Evolutionary Energy Performance Feedback for Design (EEPFD)

Interaction and automation for a design exploration process framework

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Abstract. *In order to understand the applicability of multidisciplinary design optimization (MDO) to the building design process, a MDO framework, titled Evolutionary Energy Performance Feedback for Design (EEPFD), along with the prototype tool, H.D.S. Beagle, were developed to support designers with the incorporation of partially automated performance feedback during the early stages of design. This paper presents 2 experimental case studies, one from the design profession and the other from a design studio, that evaluate the applicability and impact of EEPFD on the early stage design process. Through these two case studies two different interaction and automation approaches for applying EEPFD are explored as part of the framework validation. Observed benefits, challenges and suggestions of EEPFD's implementation are then presented and discussed.*
Keywords. *Conceptual energy performance feedback; design decision support; performance-based design; multidisciplinary design optimization; genetic algorithm.*

INTRODUCTION AND MOTIVATIONS

In the interest of promoting sustainable design, energy consumption has become increasingly significant to the overall design process for architecture and building engineering. However, there is currently little direct or validated feedback between the domains of energy simulation and the early stages of the design process where such decision making has the greatest impact on the overall design's performance and lifecycle. Acknowledged obstacles include: disconnection between and the lacking of domain knowledge, tool interoperability, intensive analysis time requirements, design cycle latency amongst a diverse set of design expertise, and limitations of design cognition and complexity as previously researched in numerous precedents (Augenbroe, 2002; Oxman, 2008; Attia et al., 2012). Consequently, performance assessments are typically made after the initial design has been finalized with a limited set of explored design alternatives, as opposed to earlier design stages where a broader range of potentially more optimal solutions may exist (Radford and Gero, 1980). In addition, designers must balance the needs of multiple competing objectives, often through inefficient and imprecise means, to identify the best fit design through an understanding of trade-offs between energy performance and other design objectives.

The motivation of this research stems from the potential of multidisciplinary design optimization (MDO) methods to alleviate issues between the design and energy simulation domains. MDO is a general term used in reference to the method of coupling parametric design and optimization algorithms in an automated or semi-automated design process framework or workflow with the intent of identifying "best fit" solutions to complex problems with competing criteria. MDO methodologies have been successfully adopted in the aerospace industry and other engineering fields and have been gradually explored in the building industry as a means of potentially mitigating existing issues between building design and other performance analysis domains. Current research into applied MDO has initially demonstrated a capability to overcome interoperability issues between domain specific platforms. Optimization algorithms automated by MDO have also been identified as being capable of increasing feedback results and designer interaction. By virtue of the automation and optimization more efficient access to performance evaluations of design alternatives inclusive of trade-off studies between competing design criteria in support of design decision-making is also indentified (Flager et al., 2009; Yang and Bouchlaghem, 2010). Given the trend of computing availability, e.g. cloud computing our research into MDO is becoming more obviously suitable to the particularities of the architectural practice. We hypothesize this computing trend results in an exponentially expanding potential of MDO applicability. When observed in the context of this expanded computing capability, the plausible bridging of the observed gap between energy performance and design through MDO serves as another driving force behind this research. MDO is therefore understood as a key component to achieving the research motivation of "designing-in performance" which is defined in this research as the idea of utilizing performance feedback to influence design exploration and subsequent decision making under the assumption of pursuing higher performing designs much earlier in the design process and arguably intrinsically coupled, not the norm in contemporary practice.

PROBLEM STATEMENT AND RESEARCH OBJECTIVE

While current precedents in the building design industry demonstrate the potential of MDO as a means of solving performance feedback issues, there are several inherent and unique challenges for MDO to be more robustly and pervasively applied in architectural practice. For example, when MDO is applied to the aerospace industry an identified "best fit" solution can be mass-produced once it has been fully optimized. In comparison, to apply MDO to find a best fit for building design problem always with a unique set of requirements, circumstances, and preferences appears less cost effective by nature. In addition, the objective nature of evaluating design in other engineering industries provides more suitability towards MDO application than the more subjective nature of building design, where architecture is inclusive of aesthetic motivations as well. Furthermore, a deep rooted disconnection between design and energy simulation domains, enumerated previously adds to the factors impeding the application of MDO to be fully explored and implemented within the design and energy simulation domains. Another of our research observations is that the majority of the MDO applications in architecture related to building energy performance are conducted by researchers predominantly engineering based with a focus on optimizing mechanical systems or façade configurations, typically much later in the design process after the building envelope has been finalized (Wright et al., 2002; Adamski, 2007). The importance of form exploration during the early stages of the design process is to date seldom addressed and typically through overly simplified geometry for proof of concepts observed to be due to the limited flexibility of existing frameworks (Tuhus-Dubrow and Krarti, 2010; Janssen et al., 2011). Furthermore, there is only a limited number of published MDO frameworks for building energy performance that have been fashioned and explored through a designer's perspective (Caldas, 2008; Yi and Malkawi, 2009; Janssen et al., 2011). Yet, within these applications, emphasis on the applicability and designer interaction of MDO frameworks for the early stage design process have not been adequately researched.

In response to this existing gap –emphasizing the early stage of design and design exploration stages- and the potential of technological affordances and trends, a design centric MDO framework, titled Evolutionary Energy Performance Feedback for Design (EEPFD) was developed and has been initially tested and benchmarked against conventional design processes to understand applicability to the early stage of design (Gerber et al., 2012). The objective of this research step presents a focus on the issue of designer interaction within EEPFD through observation of two case studies: 1) a practice based case study involving a K-12 facility; and 2) a design studio based case study involving a single family residence. To provide a consistent point of comparison a series of measurements regarding design alternative performance, process efficiency, as well as designers' interaction and communication with EEPFD are established, collected, then discussed. Through a comparative study of these two processes adopted by these designers, the applicability and impact of EEPFD during the early stage of the design process is then presented.

THE FRAMEWORK: EVOLUTIONARY ENERGY PERFORMANCE FEEDBACK FOR DESIGN

Evolutionary Energy Performance Feedback for Design (EEPFD), a design centric MDO framework, is developed to incorporate conceptual energy analysis and design exploration of simple to complex geometry for the purpose of providing early stage design performance feedback (Gerber et al., 2012). It is intended to be used by designers during the conceptual design stage where overall building form has not been finalized. EEPFD utilizes an automated evolutionary searching method and a custom genetic algorithm (GA) based multi-objective optimization (MOO) algorithms, to provide energy performance feedback (i.e. energy use intensity (EUI)) to assist in design decision making. Also included are spatial programming compliance (SPC) and a schematic net present value (NPV) calculations for consideration in performance trade-off studies. The automation engine of EEPFD was developed as a prototype plug-in for Autodesk® Revit® (Revit), titled H.D.S. Beagle, to integrate design, energy, and financial domains. The integrated platforms are Revit, Autodesk® Green Building Studio® (GBS) and Microsoft® Excel® (Excel) respectively. The three competing objectives in the algorithm are to maximize spatial programming compliance (SPC), minimize energy use intensity (EUI), and maximize net present value (NPV). The detailed functionality of each platform, objective functions, and GA-encoding method can be found in previously published work (Gerber et al., 2012).

The process of applying EEPFD to obtain performance feedback for design decisions is illustrated in Figure 1. The first step has two subcategories: the generation of the initial design and the generation of design alternatives. In EEPFD, the initial design is generated by the user through a parametric model in Revit and a constraints and parameter range file in Excel. At this point the initial geometry, parameters and ranges, site information, program requirements, and available financial information are provided manually by the user. As a result, in order for designers to use EEPFD, it is essential for them to have the ability to formulate their design problems in the form of a parametric model in Revit with their exploration interests translated into a series of parameters and ranges. An understanding of and capability with parametric practices, solution space thinking, and design exploration is an essential prerequisite in the implementation of EEPFD (Gerber, 2007). The generation of design alternatives is part of the automated process driven by the customized

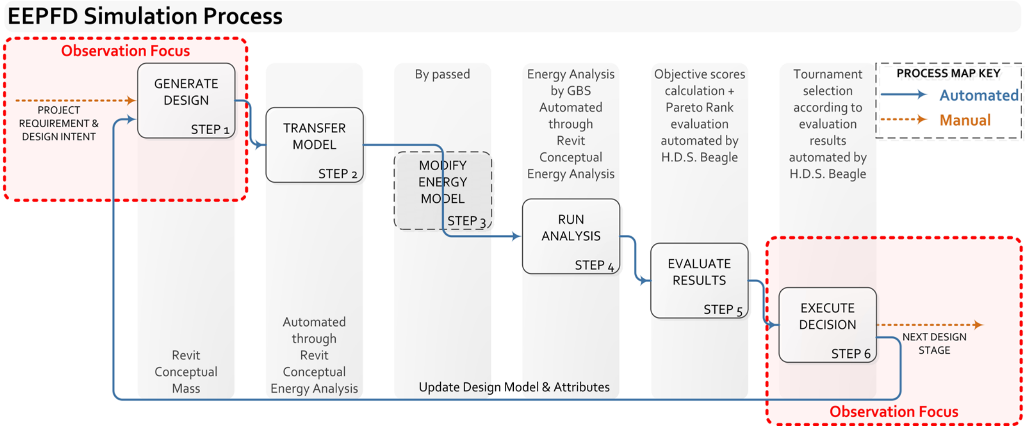


Figure 1
EEPFD's illustrated simulation process in accordance to the identified six step conventional energy simulation process. Highlights are the observation foci of this paper, emphasizing the interfaces inclusive of the interaction between designers and EEPFD.

GA-based MOO in EEPFD. Once the initial design is modeled and entered into the automated system, the following steps are then cycled through until the automation loop is terminated either by the user or by the meeting of the system's termination criteria. Once the automation loop is terminated, there are two ways of proceeding: 1) a design alternative is selected based on the multi-objective trade off analysis provided by EEPFD and the design proceeds to the next stage of development or; 2) the user manually implements changes in the initial design or constraints file based on the provided feedback before reengaging the automation loop. A detailed description of each step and the process of applying EEPFD implemented by users can be found in previously published work (Gerber and Lin, 2013). Currently, EEPFD has demonstrated the ability to automatically breed, select, evaluate and identify better fit design alternatives for varying degrees of building typologies and geometric complexity. EEPFD has also been validated against the human decision making process and is able to provide a solution space with an improved performance over a manual exploration process (Gerber and Lin, 2013). This paper further validates EEPFD with a focus on understanding the usability of the framework by designers, which is described and measured through their interaction with EEPFD prior to and after the automation system has been engaged, as highlighted in Figure 1.

RESEARCH METHODS AND EXPERIMENT DESCRIPTIONS

To explore the applicability of EEPFD to the design process this research provides an environment in which the interaction between designers and EEPFD during the early stages of design is observed. This research presents two case studies observed in this manner; Case Study I as a practiced based study involving a K-12 school design, Case Study II as a design studio based study involving a single-family residential design. In both cases the general program layout and overall building envelope design concept has be decided upon, as illustrated in Figure 2.

Through these case studies, two methods of implementing EEPFD were explored with a divergence occurring during the two steps of EEPFD that require human interaction. While both case studies followed the previously described six step process, Case Study I requires a consultant to provide technical expertise while Case Study II requires only minor technical support. In both cases the authors served as the technical process experts, thereby bypassing any technical complications encountered through the prototype's use, and were available throughout the process to provide necessary technical support

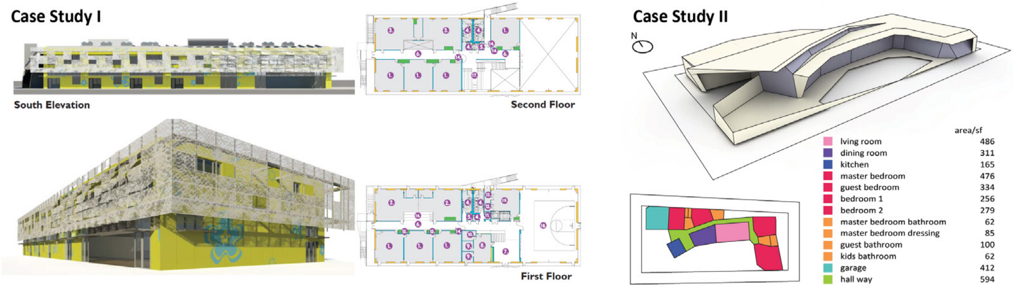


Figure 2
Case Study I and Case Study II conceptual design development before initial engagement of EEPFD. Image courtesy of Xinyue Ma (Case II) and Swift Lee Office (Case I).

and to enable direct observation of EEPFD on the early stages of this design process and design team.

The specific focus of our research observation is the interaction between the designer and EEPFD in the initial problem formulation and utilization of generated data, steps 1 and 6 as shown in Figure 1. During this study three aspects of performance are considered and discussed. The first performance definition is that of the generated design alternatives as measured through the set of three objective functions when compared with the initial design. This represents the affordance of the current technology and the built in evolutionary search method of EEPFD. The second performance definition is overall quantity and quality of feedback generated through EEPFD. In this research the qualitative and quantitative analysis data regarding the design problem, process, and product was collected and compiled into the metrics defined in Table 1, which summarizes the recorded data during the explora-

Table 1
Utilized evaluation metrics, categories, recorded data and units of measure in this research step.

	Recorded Data	Data Type
Design Problem Measurement		
Project Complexity	1. Project type	descriptive
	2. Project size	sqft
	3. Space type number	number
Design Complexity	1. Energy model surface count	number
	2. Explored parameter numbers	number/ descriptive
Design Process Measurement		
Speed	1. Time spent to create design geometry	minutes
	2. Performance feedback time per result	minutes
	3. GA settings	
Design Product Measurement		
Feedback method	1. Feedback number per 8 hours	numbers
	2. Solution space quantity - feedback design alternative number	descriptive
	3. Solution space quality - solution space range in NPV, EUI and SPC. Pareto solution number	
Actor		
Actor	1. Main actors role	descriptive
Experience	1. Parametric model experience	descriptive
	2. Energy simulation domain experience	descriptive

tion processes. Overall, quantity is defined as the number of design alternatives analyzed and time required for each analysis, while overall quality is defined by the number of Pareto solutions generated by EEPFD. The final performance metric is that of the observed design process itself when compared and contrasted with the six step simulation format of the experimental design scenarios. Particular emphasis is placed on the observed interaction between the designers and EEPFD and their ability to 1) identify and translate their design objectives and intentions into a functional parametric model for the system, and 2) the perceived relevance of the overall results by the designers to assist in their early stage decision-making.

DESIGN PROCESSES AND RESULTS

Case Study I: Practice Based Project

Case Study I focuses on a K-12 school design with approximately 30,000 square feet of usable program space using a method allowing for easy adaptability to multiple sites throughout the greater Los Angeles area. Due to flexibility requirements by the client, a kit-of-parts design concept was developed to allow for multiple site adaptability and to allow for future reconfiguration for various educational uses. In addition the pursuit of a net Zero Energy Building configuration for each site was added to the design goals by the designers.

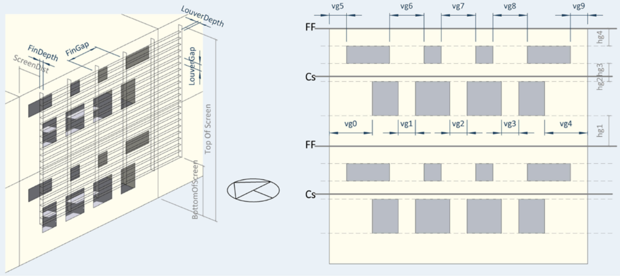
For Case Study I, the designer role was filled by the two principal architects whose design philosophy of doing "the most with the least" focuses on economical and sustainable qualities as prerequisites to design. While the designers for Case Study I demonstrated an interest in utilizing innovative technology and methods, neither designer had any experience with parametric modeling or the Revit platform prior to this case study. Prior to this case study, however, the designers did have experience with attempts to integrating performance feedback as part of the design process with both in-house performance analysis and collaboration with an outside MEP consultant. While energy performance feedback was made available through the prior two approaches, the ability of these approaches to provide relevant information at the speed necessary for supporting the designers' rapid determination of optimal configurations for different site conditions was still in question. As a result, the implementation of EEPFD was explored and researched by the designers and research team to understand whether EEPFD could provide a suitable alternative approach.

In Case Study I the design problem itself was limited to optimizing one standard classroom unit using the defined kit-of-parts through manipulation of varying façade elements. As parametric design had not been a part of the designers' practice prior to this experiment, the authors served as consultants to assist in the translation of the design into a parametric model. Due to unfamiliarity with parametric modeling, the Revit design platform, and the inherent limitations of both, a week and four iterations were needed before the parametric model could be finalized. The parameters explored for façade configurations included customized opening sizes, solar screen depth, density, and mounting distance from the building, as illustrated in Figure 3. Following the completion of the parametric model, necessary supplemental information regarding financial estimates, material properties, etc. was compiled by the authors. In order to closely emulate the future implementation process, the financial model of this experiment was calibrated according to the cost estimation of the project. Also the material assignment and HVAC assignment were based on prior guidelines provided by the MEP consultant.

Figure 3 illustrates the collected data and resultant solution space in a quantified format. Through the GA run by EEPFD a total of 384 design alternatives were generated over a period of 4 hours with an average speed of less than a minute per result. The solution space improved from the initial EUI = 70.08 to 69.30 kBtu/sqft/yr and NPV from -0.51 to -0.48 million dollars. Since the program explored was fixed in value, the SPC score remained consistent throughout the generated solution pool. After

Figure 3
(Top Left) parametric model of Case Study I. (Top Right) parametric model of Case Study II. (Bottom) the collected quantitative measurements of Case Studies I + II according to the established metric.

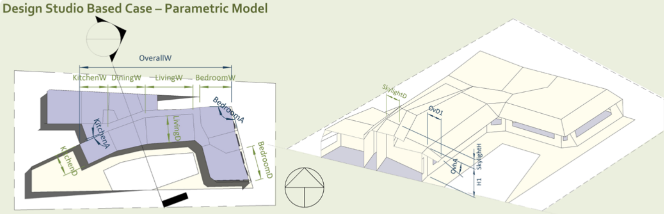
Practice Based Case – Parametric Model



Driving = 14

Name	Type/Unit	Range
vg0	Length/ft	[0.1, 5.9]
vg1	Length/ft	[0.1, 5.9]
vg2	Length/ft	[0.1, 5.9]
vg3	Length/ft	[0.1, 5.9]
vg4	Length/ft	[0.1, 5.9]
vg5	Length/ft	[0.1, 5.9]
vg6	Length/ft	[0.1, 5.9]
vg7	Length/ft	[0.1, 5.9]
vg8	Length/ft	[0.1, 5.9]
vg9	Length/ft	[0.1, 5.9]
FinGap	Length/ft	[0.25, 6]
FinDepth	Length/ft	[0.25, 2]
LouverGap	Length/ft	[0.25, 3]
LouverDepth	Length/ft	[0.25, 1]

Design Studio Based Case – Parametric Model



Driving = 9

Name	Type/Unit	Range
OverallWidth	Length/ft	[70,110]
DepthRatio	Number	[0.3,0.84]
KitchenAngle	Angle/°	[-15,20]
BedroomAngel	Angle/°	[90,120]
H1	Length/ft	[8,15]
SkylightHeight	Length/ft	[0.1,8]
SkylightRatio	Number	[0.1,0.99]
ovhA	Angle/°	[0,45]
ovhD1	Length/ft	[0.1,10]

		Design Problem Measures				Design Process Measures			Design Product Measures		
	Main Actors	Project type & size	Initial energy model surface no.	Space type no.	Explore parameter no. (design/energy)	Time to formulate design	Feedback time per result	GA settings	Feedback no. per 8 hours	Total solution space quantity	Solution space quality
Practice Based Case Study	**Designer** Design Intent: + **Consultant** Parametric modeling + Run H.D.S. Beagle	one classroom of a K-12 School 1,885 sqft	156	1	14 / 0	Approx. 2 week	0.63 min.	Initial population no.= 24 Population no. =24 Selection size = 12 Max. gen. no. = 16 Crossover ratio = 0.7 Mutation ratio = 0.01	762	384 Approx. 4 hrs.	Initial NPV = -0.51 million \$ Initial EUI = 70 kBtu/sqft/yer Initial SPC = 100 NPV = -0.56~-0.24 million \$ EUI = 69~72 kBtu/sqft/yer SPC = 100 Pareto solution no. = 46
Design Studio Based Study	**Designer** Design intent + Parametric modeling + Run H.D.S. Beagle	Single Family 3,000 sqft	197	7	9 / 1	Approx. 2.5 months	0.91 min.	Initial population no.= 10 Population no. =20 Selection size = 20 Max. gen. no. = 50 Crossover ratio = 0.6 Mutation ratio = 0	527	1,010 Approx. 17.8 hrs.	Initial NPV = -2.92 million \$ Initial EUI = 59 kBtu/sqft/yer Initial SPC = 92 NPV = -5.47~-1.86 million \$ EUI = 44~89 kBtu/sqft/yer SPC = 44~99 Pareto solution no. = 227

the completion of the runs, the authors provided to the designers the final trade-off analysis along with 3D design visualizations for their final decision making purposes. After the generated data had been provided more guidance was requested from the designers to discern desirable results from the abundantly populated solution pool provided by the Beagle. However, the designers indicated a positive response to inclusion of 3D imaging of all the design alternatives along with the energy performance feedback, which was not available through their prior experience with either in-house analysis or through the MEP consultant. As a result, the designers were able to include aesthetic preference as part of their trade-off analysis when examining the generated results.

Case Study II: Design Studio Based Project

In Case Study II an architectural design student was provided a single family residential design problem located along Wonderland Park Avenue in Los Angeles, CA. The program requirements for the single family residences are designated as including: 4 bedrooms, 3 full bathrooms, 2 car garage, and living, dining, and kitchen areas not to exceed a total of 3,000 sqft. All room areas are subject to designer preference, with a maximum being placed on bedroom dimensions as not to exceed 20'x20'. A 10' set back from all site boundaries is also specified. The overall design goals are defined to include a meeting all design requirements combined with consideration for a maximum decrease in energy consumption. The designer for Case Study II is a master architectural candidate with 6 months instructional experience in use of Revit but no prior experience of actual application of Revit to a design project or parametric design in general. The designer's prior environmental design experience is limited to the building physics context within the typical architectural education curriculum with no environmental simulation tool use experience or as part of the design requirements typical to her studio design briefs.

For Case Study II the EEPFD development and research team acts as both owner and consultant, providing all necessary project requirements and technical support as needed. After the determination of her design intent to explore shading, opening and each space's spatial compositions through the parametric model, the designer then proceeded to define the parametric model in Revit according to the proposed parameterization logic and initial design concept. The final parametric model is illustrated in Figure 3 and was generated over the course of 2.5 months. This recorded time includes the designer's required time to familiarize herself with the use of Revit for conceptual design through a trial and error period. As one of the goals of this case study is to observe the ability of a designer to translate their intended design concepts into a parametrically oriented mathematically defined form, the designer was asked to avoid any geometric simplifications from their original design geometry for the purposes of expediency. As such the complications of the original design geometry and the designer's unfamiliarity with parametric design and use of Revit in application to parametric design can be considered as contributing factors to the extended experienced parameterization process. Another contributing factor can be identified in the trial and error period necessary to define the design's constraint file so as to maintain both design intent and model robustness during the optimization process as the current version of H.D.S. Beagle will terminate if the geometry breaks.

Figure 3 illustrates the collected data and resultant solution space in a quantified format for Case study II. A total of 1,010 design alternatives were generated over the course of 17.8 hours. After all data had been generated, the designer did not limit their analysis to the design alternatives receiving the highest ranking from the provided data set. Instead, the designer proceeded with their own design decision making strategy, taking into consideration the context of the generated solution pool. Overall the generated solution pool through EEPFD provided an improvement in EUI from 59 to 44 kBtu/sqft/yr , in NPV from -2.92 to -1.86 million dollars, and in SPC from 92 to 99. From the full data set the designer first narrowed the solution pool according to EUI performance. The solution pool was then further narrowed to only include design alternatives with an SPC score greater than 95. From this narrowed solution pool the final design was selected based on aesthetic properties through the designer's analysis of the provided 3D images of each design alternative. The objective scores of the final selected design were: NPV = -2.38 million dollars; EUI = 52.04 kBtu/sqft/yr; and SPC= 99.29. Once this final selection was made, the designer proceeded to the next stage in design development with the generated Revit massing model. In this case study, despite the dominance of aesthetic preference as the determining factor for the final design, an improvement in all three objective scores over the initial design was observed.

CONCLUSION AND DISCUSSION

EEPFD is a framework that provides a new method of applying MDO techniques through a customized GA to integrate previously inaccessible performance feedback into the early stage building design process. While EEPFD has been validated through tests of accuracy and efficiency, the development of best practices through the key metrics of interaction, communication, and designer ease of use is the focus of continued research. Bridging the gap between the energy domain and geometric exploration remains the motivating challenge of the research that begins to address the previously established gaps. Secondary contributions of this research include the demonstrated usability of EEPFD by designers through direct interaction during the early stages of design. This addresses in part the disconnection of domain expertise as an issue for the integration of energy simulation for early stage design. Through a comparative study of the two processes implemented in the case studies, with specific focus on observing the interaction between designers an EEPFD, several general observations can be made. First, in both cases, designers were observed to have difficulty with translating their design intent into a viable parametric model. This may in part be due to unfamiliarity with both the design platform, and parametric modeling and parametric design methods. While these issues remain, they may be mitigated through increased experience and industry trends indicating an increased used of parametric design. Secondly, while the designers in both case studies acknowledged the potential applicability of the EEPFD generated results, Case Study II utilized the results in both steps 1 and 6 more completely. In Case Study I, a net zero energy building objective was desired, and therefore the scope was an over extension of the capabilities of the current form of the prototype used by EEPFD. Of particular note, there is a need to include daylighting strategies as part of their analysis. In the current implementation of the EPFD dayliging is aggregated within the more generic EUI calculation handler GBS. As a result Case Study I was not able to fully utilize the generated solution pool, however the framework as it is intended is extensible and conceived to include other tools and design objectives. Finally, in both case studies the generation of unexpected results occurs in part based on the designer provided parametric ranges and there lack of expertise in design intent to parametric modeling transcription. In Case Study I this led to undesirable window sizes, in Case Study II this led to undesirable ceiling heights. Since EEPFD possesses neither aesthetic preference nor prejudice when generating design alternatives, consideration must be made when formulating the parametric model for maintaining of design intent or an exhaustive exploration of design alternatives is desired. It can be noted that EEPFD is adaptable to either scenario, broad or specific, dependent on designer preference. Overall, in both case studies the final result was observed to be a broader based design solution pool with an overall improved multi-objective performance to enable more informed design decision making inclusive of a more expansive simulated aesthetic and formal range. While these case studies provide initial observations regarding the impact and interaction of EEPFD on the early stage design process when implemented through the designer, a subject for future research is the engagement of a more extensive experimental user group so as to further observe the impact of EEPFD on the design process. Another subject for future research is the inclusion of additional performance considerations, such as structural and daylighting, so as to meet the complexity demands of design problems through applied MDO.

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