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Integrating illuminance and energy evaluations of cellular automata controlled dynamic shading system using new hourly-based metrics

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ABSTRACT

In cooling-dominant climates, the solar heat gain due to sunlight is inevitable, and should be considered when designing energy-efficient façades. This research explores the potential contribution of utilizing monotonous-free Elementary Cellular Automata patterns as climate-adaptive shading systems, to be applied on buildings' façades in order to mitigate the undesirable impacts by excessive solar penetration in cooling-dominant climates. It also presents a new approach for evaluating the daylighting performance and energy demand for the dynamic shading systems at the early stages of design. Grasshopper is exploited for parametric modeling of Elementary Cellular Automata patterns. The methodological procedure is realized through two main phases. The first evaluates all 256 Elementary Cellular Automata possible rules to elect the ones with random patterns, and to ensure an equitable distribution of the natural daylight in internal spaces. The computational simulations are then conducted in the second phase using DIVA-for-Rhino and Archsim to evaluate the performance of the elected Elementary Cellular Automata patterns that are applied as dynamic shadings. Based on the newly developed hourly-based metrics: Hourly Daylight Illuminance ($HDI_{300/HOY}$), Hourly Sunlight Illuminance ($HSI_{3000/HOY}$), and Hourly Energy Consumption (HEC), the adaptive façade variation configuration could be formalized that maximizes daylighting and minimizes energy demand. The simulation results showed that the adaptive façade outperformed the static shading configurations, and exhibited its ability to obtain adequate level of natural daylighting, while mitigated the undesirable impacts of excessive solar penetration, and maintained a minimized amount of cooling load and artificial lighting energy demands throughout the year. This developed tool can aid architects navigating climate-responsive façade designs in order to promote the indoor environmental quality in cooling-dominant climates, in addition to redefine the evaluation criteria to meet their local building performance requirements, and improve the architectural aesthetics and human health.

1. Introduction

Given the digital nature of design, parametric design is becoming an essential tool that brings pronounced generative approaches to form transformations in architecture, which provide a medium for the structure of design models according to various relationships of the design concept, the design processes, and the design object itself (Oxman, 2006). One of these approaches is the Performative Approach, which supports explorations of building design with regard to its performance using simulations and modeling tools for the modification and optimization of geometrical forms towards a suggested design (Fasoulaki, 2008; Oxman, 2008; Shi and Yang, 2013). In architecture, this approach is often considered as an algorithm-driven process in which building performance becomes the design guiding factor, and can be employed to resolute meaningful variations that could not have been pictured by the designer (Ayoub, 2016). In addition, the adaptation of certain Computational Generative Systems in architecture, such as Cellular Automata, Shape Grammar, and Genetic Algorithms, in compliance with the performative approach contributed in breaking the barriers of design explorations, aiming to even more expanding the versatile design solutions space. However, this approach cannot deliver aspired results of building performance without a proper integration with computational simulation tools (Fathy et al.,2015). While recent advances in these tools, such as DIVA-for-Rhino and Ladybug, allowed for accurate predictions of indoor and outdoor environmental conditions, yet for more complex situations, in hot-desert climate for instance, the investigation of dynamic shadings and other climate-adaptive systems coupled with the calculation of dynamic daylight metrics became a necessity. Therefore, the need has arisen for exploiting computational systems with regard to performance requirements as design generators that would sculpt the external envelop of buildings forms.

This research presents reviews, methodological tools, and measurements aiming to help researchers and designers addressing and

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quantifying the potential contribution of exploiting computational systems applied as dynamic shadings in terms of enhancing natural daylighting and energy consumption for indoor environmental quality. It starts with a general overview of the related studies on the static and dynamic external shading systems, the current daylighting performance metrics, and the adapted computational generative systems. The findings of this review pinpoints the areas of inconsistencies in this subject, and accordingly, presents the aims of this research. Then, the methodological procedure section defines the computational simulation tools, evaluation criteria, and describes the two-phased study that are developed in this research. Lastly, the research discusses the results of the case study that examines both the implementation of computational systems as applied dynamic shadings, and the dynamic measurements of daylighting using newly developed metrics, and concludes the outcomes for future directions in this subject.

1.1. Related studies on static and dynamic shading systems

Windows are key elements in architecture, as they represent the basic source for allowing natural daylight into buildings and providing visual comfort for the occupants (Treado et al., 1984). A properly designed façade can improve daylight autonomy, maximize visual comfort, and reduce energy required for artificial lighting and achieving thermal comfort significantly (Li, 2010; Alzoubi and Zoubi, 2010; Krarti et al., 2005). It is reported that an ideal envelope design could reduce 33% of annual energy demands without consideration for daylighting (Futrell et al., 2015). However, the solar heat gain due to sunlight is inevitable, and should be considered when optimizing energy-efficient façades, especially in cooling-dominant climates such as hot-desert. The use of external shading systems is known for its ability to mitigate the undesirable impacts on the indoor environmental quality by excessive solar penetration, which can be achieved by carefully controlling the amount of sunlight that enters the internal spaces (Gago et al., 2015; Manzan and Padovan, 2015; Wagdy and Fathy, 2015; Wu, 2012). Nevertheless, in hot-desert climates, these criteria could create opposing requirements, as the necessity of decreasing the heat gain may conflict with the need for maintaining adequate level of natural daylight (Nielsen et al., 2011; Xue et al., 2016). Thus, it is clear that generalized principles are hard to be defined due to the diversity of weather conditions, which implies that each situation has to be investigated and evaluated individually on a much smaller time step, rather than on an annually basis (Grobman et al., 2016). This section presents a number of recent researches that studied the subject of static and dynamic shading systems, with the focus on dynamic ones. As there is no standardized procedure to investigate the effects of shading systems, the reviewed researches considered different parameters and criteria regarding climate, shading type, orientation, building function, used methodology, etc.

It is noticeable that the Window-to-Wall Ratio (WWR) is a commonly examined parameter for windows configuration and façades design in many of the reviewed researches (Acosta et al., 2016; Konis et al., 2016; Mangkuto et al., 2016; Shen and Tzempelikos, 2013; Wu, 2012), and they include one or two daylight metrics for façade optimization. Other group of the reviewed researches have focused more on the implementation of different static solutions and techniques regarding light shelves, solar screens, and other external shading systems, and their different configurations to enhance the daylighting conditions in the internal spaces (David et al., 2011; Gonzalez and Fiorito, 2015; Lim et al., 2012; Manzan and Padovan, 2015; Meresi, 2016; Moazzeni and Ghiabaklou, 2016; Sheikh and Gerber, 2011). These researches investigated the influences of various quantifiable performance criteria, such as energy consumption for cooling and lighting, natural daylighting, and glare levels. However, it is disadvantageous to consider such static techniques as a definitive solution to offer an improvement to indoor environmental quality in certain climate zones, such as hot-desert climate, as they do not take into account the weather changes and the resulting fluctuations in natural illuminance intensity levels throughout a year.

On the contrary, dynamic shading systems provide an enhancement to the building performance, especially daylighting, by adjusting their behaviour and configurations in response to the performance requirements and the changing weather conditions (Loonen et al., 2013). This subject has witnessed extensive developments over the last twenty years in the pursuit to deal with complex designs and gain more accurate information and results. Numerous studies put the focus on the investigations of dynamic shading systems impact on improving indoor environmental quality, which can be divided into two lines of trends. The first line of research includes attempts to develop sophisticated performance-driven designs and evaluation techniques that can be directly used by architects during the early stages of design process to achieve improvements in daylighting performance. Nielsen et al. (2011) presented a new quantification tool for dynamic shadings, based on the Daylight Factor metric, as will be described later, and total energy demand. They considered several design performance criteria in their study, such as energy demand, indoor air quality, daylighting available, and visual comfort. The case study was simulated as a single unit in a larger office space building located in a temperate climate zone. The simulations were conducted on façades without shading, with fixed shading, and with dynamic shading, all with regard to various window heights and orientations. Generally, the simulation results showed a significant improve to amount of daylight by 70–150% using dynamic shading compared to other façade configurations. Moreover, the use of this shading system showed 16% reduction in energy demand. However, some differences and conflicting tendencies were revealed when the energy needed for heating, cooling and artificial lighting were considered separately. Grobman et al. (2016) suggested a similar approach to quantify and compare the impact of utilizing static and dynamic louvers as shading systems, during the early design stages. Yet, they proposed a new dynamic evaluation tool, which is considered a variation of the Useful Daylight Illuminance metric, as will be described later. A case study of an office space in the Mediterranean climate was tested, where the simulation results of the static, seasonally adjusted, and dynamic louvers were compared to those without any shading system. The results showed an increase in the amount of daylighting by -1.82% to 7.99%, -1.4% to 11.67% and 10.86% to 33.6% in static, seasonally adjusted and dynamic louvers correspondingly, compared to the no external shading scenario. Xue et al. (2016) conducted another study that adopted the idea of balancing daylighting design with energy demand without compromising the luminous conditions. Dynamic and static daylight metrics were developed and tested to quantify daylighting performance with the data from a questionnaire survey and simulations of 108 cases located in a sub-tropical climate zone. Luminous comfort zone was also proposed and the units with higher value of these two metrics, have a great potential of energy saving and adequate daylighting performance. He et al. (2017) proposed a practical method to immediately evaluate the illuminance performance of a perforated façade that actuates in response to dynamic daylighting conditions, rather than using conventional simulations in the early design stages. The case study is located in humid subtropical climate zone, where a series of parametrically generated façade openings were created and tested. Based on the preliminary results tendency, different performance criteria were chosen to be adjusted for further detailed analysis. The results concluded 29 façade configurations that met the local illuminance requirements, where their perforated arrangements were optimized according to the gradually changing opening sizes and positions. Alternatively, further group of researchers investigated the use of smart glazing for window system, which should provide higher transmittance in visible spectrum and lower transmittance in infrared region (Xue et al., 2016). In some cases, the use of intelligent glazed façade can the energy consumption of a building by 60% (Liu et al., 2015). Electrochromic glazing was proved to reduce of energy consumption and controlling solar gain (Ghoshal and Neogi, 2014). For both daylighting