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Evolutionary energy performance feedback for design: Multidisciplinary design optimization and performance boundaries for design decision support

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ABSTRACT

In pursuit of including energy performance as feedback for architects' early stage design decision making, this research presents the theoretical foundation of a designer oriented multidisciplinary design optimization (MDO) framework titled evolutionary energy performance feedback for design (EEPFD). Through a comprehensive literature review and gap analysis EEPFD is developed into an MDO methodology that provides energy performance as feedback for influencing architects' decision making more fluidly and earlier than other approaches to date. Secondly, in response to the lack of an MDO best practice EEPFD is investigated and evaluated through two experiments. The first experiment demonstrates the ability to utilize EEPFD provided energy performance as feedback to pursue multiple architectural designs with competing objectives and tradeoffs. The second experiment identifies performance boundaries as a best practice for MDO applications to the early stage architectural design processes. The research synthesizes the results into the basis for measuring these performance boundaries as a best practice in the context where architects must gauge multiple design concepts with varying complexity coupled with performance objectives through EEPFD, thereby enhancing the influence of energy performance feedback on the early stage design process. Finally, future research into the use of performance boundaries for conceptual energy performance design exploration is discussed.

1. Introduction

In the current field of architecture the issue of sustainable design and building performance, especially with respect to energy performance, has become increasingly significant to the overall design process. This growing emphasis is primarily attributed to the fact that buildings account for a majority of all consumed energy, nearly one half (48.7%) in the United States [1] and up to 40% of all energy consumption in the European Union [2]. Research indicates that incorporation of energy performance feedback at the early stage of the design process can potentially increase the energy efficiency over a building design's entire lifecycle [3–8]. However, multiple obstacles exist inhibiting seamless and timely inclusion of energy performance feedback during this design phase. This leads to the research pursuit of a "designing-in performance" methodology and "best practice" where architects are able to utilize energy performance as feedback to influence their design exploration and design decision-making synchronously during the early stages of architectural design exploration. Our work is based in part on the simple hypothesis that if the energy performance data, such as first and second cost is available, designers will be influenced to choose and pursue higher performing designs.

Despite the acknowledged beneficial impact of considering energy performance early in design [9], obstacles between design and energy simulation domains often prevent the inclusion of energy performance during the early stage design process [10–12]. Multiple efforts have been made to resolve these issues, including research into improved interoperability, platform integrations, design automation, and multi-objective optimization techniques. Among these efforts, multidisciplinary design optimization (MDO), which combines multi-objective optimization (MOO) algorithms with parametric design, demonstrates a great potential as an initial design exploration methodology that is capable of providing rapid visual and analytical feedback for early stage design decision-making. However, the application of MDO during the early stage of the design process to support designers' decision making has not been adequately explored. Consequently, whether the provided energy performance feedback from an MDO can actually support

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architectural design decision making is still a key research question. Furthermore, due to the unique nature and extensive uncertainty of the early stage architectural design process, arguably distinct from other industries utilizing MDO, a best practice of MDO application for building design is needed to be defined and explored.

This research hypothesizes that by providing architectural designers with a designer-oriented MDO framework, enabling rapid access to improved energy performance feedback with visualized and quantified trade off analysis, will allow energy performance feedback to influence early stage design decision-making. Consequently, higher performing design can be more efficiently realized while pursuing the complex set of coupled and independent design goals. For these reasons, a design and energy centric MDO framework, evolutionary energy performance feedback for design (EEPFD), is first introduced and manifested through a prototype tool developed to fulfill the unique needs of the early stage architectural design process, where diversity in ideation, geometry, and programming are needed [13]. In addition, the framework provides improved results through genetic algorithm based optimization irrespective of the exploration stopping point, which is typically determined by the dominant limiting factor of time in early stage design exploration [14]. This paper continues to use the developed framework, EEPFD, to addresses two critical gaps found in precedent and literature research. The first is the lack of evidence that supports the effectiveness of using MDO for providing energy performance as feedback for influencing architectural designers' decision making. The second gap is that, due to the idiosyncratic nature of architectural design problems, a best practice for applying MDO to the early stage of the architectural design process is needed but has yet to be adequately explored and validated. In response this paper addresses these gaps through the following two objectives: (1) to observe whether the provided energy performance feedback from EEPFD influences designers' design decision making; and (2) to observe the use of performance boundaries to gauge competing design concepts. A performance boundary is hypothesized as advantageous as it is found automatically within the solution space being generated by EEPFD more rapidly than the mathematical convergence of a single design concept, as is the current norm. Therefore, this paper first provides a literature review identifying gaps in current efforts for bridging design and energy simulation domains followed by current applications and gaps related to energy performance optimization. Second, EEPFD is introduced and explained in brief. Thirdly, the experiment to observe the influence of the provided energy performance feedback from EEPFD on the designers' decision making is outlined along with the experiment to support the development of a best practice for using performance boundaries to gauge design concepts more rapidly while maintaining early stage ideation and design diversity. Finally, the research findings from these two experiments in the context of the literature, limitations and future work are concluded and discussed.

2. Bridging architectural design and energy simulation

It has been widely recognized that incorporating building performance feedback to support design decision making can improve the building performance throughout the building lifecycle when such goals are set as a priority [3–8]. However, due to an array of challenges the obstacles between design and energy performance still remain [4,15–21]. Extensive prior research provides an exhaustive comparison analysis of the variety of energy simulation tools available along with their pros and cons [10,22–26]. Separately, additional reviews have focused on the specific needs of architectural designers looking to utilize energy simulation tools [8,16,27–29]. However, an overall holistic approach to bridge the gap between the design and energy simulation domains is still undefined. In order to provide a different lens and isolate a potential holistic approach to bridging the gap, this research reviews and synthesizes current efforts from a design process standpoint and groups the current obstacles and potential solutions into three major categories for discussion: (1) tools and tool interoperability; (2) domain knowledge integration; and (3) design decision systems support.

2.1. Tools and tool interoperability

Previous researchers reveal that currently available energy simulation tools are not considered to be "architect-friendly" for use by designers during the early phases of design [16,27–29]. More specifically, only 10% of the tools available are intended for architects' use and only 1% of these are able to support the early design stage [30]. In addition to the limited tool availability, seamless integration between software programs is typically lacking. Thus, the necessary data transfer between tools leads to the loss of information and knowledge capture, incurring inefficient manual modification of models between design and energy simulation tools [20,21]. While some of these issues can be resolved by a standardized data exchange format such as IFC or gbXML, translating the solid building element geometry into space boundaries for energy simulations, these formats are presently still limited in supporting complex geometrical exploration, a critical requirement for assisting contemporary architectural design [31–33]. Consequently, despite the resolution of the data translation issues, these tools are ill suited for architectural designers' use during the early stage design process [16,27,34,35].

Others attempt to improve the user interface to expand the usability of the tools or facilitate greater data translation among different platforms. The majority of these efforts have focused on addressing the critical obstacle of interoperability across different software platforms, applications, or user groups, including software developers, researchers, and variable members of the building industry. These aforementioned efforts have explored scripting interfaces and self-developed plugins attempting to solve existing interoperability issues between the design and performance analysis domains. While solutions to tools and tool interoperability would ease the process in the generation and evaluation of design alternatives, this effort is arguably insufficient [36]. The information transferred from a design tool to an energy analysis tool is still a one-way trip. In other words, there is no way of implementing the knowledge gained or the changes identified to the design performed in the energy simulation tool, except through manually re-entering the information.

2.2. Domain knowledge integration

In addition to the limited number and availability of designer-oriented energy simulation tools, design professionals are often unfamiliar with energy simulation tools as the functionalities are often outside of their expertise [27,31,33]. This is reported as one of the major reasons preventing architects from using energy simulation tools [34]. As a result, environmental simulation software is routinely operated by domain experts who are familiar with the specialized nature of these tools [37]. Consequently, domain expert engineers regularly conduct energy simulations and their work is typically used for performance validation post priori or later in the design development phase rather than to support earlier design decision making [26,38]. In addition, designers are faced with challenges in interpreting the results and successfully incorporating the feedback into their design process [21].

Another stream of research has focused on the knowledge exchange between different expertise domains. Examples of these