria was to be in the ranges that achieve more than 50.5% of annual outdoor comfort and less than 121,000 m² of residential floor area. (Figure 4-1).

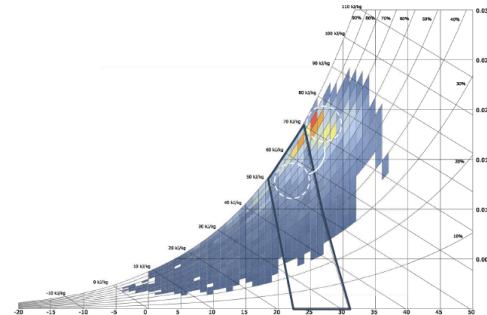


Figure 2 A psychrometric chart of New Orleans

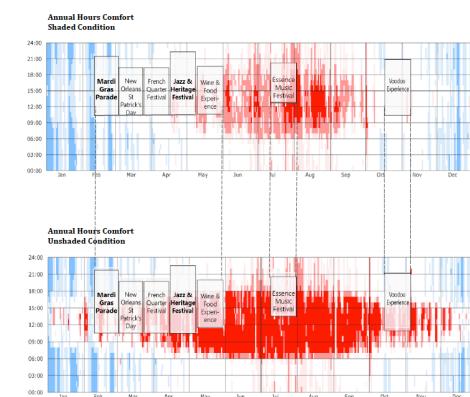


Figure 3 Annual outdoor comfort chart and festival schedule: shaded condition and unshaded conditions
(White: comfortable; red: extremely hot; blue: cold)

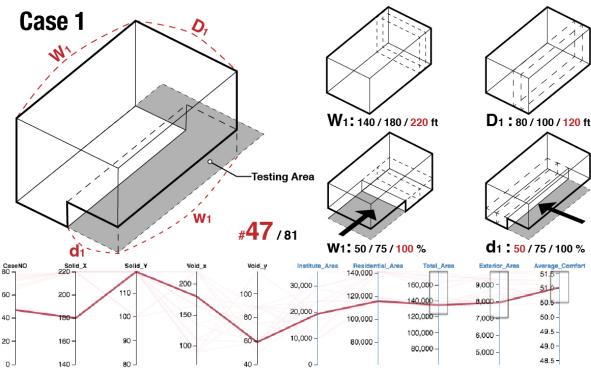


Figure 4-1 Design iterations of 81 options in Case 1

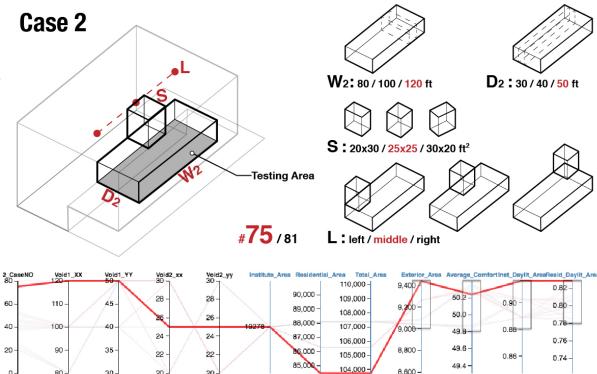


Figure 4-2 Design iterations of 81 options in Case 2

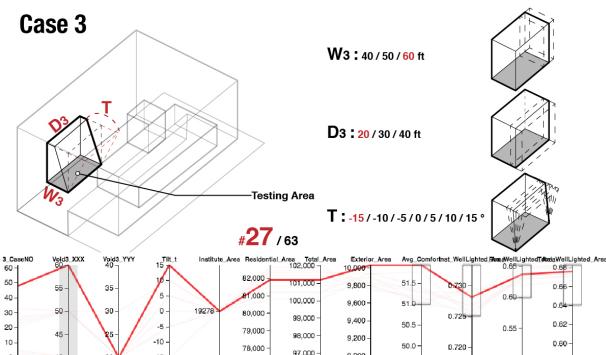


Figure 4-3 Design iterations of 63 options in Case 3

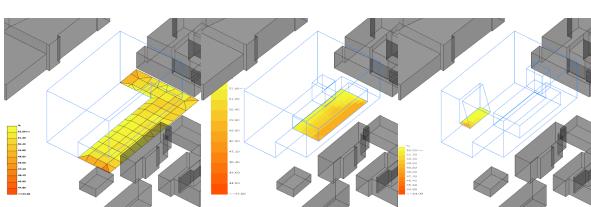


Figure 5 Outdoor comfort simulation results

Case 2: City Balcony Level

The city balcony is designed to attract visitors with city views and to distribute more natural light into the indoor space. From this case, the sDA was also tested along with outdoor thermal comfort to reveal the impacts of void space on indoor daylight conditions. Considering daylight with thermal comfort promotes the balance between indoor and outdoor conditions.

Four input parameters defined the balcony's dimensions. The width (W_2 : 80, 100, 120 ft.) and depth (D_2 : 30, 40, 50 ft.) vary by 3 degrees separately, and the void space connected to the roof is changed in shape (S : 20x30, 25x25, 30x20 ft²) and location (L : left, middle, right). The selected geometry has a relatively larger floor area than the other options, and the above void is placed in the middle with the square shape. The criteria for this selection were the larger exterior surface area, the longer comfort hours, and the larger daylit floor area (Figure 4-2).

Case 3: Residential Level

A communal relaxing space was placed across the residential floors to distribute daylight deeper. The geometries were manipulated with the dimensions of depth (D_3) and width (W_3) along with the tilted angle (T) of the southeast-facing wall, widened or narrowed at an interval of 5°.

Here, a space with greater depth (D_3), narrower width (W_3), and a more tilted inward wall (T) provides better thermal comfort. This implies that the smaller opening on the elevation and the deeper space cuts off more unnecessary solar radiation. This fact can be applied when the need for additional small open spaces arises. Additional criteria for this selection were the larger exterior surface for releasing heat from the indoor space to the outside (Figure 4-3).

Results

The geometry was finalized through three series of simulations (Figure 5). Because simulation models tend to be simplified for efficiency, architectural design and planning should be conducted continuously to conceive a balance of building performance with realistic features of buildings.

SIMULATION - STEP 2: FAÇADE

Purpose

The purpose of this step was to develop façade components for residential units to enhance indoor thermal comfort and daylight quality. This façade design was only applied to the residential floors where the attached balcony cuts off unnecessary direct sunlight and invites daylight to the deeper part of the

narrow residential units. The office space on the lower levels will have another strategy in step 3 due to the occupancy schedule of workplace. Once the initial geometry was matched with the floor plan outlines, the enclosure details followed to be designed, such as the combinations of Window-to-Wall Ratio (WWR), glass types, and the depth of shadings. The selected façade components can be arranged according to the floor plans.

Strategy

In this hot climate, a conflict exists between thermal comfort and daylight. Thermal comfort depends on the reduction of solar radiation, while daylight does on the transmittance for daylight penetration. To maintain a balance, the enclosure must prevent solar heat gain and distribute daylight with proper values in WWR, glazing performance, and shading depth. The combinations of three factors were tested regarding thermal comfort and daylight availability. Multiple façade components were selected to be mix-matched rhythmically.

Simulation Settings

The tested residential unit, with a southeast orientation, is 13 feet (4 m) wide and 30 feet (9 m) deep. The façade options were manipulated with the combinations of the façade's glazing ratio (20, 40, 60, 80%), glazing type (A, B, C, D), and shading depth (0.0, 0.3, 0.6, 0.9, 1.2, 1.5 m) (Figure 6). Each type of glazing has varied values for U-Value (the rate of heat transfer through a material, the mathematical reciprocal of R-value), Solar Heat Gain Coefficient (SHGC), and Visual Transmittance (VT, the fraction of visible light through a material). Using combinations of those factors, the options were evaluated with UDI and adaptive comfort.

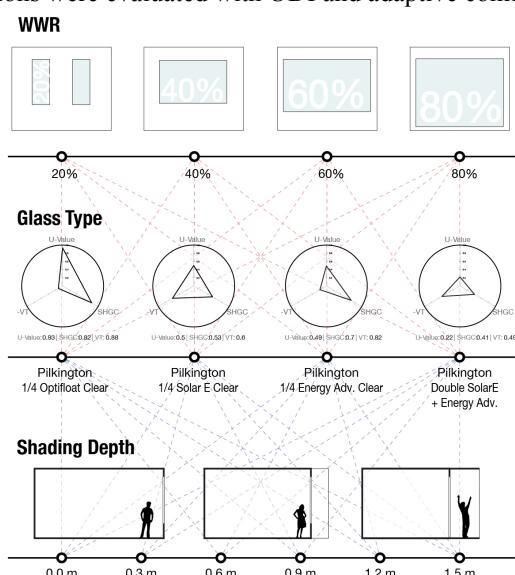


Figure 6 Combinations of façade components

Results

Through another upload, DesignExplorer indicated that the UDI value ranged from 16% to 58% and the annual adaptive comfort ranged from 57% to 65%. Because obtaining high values for both is almost impossible, some degree of compromise was unavoidable.

Regarding the balance between UDI value and adaptive comfort, seven options were selected (Figure 7). In the case of the selected combinations, the UDI ranged from 29% to 55% and the adaptive comfort ranged from 62% to 64%. By acknowledging the incompatibility, the criterion for prototype selection became balancing conditions properly rather than achieving best value in either UDI or adaptive comfort.

SIMULATION - STEP 3: SCREEN

Purpose

After shaping the building mass and façade details, the energy balance of the building was calculated to plan further improvements (Figure 8). According to the chart, the indoor space was still exposed to an excessive amount of heat attributed to opaque conduction, infiltration, and solar radiation. The chart also illustrates the uncomfortable hours due to heat gain. By operationalizing three factors, it was able to reduce both the building's peak energy loads and its annual loads significantly. The reason for considering peak energy load is to avoid peak-use tariffs and, ultimately, achieve savings on utilities (Samuelson, 2015).

Strategy

According to the differing programs between the upper and lower parts of the building, each part of the screen requires different functions that consider each occupancy schedule.

Evaporative Cooling Screen: Office

For the office, occupancy is concentrated in the daytime when the sunlight is relatively strong. The evaporative cooling function can augment the screen's impact dramatically because excessive solar heat on the screen can be transformed to cooling effects of evaporation while the office workers are present.

The feasibility was confirmed based on the climate comparison with Tokyo where a successful reference takes place. The Sony Research and Development Center in Tokyo, Japan, has an innovative exterior system, BioSkin. This adapted evaporative cooling method that decreased the building's temperature and even that of the surrounded area by 1 to 2 °C (1.8 to 3.6 °F) (Yamanashi 2011). Due to the higher temperature and humidity of Tokyo, the probability of evaporation in New Orleans is more likely than in Tokyo (Figure 9).

The evaporative cooling screen made from high water-retentive terracotta also functions as shadings. Replacing dry bulb temperature with 60% of the efficiency of wet bulb temperature reduced the temperature 2.7 °C from the baseline on the testing surface on June 21 at 12 p.m. This method was examined based on Penman's evaporation rate equation (Figure 10).

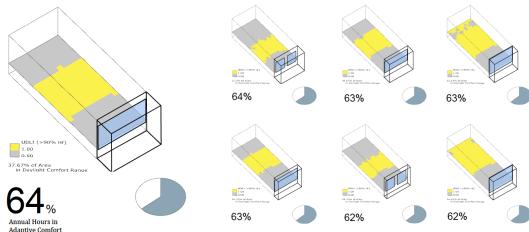


Figure 7 Selected components of residential units

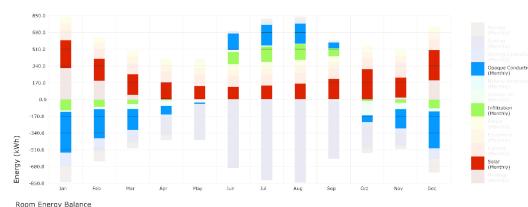


Figure 8 Energy balance chart after step 2

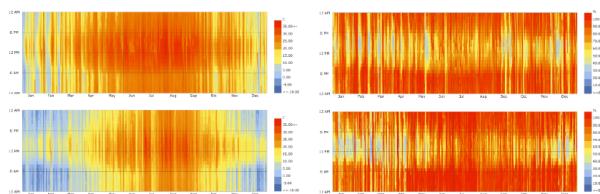


Figure 9 Dry bulb temperature (left), relative humidity (right) (Up: New Orleans, US; Down: Tokyo, Japan)

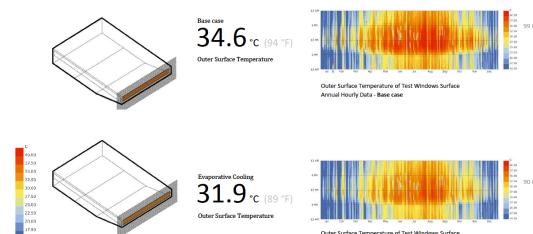


Figure 10 Evaporative cooling effects calculated with cooling tower model

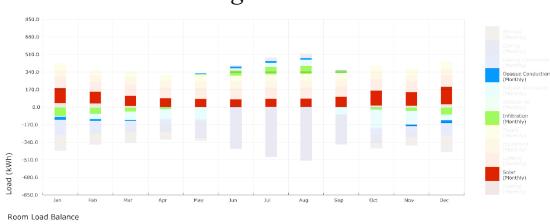


Figure 11 The energy balance after Step 3

Operable Sliding Screen: Residential Units

In residential units, the proposition of furniture and positions of occupants are not as predictable as they are in offices. Thus, an operable sliding screen system is a practical way to avoid glare near the window. The operable function is useful for residential spaces where people may want to move the screens around depending on sun position and their individual preference.

Results

The multi-function screen system, which functions as evaporative cooling and shading, significantly reduced heat gain from solar radiation, as the energy balance chart indicates (Figure 11).

DISCUSSION

This paper suggests a design workflow that integrates environmental simulation into the parametric design in the early phase. The essence of this integration is evidence-based design approach. Providing rationale to design can facilitate the entire design process and enhance the cross-disciplinary collaborations during the process. The climate analysis is a fundamental prerequisite that allows designers to develop valid bioclimatic design strategies. In this paper, the climate analysis, spatial program, and urban context effectively delivered guidelines to create self-shading as a means of moving discomfort hours into the thermal comfort zone of the psychrometric chart in response to the hot and humid climate of New Orleans, LA.

Before setting simulation, it is crucial to select relevant thermal comfort models and daylight metrics and include the whole range of design possibilities. Given the wide range of possible geometries, designers should coordinate inputs with adequate intervals to limit the numbers of options. For instance, the self-shading design had 3 options for each parameter to understand the tendency of geometries. Once designers understand the tendency, they should interpret the hidden lessons from the results and adopt the knowledge when adjustments or modifications are needed.

The lessons of self-shading design can be summarized as follows. The wider and deeper the ground level open space is, the more outdoor thermal comfort can be obtained. Also, to achieve more thermal comfort hours and better daylight distribution, the open space on the fourth floor needs to be deeper, wider and placed in the middle of the building. For the smaller communal area, outdoor space tends to obtain better thermal comfort and daylight quality when it has a deeper floor and the wall is tilted inwards, which results in blocking more direct sunlight. Making a balance between thermal condition and daylight is challenging in design because cooling, heating, and lighting loads are intercorrelated.



Figure 12 A section-perspective view of the building

These lessons are mostly related to the balance, how much direct solar heat gain can be cut off while sufficient daylight is allowed to indoor directly or reflectedly. These ideas can be applied for future projects if the shaded condition is more thermally comfortable than the unshaded condition. The façade component design indicated that the combination of WWR and shading is important. As the WWR increases, the shading should be longer to create a balanced condition. The last step, multi-function screen design, revealed evaporative cooling can effectively decrease the temperature of the building surface even in this humid climate and the operable sliding screen is suitable for residential units.

The selected geometry was not the option that achieved the best comfort hours. Instead, it has a decent balance between architectural functions, thermal comfort, and daylight. In the later design phase, the design should be developed and adjusted to other functional and aesthetic demands in a minor scale, rather than being trapped in the geometry established by building simulation results.

CONCLUSION

This paper presents a workflow for decision-making in the early design process by parametric design and environmental simulation. With bioclimatic strategies, the energy consumption estimation is 31 kBtu/sqft, eligible to earn 10 energy credits of LEED certification.

ACKNOWLEDGMENT

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REFERENCES

- ASHRAE. 2010. Thermal environmental conditions for human occupancy, ASHRAE Standard 55-2010. American Society of Heating, Refrigerating and Air-Conditioning Engineers, US.
- Brager, G. S., de Dear R. J. 2001. Climate, comfort & natural ventilation: A new adaptive comfort standard for ASHRAE Standard 55. *The proceedings of Moving Thermal Comfort Standards into the 21st Century*, UK.
- Crowley, S. J., Molina, T. A., Burgess, H. J. 2014. A week in the life of full-time office workers: Work day and weekend light exposure in summer and winter. *Applied Ergonomics*, 46(A), 193–200.
- de Dear, R.J., Brager, G. S. 1998. Towards an adaptive model of thermal comfort and preference. *ASHRAE Transactions*, 104(1), 145–167.
- Fanger, P. O. 1970. Thermal comfort: Analysis and application in environmental engineering. Danish Technical Press, Copenhagen.
- Heschong, L., Wright, R. L., Okura, S. 2002. Daylighting impacts on human performance in school. *Journal of the Illuminating Engineering Society*, 31 (2), 101–114.
- IESNA Daylighting Metrics Committee. 2012. IES LM-83-12 IES Spatial Daylight Autonomy (sDA) and Annual Sunlight Exposure (ASE), New York: IESNA Lighting Measurement.
- Nabil, A., Mardaljevic, J. 2000. Useful daylight illuminance: A new paradigm for assessing daylight in buildings. *Energy and Buildings*, 32(2), 167–187.
- Olgay, V., Olgay, A. 1953. Application of Climate Data to House Design and associates, U.S. Housing and Home Finance Agency, Washington D.C.
- Reinhart, C. F., and O. Walkenhorst (2001). Dynamic RADIANCE-based daylight simulations for a full-scale test office with outer venetian blinds. *Energy & Buildings*, 33(7), 683–697.
- Roudsari, M. S., Pak, M. 2013. Ladybug: A parametric environmental plugin for Grasshopper to help designers create an environmentally-conscious design. *The Proceedings of BS2013: 13th Conference of International Building Performance Simulation Association*, August.
- Samuelson, H. W., Claussnitzer, S., Goyal, A., Chen, Y., Romo-Castillo, A. 2016. Parametric Energy Simulation in Early Design: High-Rise Residential Buildings in Urban Contexts. *Building and Environment*, 101, 19–31.
- Ward, G. J. 1994. The RADIANCE lighting simulation and rendering system. *Proceedings of the 21st annual conference on computer graphics and interactive techniques*, Orlando.
- Yamanashi, T., Hatori, T., Ishihara, Y., Kawashima, N., (Nikken Sekkei Ltd), Niwa, K., and Nikken Sekkei Research Institute. 2011. BIO SKIN Urban Cooling Facade. *Architectural Design*, 81 (6), 100–107.