Integrated analysis of building perimeter zones with multi-functional façade systems

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ABSTRACT

Energy efficiency of buildings is a primary topic of interest. It not only leads to energy and cost savings but also reduces carbon emissions and enhances overall sustainability efforts. An equally important topic is indoor environmental quality and comfort. Indoor environmental conditions affects occupant satisfaction, productivity, health and well-being. High performance buildings are able to achieve significant energy savings with simultaneous increased human comfort. Ideal building design and operation strategies should balance energy use and human comfort and satisfaction. This is particularly challenging for perimeter building zones of commercial buildings, which separate the outdoor from the indoor environment. In modern buildings, perimeter zones have glass facades, often accompanied high solar gains, intense daylight, as well as variable systems and controls, significantly affecting the comfort conditions in these zones as well as the overall building energy performance.

This Thesis is focused on dynamic façade solutions for integrated perimeter zone design and operation. The integration of façade systems with lighting and thermal systems can lead to lower energy use for lighting and air-conditioning, and improve comfort conditions through efficient design and coordinated control. Dynamic and complex fenestration systems and light-redirecting devices are able to adjust depending on outdoor and indoor conditions. However, their optical and solar properties are complex, and there are no standards for selecting appropriate products. Moreover, there are no reliable guidelines for controlling dynamic shading systems for efficient solar protection and coordinated indoor environmental control.

A flexible, open-source dynamic integrated daylighting and thermal simulation model was developed, applicable to perimeter spaces with one or several exterior facades equipped with any type of dynamic and complex fenestration systems (dynamic glazing, interior roller shades, venetian blinds, light-shelves, window films and materials with associated BSDF files) and custom controls for each section.

A major milestone was the development of the hybrid ray-tracing radiosity method, which balances computational speed and accuracy when modeling dynamic and complex fenestration systems and related controls, and its integration with visual comfort calculations, to predict the impact of façade solutions on daylight glare. The model can be used for an overall annual evaluation of façade and fenestration dynamic technologies, providing annual metrics in a fast and reliable way.

Innovative shading control methods were developed for maximizing daylight utilization, reducing building energy consumption, and maintaining occupants' visual comfort, both for roller shades and for venetian blinds. These control strategies were implemented in the integrated model, and their efficiency was demonstrated in full-scale test offices at the Purdue Architectural Engineering Laboratories. The offices have reconfigurable façade and lighting systems and allowed extensive testing and comparison of design and control alternatives, which were also used to validate the models.

The developed simulation models and control strategies were then used for (i) efficient investigation of fenestration design and control options on a relative basis and (ii) recommendations for selecting properties and control for dynamic façade systems, considering energy and comfort aspects. Recommendations for selecting roller shade properties were made based on a new systematic

methodology that utilized detailed modeling, new glare metrics, and the new Annual Discomfort Frequency index. The results provide useful insights for selecting shading properties to avoid glare, which is a baseline for design before employing controls. The models developed for venetian blinds were used to quantify and compare the impact of advanced control strategies on daylighting performance and visual comfort. These will lead to efficient model-based controls and integration with other building thermal controls.

Finally, the different parts and findings of this Thesis were combined to investigate the potential of multi-sectional facades as integrated solutions –for providing useful daylight while achieving visual comfort targets. Multi-functional façade concepts with different light-redirecting systems and fenestration controls were evaluated using the integrated model and developed control strategies for each section. The important design factors were identified, and the effects of different design and control options were quantified, allowing recommendations for decision-making guidelines for design of such advanced systems. The work of this Thesis, with the development of flexible and reliable integrated models, opens the way for new research towards developing a systematic approach for integrated design and operation of multi-functional facades, which will be intelligent, adaptive to climatic conditions and occupant preferences, and will be fully integrated with cyberinfrastructure in buildings of the future.