DISCOVERY-PERFORMANCE-DESIGN

Jihun Kim[1, 2], Brian Phillips[2], and William W. Braham[1, 2]
[1]The T. C. Chan Center for Building Simulation and Energy Studies,
University of Pennsylvania, Philadelphia, PA, USA
[2]Department of Architecture, School of Design,
University of Pennsylvania, Philadelphia PA, USA
jihun@design.upenn.edu

ABSTRACT

This paper reports on the use of advanced building performance simulation in the post-graduate design studio, which explored the role and limits of analytical tools in the early stage design process. Each project began with the environmental accounting diagram technique to situate the project in its social, ecological, and economic context. Within the discovered context, performance simulations were engaged for design synthesis rather than analysis of finalized building. Simulation tools included EnergyPlus to evaluate building energy usage, Radiance for daylighting, and ANSYS Fluent for natural ventilation and passive cooling effects.

INTRODUCTION

This post-graduate design studio explored the territory of design that lies between the problem context and the energy model. What tools do designers need to negotiate the territory between program, client, site, aesthetics and energy consumption? The goal was to amplify and accelerate the utility of the project for its occupants—visual, performative, economic, etc.—that propels a project to the point of maximum impact.

Discovery

Architecture is a process of discovery, of deciding what to work on, before it ever becomes a matter of design. For environmental building design, the process of discovery is even more profound, involving issues of resource consumption, modes of living and working, and of ecological interconnection that have to be explored before questions of performance can even be addressed. This kind of discovery involves the identification of the topics or narratives that make design meaningful, and that are typically taken for granted. Sites, programs, climates, and means of construction are classic sources for developing architectural topics, as are types and classes of buildings, and more recently, design techniques and the dynamic performance aspects of buildings.

The general site for the studio was the Philadelphia Navy Yard, which is effectively a 1,200-acre island attached to the city at two points. Five teams of two or three students prepared five projects, of which we will use two—one called Adaptive Reuse and another called Urban Cloud—to illustrate the argument of the paper. Each team began the project with an environmental accounting diagram, using the energy language, developed by H. T. Odum. This was based on collective research about site resources, climate, programs, construction, codes, and design methods (Odum 1995; Taylor 1988; Odum 1983). This diagraming technique has been regarded as an essential step of environmental design process to understand and to discover the flow of energy in and out of the building (Srinivasan et al. 2012; Srinivasan et al. 2011). The resulting diagrams enabled each team to establish the context for performance assessment and design propositions. As a result, most projects combined strategies for increasing the efficiency of building operating energy with strategies for reducing the energy costs of transportation, food, water, or waste, and developed designs that shifted from high-intensity to lower intensity solutions. Figure 1 shows that the Adaptive Reuse team proposed atrium as active system to control environmental budget for both existing commercial area and new residential area.

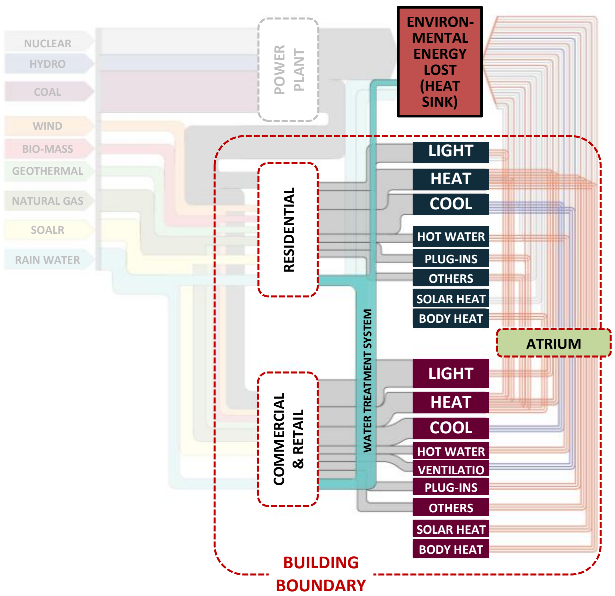


Figure 1 Adaptive Reuse – Environmental accounting diagram of mixed-use programming with atrium

PERFORMANCE SIMULATION FOR DESIGN SYNTHESIS

After the discovery process for problem domains, available natural resources, potential architectural design solutions in the previous stage, advanced simulation tools were incorporated in the fast track process of early phase architectural design development, in the context of performance-based design (Oxman 2008). The role of simulation was intended to support the design synthesis for design discovery, which is quite different from the more detailed analysis of fully developed design proposals. Iterative approach was taken as the desirable use of building simulations in the process so that the impact of morphological changes can be learned to pursue the performance (Augenbroe 2004). The simulation programs used include EnergyPlus, ANSYS Fluent, Radiance through Ecotect and DIVA for thermal, fluid, and lighting consecutively.

Through passive design strategies and active system integration, the Urban Cloud project set the ambitious goals of 'net zero energy' and the Adaptive Reuse project aims to reduce 50% of the energy use, compared to the base line of their own. This gives the rise of importance in modeling of base line as the measure of overall thermal performance throughout the design iterations. With this in mind, the techniques were developed to test concepts rapidly and to provide feedback to the direct project development.

Energy: thermodynamic equivalence

Each team built a base line energy model with EnergyPlus as the thermodynamically equivalent point of comparison to evaluate design proposals and iterations. Main task is to create the abstract simple form that represents the actual complex building with the similar short-wave radiation budgets, similar method found in urban modeling technique (Rasheed 2009). The base line models typical box-shaped building with the same volume and total built surface area to the complex shape as well as other comparable physical properties, typical mechanical systems for the building use type, and ASHRAE-defined operating schedules. Establishing assumptions for the base line proved itself a valuable process, as it helped students understand the underlying thermodynamic behavior of the building, and to begin framing design propositions in simpler terms. One of the common points of argument was the assumption of an all glass wall for its potential unfairness to exaggerate the performance.

Retractable shading device in thermal prediction

The Adaptive Reuse project proposed a new volume on top of an existing building, doubling its overall size, and adding a responsive skin. A retractable exterior shading device was implemented to modulate daylighting and to control heat gain. The main modeling challenge was how efficiently evaluate the impact of different configurations on thermal performance through different seasons as well as occupant preferences. Seasonal changes were accounted with optimal configuration for entire portion of building to respond the climate condition, which set the average performance. Then, a small portion of building was isolated and analysed to learn the sensitivity of the shading on energy use, Figure 2. Different degree of openings, every 25% from 25 to 100%, were analysed by simply changing the

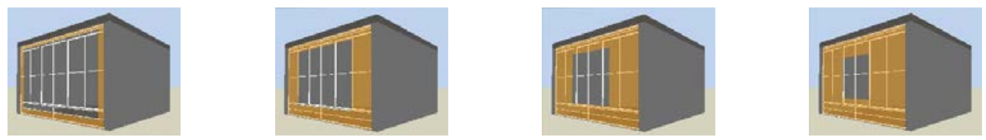
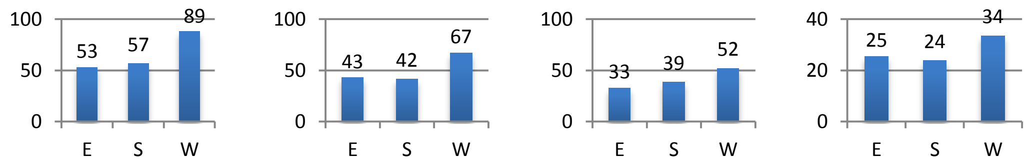
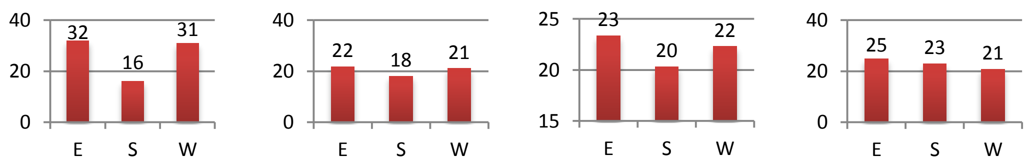
Opening ratio	*1*	*0.75*	*0.5*	*0.25*
Proposed retractable shading device				
Thermodynamically equivalent model in EnergyPlus				
Annual cooling energy prediction (BTU Hr/Ft^2)				
Annual Heating energy prediction (BTU Hr/Ft^2)				

Figure 2 Thermal prediction by EnergyPlus for each unit in per retraction ratio

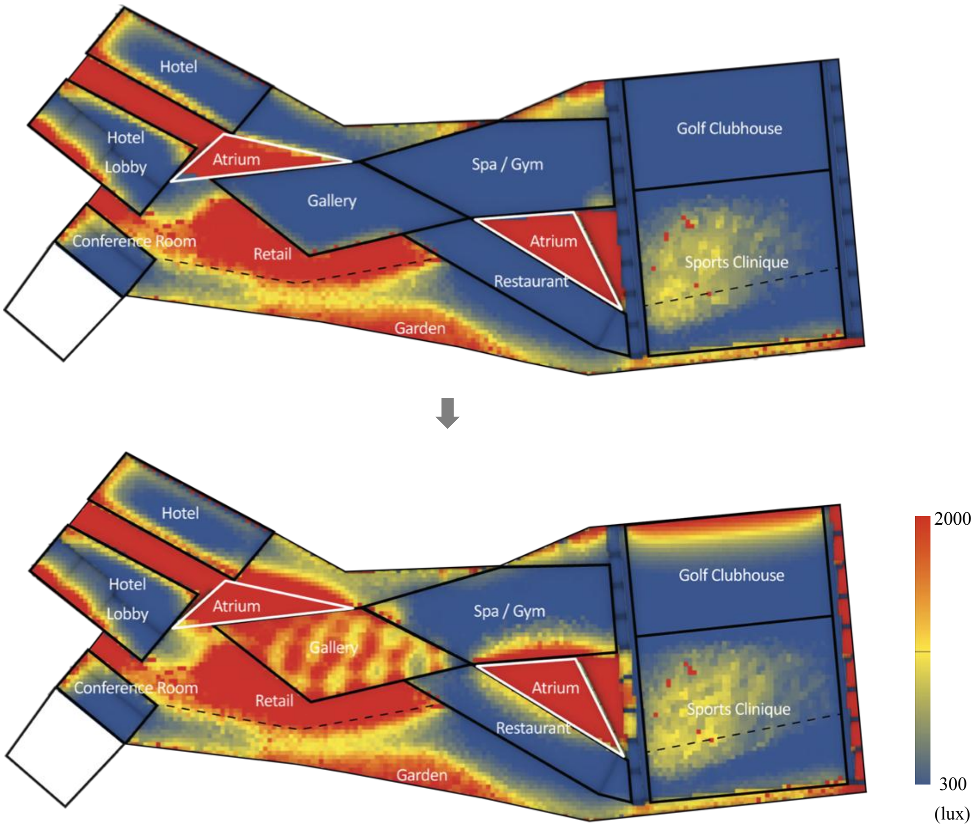


Figure 3 Urban Cloud - Modified daylighting performance (lower) after design decision support by simulating the initial design (upper), plane at +1m from ground, June 21 12:00

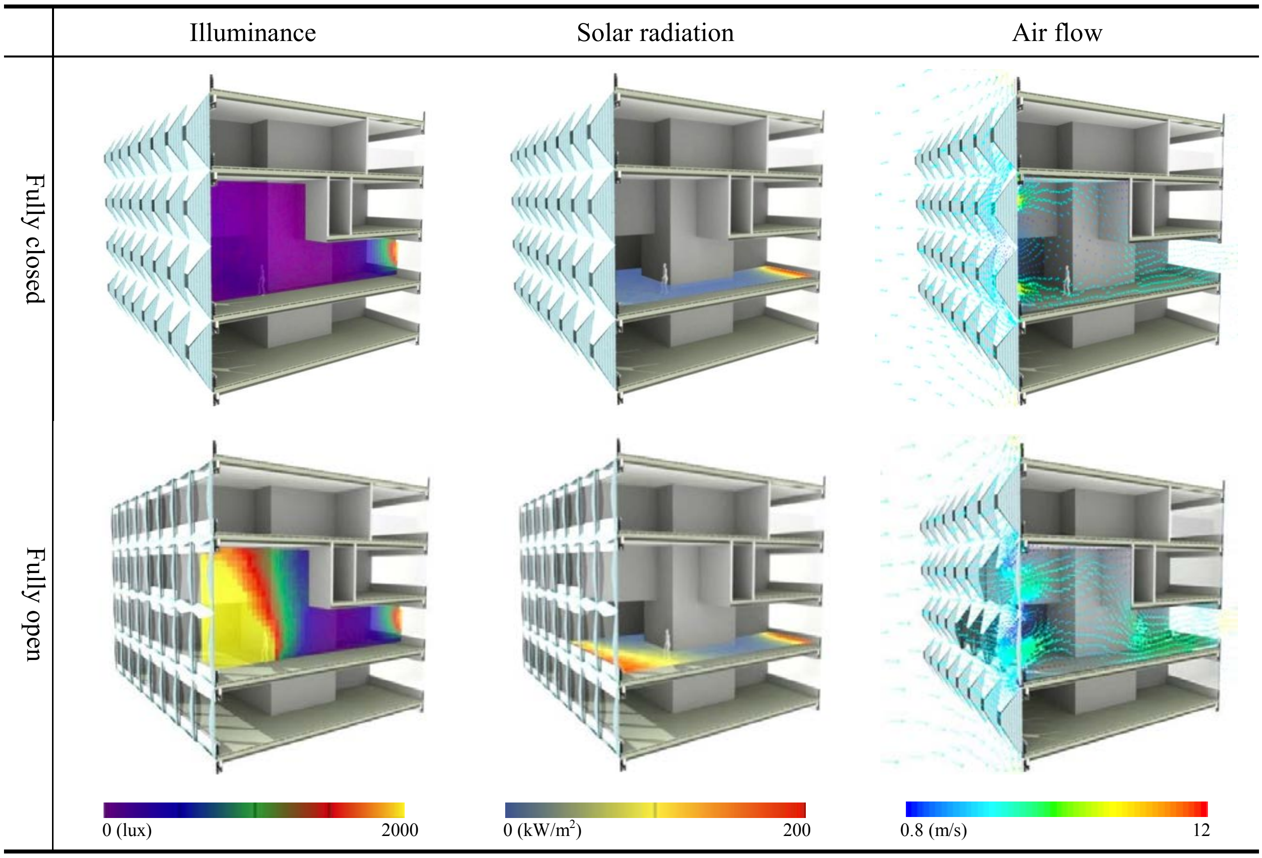


Figure 4 Illuminance, Short-wave radiation, flow analyses with retractable outdoor shading device

window-to-wall ratio in EnergyPlus instead of analysing physics-based complex shapes. The four basic orientations were considered and used to differentiate the facades of the building. The result of the small-scale analysis constitutes the range of performance due to occupant preference along with the aforementioned average value for the overall optimal shape.

Geometrical complexity and equivalent geometry

The Urban Cloud project proposed to install a large, lightweight skin over existing buildings, altering their microclimate and radically reducing the construction cost of the renovation. The complex form and expansive indoor volume of the building brought two challenges in thermal modeling. Geometrical complexity with its computational expanse for thermal modeling is the first one. For the current early phases of design discovery, a geometrical simplification was used as previously described for thermodynamic equivalency, Figure 5. This model was used for thermal calculation and to answer fundamental questions about the proportion of glazing and the trade-offs between thermal and daylighting performance. A more realistic geometry was required to simulate daylighting and natural ventilation, both of which were more dependent on geometric configuration and details. For design iterations, the surface and volumne of equivalent geometry shall be updated to respond the significant changes in overall building form to increase the accuracy of the thermal calculation, Figure 6. For each wall in thermal model, changes are made in glazing types and window-to-wall ratio in conjunction to strategic depolyment of modular building skin system. The team developed the modular system in that the elements with different shading coefficients, insulation values, and other properties could be deployed to adjust over-heating or over-lighting. The second challenge is the lack of thermal stratification for the expansive indoor space in the EnergyPlus due to its well-mixed air assumptions (UIUC 2005). Even if indoor heat and air flow are analyzed with CFD, it remained questionable on the design team's coarse thermal estimation by discounting total energy consumption for the hours in the comfort range of very few instances.

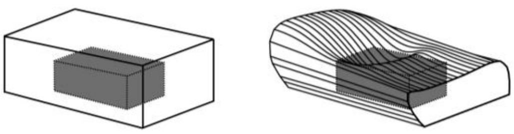


Figure 5 Equivalent geometry (left) & complex geometry (right). (The shaded box represents existing building, specific to the Urban Cloud project)

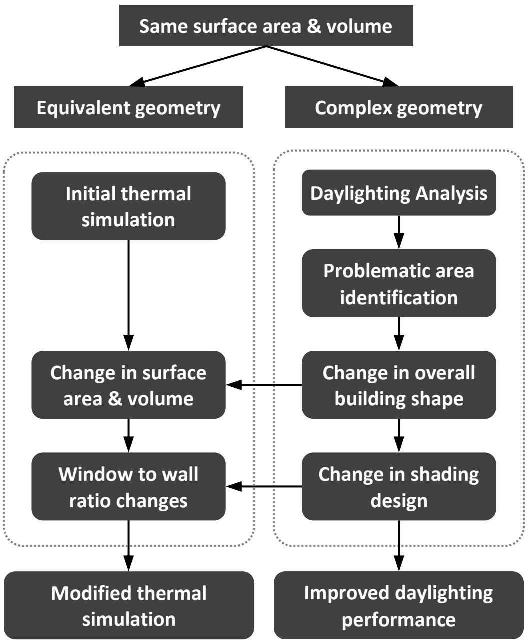


Figure 6 Equivalent geometry for thermal prediction with daylighting analysis of the complex geometry

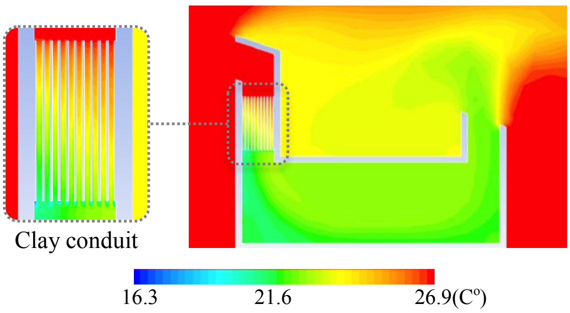


Figure 7 2D-CFD Template with heat source for passive cooling effect

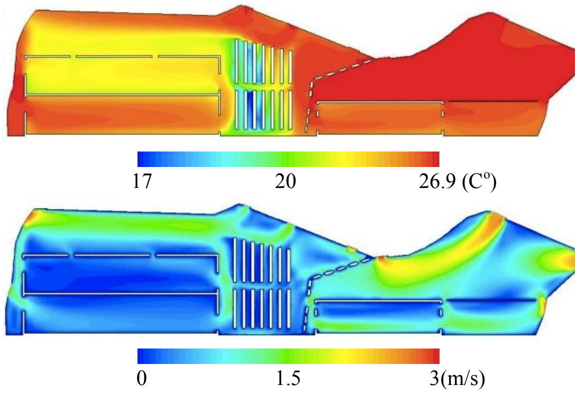


Figure 8 Urban Cloud – Passive cooling (upper) and natural ventilation analysis (lower)

Two-Dimensional Computational Fluid Dynamics

For intra-zone air movement and indoor comfort study, the role of CFD is crucial (Clarke 2001). However, the quick pace with the high geometric resolution prohibits the use of three-dimensional fluid analyses in early stage design stages. The constant adjustments in a building form particularly discourage its usability. Therefore, to facilitate the design processes, a 2-dimensional CFD template was implemented, Figure 7. The 2D-CFD template was specifically designed to simulate evaporative cooling and wind-driven passive ventilation on the site. Clay conduit, as evaporative cooling feature, is configured to be part of the wind tower, responding the recent commercial development (Hughes, Calautit, and Ghani 2012). The temperature of the conduit is provided by designer as a boundary condition for the sprayed chilled water. Temperature distribution is the main consideration of the template. Other boundary conditions include a fixed temperature for inlet air and atmosphere, and inlet wind velocity from the weather data. 2D-CFD is pressure-based, steady state with Discrete Ordinate model for radiation model. K-epsilon model is used for turbulence and energy and gravity is considered. Conductive heat transfer between walls is ignored.

In the Urban Cloud project, 2D-CFD analysis informed the use of water features to provide evaporative cooling in conjunction with induced natural airflow through multiple envelope openings. Natural ventilation proved to be successful with the assumption of basic boundary conditions, Figure 8. This reduced-dimensional tool allowed the rapid evaluation of microclimate conditions in the building, which was critically influential to the occupant comfort and thermal assessment.

The Adaptive Reuse project proposed an elaborate system of cross-ventilation for each unit, combining wind and buoyancy-driven effects at the atrium that together charged a variety of thermal mass elements.

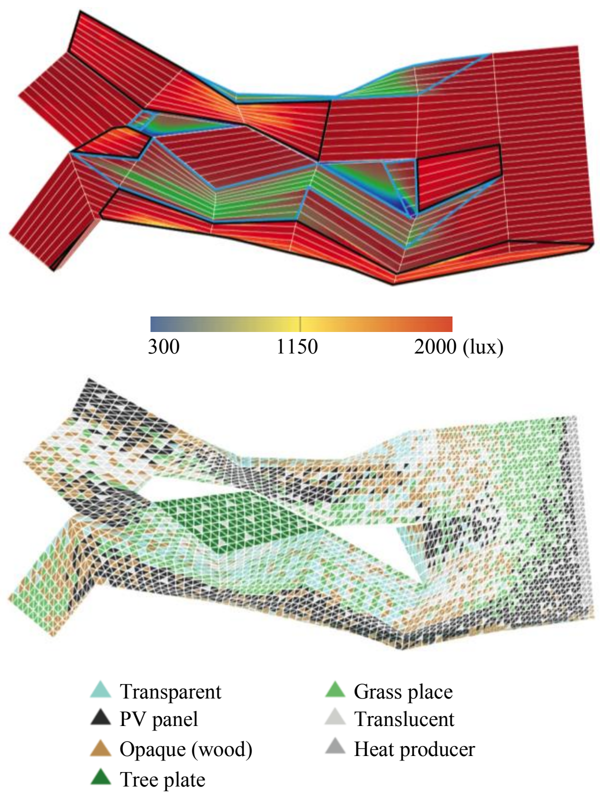


Figure 9 Urban Cloud - Initial insolation analysis (above) and strategic panel distibution (below)

The basic configuration was analysed using 2D-CFD for the retractable devices in that the minimum opening size was decided for the marginal ventilation performance. Figure 4 also shows other performance domains that are engaged with retractable devices.

Even though indoor comfort was the only performance index for the project, it was argued that other considerations could be included for more comprehensive flow domain analysis, such as outdoor wind discomfort (Kim, Yi, and Malkawi 2011). Due to the lack of lateral influence in 2D-CFD, it is more desirable to use 3-dimension analysis in the later stage when the morphological changes are relatively minor. Another identified uncertainty dwells on deciding proper input value for boundary condition that requires more research on microclimate around the building for its high impact on thermal accounting (Allegrini, Dorer, and Carmeliet 2012; Bouyer, Inard, and Musy 2011).

Daylighting

The performance of the Urban Cloud project was particularly sensitive to the admission or exclusion of solar radiation; so multiple insolation analyses were conducted to evaluate the materials and distributions of the unitized panels, Figure 9. Seven modular panels were designed with different transparencies and shading coefficients for daylight and thermal transmissivity. The main concern was the trade-off between thermal performance and daylighting. Figure 3 shows the effect of strategic distribution of modular panels over the envelope. Natural light penetrates to the desired space, such as gallery, gym and restaurant. For gallery space particularly, the team effectively avoided harsh direct sunlight but allowed the diffused one for its intended light quality and illuminance level.

CONCLUSION

The methodological development of the advanced simulations was begun with the awareness of difficulties of its use for the early design stage as well as with the understanding of the inappropriateness of simplified simulation tools with intrinsic high uncertainties and limited capabilities. This paper reports the use of advanced building simulation in iterative process for design synthesis after identifying what to simulate in previous stage of 'Discovery'.

Use of equivalence geometry in thermal simulation saved significant computational expanse while being integrated with daylighting analysis for design decision. While it is suitable for fast track design iterations, it shall be desirable to take full complex geometry for more accurate calculation in the design development. The other technical challenges in thermal prediction include the over-simplified coupling method to account natural ventilation and indoor thermal stratification consideration. For fluid analysis, two-dimensional CFD showed its good usability in the fast track process when numerous morphological changes occur. Iterative design study and its impact on thermal and airflow behavior were satisfactorily correlated in terms of design decision making. However, uncertainty analysis for the lack of lateral influence needs to be further researched.

Even if the initial performance goals were claimed to be achieved, the validation of simulation result to the real world performance may become critical argument. However, it was left unanswered for the future studies due to the highly limited amount time and the nature of early stage design. Other challenges in the use of simulation in the early stage design are followed.

- Uncertainty analysis for thermally-equivalent modeling technique
- Comprehensive performance index integration
- Systematic approach to determine boundary conditions with urban microclimate condition

REFERENCE

Allegrini, J., V. Dorer, and J. Carmeliet. 2012. Influence of the urban microclimate in street canyons on the energy demand for space cooling and heating of buildings. Energy and Buildings.

Augenbroe, Godfried. 2004. Trends in building simulation. In Advanced Building Simulation, edited by A. M. Malkawi and G. Augenbroe. New York & London: Spon Press.

Bouyer, J., C. Inard, and M. Musy. 2011. Microclimatic coupling as a solution to improve building energy simulation in an urban context. Energy and Buildings.

Clarke, J A. 2001. Energy Simulation in Building Design. Woburn, MA: Butterworth-Heinemann.

Hughes, B.R., J.K. Calautit, and S.A. Ghani. 2012. The development of commercial wind towers for natural ventilation: A review. Applied Energy 92:606-627.

Kim, J., Y.K. Yi, and A.M. Malkawi. 2011. Building form optimization in early design stage to reduce adverse wind condition, using Computational Fluid Dynamics. Paper read at 12th Conference of International Building Performance Simulation Association, at Sydney, Australia.

Odum, H.T. 1995. Environmental accounting: emergy and environmental decision making: Wiley.

Odum, Howard Thomas. 1983. Systems Ecology; an introduction.

Oxman, R. 2008. Performance-based design: current practices and research issues. International journal of architectural computing 6 (1):1-17.

Rasheed, Adil. 2009. Multiscale modelling of urban climate, Ecole Polytechnique Fédérale de Lausanne.

Srinivasan, Ravi S, William W Braham, Daniel E Campbell, and Charlie D Curcija. 2012. Re (de) fining Net Zero Energy: Renewable Emergy Balance in Environmental Building Design. Building and Environment 47:300-315.

Srinivasan, Ravi S, William W Braham, Daniel E Campbell, D Charlie Curcija, and ME Rinker Sr. 2011. Building Envelope Optimization using Emergy Analysis. Paper read at 12th Conference of International Building Performance Simulation Association.

Taylor, P.J. 1988. Technocratic optimism, HT Odum, and the partial transformation of ecological metaphor after World War II. Journal of the History of Biology 21 (2):213-244.

UIUC, L. 2005. EnergyPlus Engineering Reference: The Reference to EnergyPlus Calculations. US Department of Energy.