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Passive performance and building form: An optimization framework for early-stage design support

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Abstract

To achieve low and zero net energy performance objectives in buildings, designers must make optimal use of passive environmental design strategies. The objective of this research is to demonstrate the application of a novel Passive Performance Optimization Framework (PPOF) to improve the performance of daylighting, solar control, and natural ventilation strategies in the early design stages of architectural projects. The PPOF is executed through a novel, simulation-based parametric modeling workflow capable of optimizing building geometry, building orientation, fenestration configurations, and other building parameters in response to program requirements, site-specific building adjacencies, and climate-based daylighting and whole-building energy use performance metrics. The applicability of the workflow is quantified by comparing results from the workflow to an ASHRAE 90.1 compliant reference model for four different climate zones, incorporating real sites and urban overshadowing conditions. Results show that the PPOF can deliver between a 4% and 17% reduction in Energy Use Intensity (EUI) while simultaneously improving daylighting performance by between 27% and 65% depending on the local site and climatic conditions. The PPOF and simulation-based workflow help to make generative modeling, informed by powerful energy and lighting simulation engines, more accessible to designers working on regular projects and schedules to create high-performance buildings.

Keywords: Passive design; Daylighting; Multi-objective optimization; Natural ventilation

1. Introduction

Increasing awareness of the impact of buildings on energy consumption and indirect carbon emissions is driving a growing interest among design professionals to design projects that go beyond energy code compliance thresholds and achieve whole-building energy optimization. Rather than analyzing whether a predetermined building design surpasses or fails a compliance requirement in the late stages of design development, designers are increasingly interested in obtaining rapid and iterative performance feedback on decisions in the early stages of design, where the largest impacts on building performance and occupant comfort are set. To effectively meet low and Zero Net Energy (ZNE) performance objectives, the building geometry, orientation, fenestration configurations, and thermal management strategies must become supporting pieces of the whole-building energy concept. To achieve this, designers must go beyond incremental improvement in mechanical systems efficiency and make optimal use of environmental services provided by natural systems. Therefore, workflows are needed that enable designers to

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examine and optimize the application of passive environmental strategies in early stage design. However, due to the complexity and resources required to conduct reliable simulation-based thermal energy analysis, responsibility for energy performance is often shifted outside the discipline of architecture to Heating, Ventilation and Air Conditioning (HVAC) engineering consultants, where the focus is traditionally on incremental improvements in building assemblies and systems efficiency guided by energy standards (e.g. American Society of Heating and Refrigeration Engineers ANSI/ASHRAE/IES Standard 90.1-2013). Similarly, due to the complexity and resources required to conduct photometrically-accurate lighting simulations, lighting design is often performed by external consultants and late in the design process, where the emphasis is placed on specifying high-efficiency electrical lighting fixtures and photo-sensitive lighting controls for an existing design. This fragmented approach limits the potential to explore architectural strategies (e.g. building geometry, window–wall ratio, shading devices, etc.) to minimize heating and cooling loads and the application of environmental services such as natural ventilation, exposed thermal mass, and daylighting, as passive alternatives to HVAC and electrical lighting systems. The goal of this research is to increase the utilization of passive environmental strategies in the design process by developing a design framework and simulation-based workflow enabling designers to examine and optimize the application of passive environmental systems in early stage design using validated lighting and energy simulation tools.

In commercial buildings, which account for roughly half of the energy used by all U.S. buildings, decisions related to building geometry and fenestration affect the majority of energy end uses and are thus a central area of focus for performance improvements aimed at enabling low and ZNE buildings. In the United States, lighting represents the single largest commercial building electricity end use (35%) (U.S. DOE, 2011), and is consumed primarily during daylight hours. Of this energy, it is estimated that 60% is consumed in perimeter zones located 0–12.2 m (0–40 ft) from the building facade during typical daytime work hours (8:00–18:00) (Shehabi et al., 2013). Cooling loads represent another significant energy end use (14%), and one-third is due to electrical lighting and another one-third to solar heat gains through windows (Huang and Franconi, 1999). And, because ZNE projects often implement passive or low-energy cooling alternatives such as radiant systems or exposed thermal mass with night-flush ventilation, effective solar control is an additional requirement to avoid exceeding the peak cooling capacities of these systems, which are typically lower than mechanical HVAC, and consequently more sensitive to peak solar heat gains. Consequently, daylighting strategies that optimize distribution of useful daylight across the floor plate while controlling solar loads have the potential to significantly improve building energy performance.

Many designers strive toward achieving a holistic building design process where the numerous, sometimes conflicting, design objectives are resolved. Trade-offs are considered, and designs are reworked at each stage of the building's development from sketches to construction. As project phases move from pre-design to utilization, cumulative cost goes up and level of influence decreases (Paulson, 1976). The MacLeamey curve, fine-tuned from years of his experience in architecture and as a principal at HOK, illustrates that changes made during schematic design can be cheaper to implement than if done later and can have more impact on the project (Kensek, 2014). Analysis opportunities, for example for passive energy strategies, are thus best explored during schematic and early design development.

In a worse case scenario, design happens without consideration of local climate or context. Or energy reduction strategies are considered only later in the process for code-compliance based prescriptive processes, which often fail to capture the potential of local climates. Where passive strategies are applied, designers often face a range of challenges in reliably achieving the desired project outcomes. Although "rules of thumb" (AIA, 2012) and design "best practices" (e.g. the Architecture 2030 *Palette*) are available to guide design decision-making, how best to apply one or more strategies to achieve the optimal balance between daylighting and whole-building energy objectives is often unclear, particularly for sites where adjacent buildings can create complex overshadowing conditions and where building orientation and local climate can lead to non-intuitive solar control requirements.

As growth in the building sector is increasingly occurring in dense urban environments and executed by design teams working remotely who may have limited familiarity with the local climate, the application of conventional rules of thumb, case study precedent, the designer's own intuition or past project experience may be sub-optimal or even counter-productive to achieve performance goals. In addition, the optimization of daylighting with whole-building energy objectives requires consideration of broad set of architectural design parameters. These include building massing (i.e. the overall shape and size of the building), building orientation, and the configuration of fenestration, leading to the need to evaluate a multiplicity of prototype designs, each of which may have complex interactions between parameters. And all of this must be done at a rapid pace to impact design decision-making. In practice, the large number of parameter combinations paired with the complexity of the simulation tools and resources required for conventional modes of evaluation leads to designers facing the need to choose a limited set of options picked using intuition and judgment rather evidence-based feedback. Although one or more choices may lead to a low-energy project outcome, it is unlikely to make optimal use of available environmental services. Adding to the challenge, simulation-based design support is highly