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Designing-in performance: A framework for evolutionary energy performance feedback in early stage design

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ABSTRACT

Multidisciplinary design optimization (MDO) has been identified as a potential means for integrating design and energy performance domains but has not been fully explored for the specific demands of early stage architectural design. In response a design framework, titled Evolutionary Energy Performance Feedback for Design (EEPFD), is developed to support early stage design decision-making by providing rapid iteration with performance feedback through parameterization, automation, and multi-objective optimization. This paper details the development and initial validation of EEPFD through two identified needs of early stage design: 1) the ability to accommodate formal variety and varying degrees of geometric complexity; and 2) the ability to provide improved performance feedback for multiple objective functions. Through experimental cases the research presents effective application of EEPFD for architectural design.

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1. Introduction

A widely accepted idea that the availability of simulated performance feedback will lead to improved performance in design in conjunction with the idea that automation and integration of performance analysis into early stage design will also contribute to higher performing designs has led to the authors pursuing the concept of "designing-in performance." Our concept is part of the performance based design body of research and is different only in that "designing-in performance" is defined in this paper as a method for providing performance feedback to influence design exploration and subsequent decision making that is not intrinsically available in a conventional design process, especially in the early stages. The framework is based on the finding that currently there is limited direct and validated feedback between the domains of design and energy simulation and optimization available during the early stages of the design process where it has been acknowledged that such decision making has the highest potential impact on the overall building performance [1]. "Designing-in performance" is therefore conceived of as a performance based design environment where a designer's state of mind can automatically be influenced by performance based design feedback within a designer's common parametric workflow.

The use of multidisciplinary design optimization (MDO) to provide the desired performance feedback for design decision making has demonstrated a potentially effective means to overcome the limitations of current performance-based design processes. MDO provides the opportunity for design automation to bring performance analysis to the early stages of design by providing an expanded set of design alternatives that can be easily generated, assessed, and ranked according to multiple performance criteria to generate a visualized and simultaneously quantified trade-off analysis. Motivating the research is the gap in current MDO attempts to fully explore the applicability of this approach to early stage architectural design. The scope of this research is to evaluate the suitability of applying MDO to early stage design in this context for the purpose of assisting design decision making. Therefore, an MDO design framework entitled Evolutionary Energy Performance Feedback for Design (EEPFD) is established for designer use during the conceptual stages of design where geometry and massing have not been finalized. The objectives of this paper are to first detail the development of EEPFD, the constituent integrations and steps, and the implementation of a customized Genetic Algorithm (GA) based multi-objective optimization (MOO). The overall goal of EEPFD is to provide designers with more immediate and easily accessible performance feedback within their early stage design exploration process. However, prior to the exploration of EEPFD's usability by designers, the framework must first be validated against two identified prerequisite criteria. The two critical criteria for evaluation of the framework's applicability are 1) the ability to provide a solution space with an improved performance, across the multiple competing objective functions defined in Section 3, and 2) the ability to be adaptable to a wide spectrum of design scenarios, both in typology and geometric complexity. To be considered successful both of these criteria need to be met in a timely manner,

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thereby reducing design cycle latency and improving upon aspects of design uncertainty. The focus of this paper is twofold: first on describing the development of EEPFD, and second on EEPFD's ability to successfully meet the aforementioned prerequisites. Furthermore the success of our work will be to see an intrinsic integration of energy simulation within the dynamic and differentiated concept design processes for architects. Some benchmark studies focusing on the process validation through both manual and automated exploration processes using EEPFD have been researched and described [2]. These process studies are a follow-on from this work and a precedent for future work on development of best practices.

2. Background and literature review

With the advancement of computational tools for building design, performance is claiming a more prominent role as a driving force in design decision making [3]. However, design professionals are often unable to adequately explore design alternatives and their impact on energy consumption upfront due to an array of challenges between design and energy performance domains. While several efforts were made to isolate these challenges, time constraints and interoperability issues between software and expert domains have been identified as two major contributing factors [4–10]. Consequently, in part, performance assessments are typically made after the initial design phase, where the analysis is performed on a very limited set of design alternatives rather than to support early stage design decisions where a broader range of possibly more optimal solutions may exist [11]. In addition, previous research has suggested that trade-off studies are necessary in order to provide adequate feedback for design decision making [11,12]. This is consistent with the widely accepted view that design is typically understood as an ill-defined problem [13], involving competing objectives for design professionals to design, explore and synthesize. However, these studies can become time intensive and complicated; requiring input from multiple disciplines in order to provide relevant feedback, and as such are often minimized by necessity and marginalized as a result. In order to overcome these obstacles, several researchers have made efforts to isolate tool and process requirements that can facilitate the “designing-in performance” environment [6,7,9,14]. To summarize their efforts, a design framework and tool not only require a user friendly environment, but also have the ability to provide 1) rapid generation of design alternatives; 2) rapid evaluation of design alternatives; 3) trade-off analysis for competing criteria; and 4) a search method to identify design alternatives with better fit performance.

When facing the challenges of integrating design with energy simulation and performance analysis, efforts can be encapsulated into two groups. One focus has been on the interoperability issue among software and different domain expertise. Examples of these efforts can be found in data model and process standardization [15–17] along with collaborative framework development [18–22]. While solutions to interoperability would ease in the generation and evaluation of design alternatives, it is arguably insufficient [23] and cannot fulfill all the identified requirements for “designing-in performance” in early stage conceptual design. This leads to a second research focus on providing an intelligent search method which incorporates rapid evaluation and trade-off analysis to further support design decision making during the early conceptual stages. This second category of research has two thrusts: sensitivity analysis [24–26] and the development of optimization techniques [10,27–34] as intelligent searching methods that support trade-off analyses for identifying “best fits” across competing objectives. In this case sensitivity analysis is used as a means to decrease uncertainties of often changing and complexly coupled and de-coupled variables during the design process. However, design objectives are often non-commensurable with their relative importance and difficult to evaluate before post sensitivity analysis [12]. In addition, even with sensitivity analysis in place, a method that can quickly identify higher performing design is still needed. Therefore, considering that time is still a dominant factor in dictating stopping points during the early design stage, and while both research thrusts present promising potential in supporting decision making, this research questions the feasibility of sensitivity analysis alone as a primary approach to drive the generation of an early design solution space. As a result, a multi-objective optimization and search inclusive of sensitivity analysis approach is chosen as the foundation and focus of this research.

The utilization of parametric modeling coupled with optimization techniques has drawn attention as a potential solution to provide an *intelligent searching method* for efficient feedback. This method is usually referred to as multidisciplinary design optimization (MDO) in the aerospace and automobile industries [35]. In this research, MDO is referred to as a general term of the approach that couples parameterization and optimization techniques to solve multi-objective problems. While MDO has been demonstrated as an effective means for integrating multiple expert domains along with impacting decisions made during the product design process [36], it has also demonstrated potential when applied to the Architecture, Engineering and Construction (AEC) industry. However, the majority of MDO applications to aspects of building design and energy performance have been limited to mechanical system design [37–40], glazing and façade designs [10,38,41–43], retrofitting strategies [44], or studies on the effectiveness of optimization algorithms [29,45]. Where research has shown interest into the relationship between design form and energy performance, overly simplified geometry is often employed as a means of proof of concept [29,30,34]. Significant to our approach and the context of these design stage limitations where form exploration with energy performance feedback is considered an essential need for “designing-in performance” during the early stage of the design process, the potential value of MDO to facilitate the process has as of yet been fully explored.

A critical distinction of this research is the focus on the application of MDO by the architectural design field whereas previous researches have been primarily through the fields of building science or engineering [46]. Other recent representative efforts focused on designers' utilizing parametric design and optimization techniques in energy simulation include: Janssen's EPPD [29], Caldas' GENE_ARCH [28] along with the collaborative works of Yi and Malkawi [31,32]. Janssen's EPPD utilizes an asynchronous decentralized evolutionary approach to accelerate the feedback process with the aim of making it easier for designers to use evolutionary algorithms. However, the lack in flexibility for designers to formulate their design problem and the lack in the amount of time required in generating feedback are reported as the remaining challenges for EPPD [29]. A user interface for non-programmers has been developed to facilitate the process but there are currently no usability studies presented outside of the EPPD research team [47]. In parallel, Caldas' GENE_ARCH [28] is a GA based multi-objective optimization (MOO) design exploration tool which incorporates energy and daylighting performance as objective functions. Currently, it has been applied to examine façade configurations and shape generations. While the stated purpose of GENE_ARCH is to assist architects in pursuing more sustainable design, Caldas asserts that, “when a design is generated and evaluated by GENE_ ARCH, it is a whole building entity that is being assessed, not an initial design concept or an abstract geometrical shape [28].” As a result, the application of GENE_ARCH to assist design exploration during the early design stage, where concept and form evaluation is needed, has not been adequately resolved. In order to extend the design problems that can be explored through GENE_ARCH, it is further integrated with a shape grammar to act as GENE_ARCH's shape generation module [48]. However, the usability and flexibility of GENE_ARCH outside of the research team have been neither explored nor evaluated. In addition, during Caldas' research, it was found that reductions in overall energy consumption were observed in direct relation to the overall building size, which unfortunately led to optimal designs only being identified as those minimizing space within the allowable design constraints [49,50]. As such, it can be argued that reliance on design constraints

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