DESIGNING IN PERFORMANCE:
A CASE STUDY OF APPLYING
EVOLUTIONARY ENERGY
PERFORMANCE FEEDBACK FOR DESIGN

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ABSTRACT
This paper explores the application of a novel Multi-disciplinary Design Optimization (MDO) framework to the early stage design process, through a case study where the designer serves as the primary user and driver. MDO methods have drawn attention from the building design industry as a potential means of overcoming obstacles between design and building performance feedback to support design decision-making. However, precedents exploring MDOs in application to the building design have previously been limited to driving use by engineers or research teams, thereby leaving the incorporation of MDO into a design process by designers largely unexplored. In order to investigate whether MDO can enable the ability to design in a performance environment during the conceptual design stage, a MDO design framework entitled Evolutionary Energy-Performance Feedback for Design (EEPFD) was developed. This paper explores the designer as the primary user by conducting a case study where the application of EEPFD to a single family residential housing unit is incorporated. Through this case study EEPFD demonstrates an ability to assist the designer in identifying higher performing design options while meeting the designer’s aesthetic preferences. In addition the benefits, limitations, concerns and lessons learned in the application of EEPFD are also discussed.
1 INTRODUCTION AND BACKGROUND

In response to the growing global concern of sustainability in the building design industry, incorporating performance feedback as part of the design criteria has become more essential during the building design process. However, current existing obstacles between the design and energy-performance domains impede inclusion of energy-performance feedback as part of the driving force to support design decision-making during the early stage of design—where decisions made have the greatest impact on the overall building performance throughout the building’s life cycle (Bogenstätter, 2000). The problems observed between the design and energy-performance domains have been extensively documented and can be summarized into two commonly encountered types of obstacles: time constraints and interoperability issues between hardware, software, and varying expert domain expertise (Augenbroe, 2002; Oxman, 2008). Moreover, an unavailability of architect user-friendly design tools adds to the final result of energy-performance assessments being typically made after the initial design phase as a means of evaluating specific design options rather than to support design decision-making (Attia et al., 2009). Motivation of this research stems from the potential in alleviating these issues as presented in current research coupling parametric design with optimization algorithms, referred to by this research as multi-discipline design optimization (MDO) (Flager et al., 2009; Caldas, 2008; Castorina, 2012). Previous applications of MDO have demonstrated the ability to negate issues of interoperability between different platforms and automate the design exploration process with increased feedback results and performance evaluations of design alternatives. MDO thereby enables the possibility of realizing “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 design. However, the majority of MDO applications related to building energy-performance are conducted by researchers within the engineering field with a focus on optimizing mechanical systems or façade configurations (Asadi et al., 2012; Adamski, 2007; Wright, Loosemore, and Farmani, 2002). Only a few applications have explored the application of MDO from a designer’s perspective, such as the works of Caldas, Janssen and Yi and Malkawi (Caldas, 2008; Janssen, 2009; Yi and Malkawi, 2009). However, these applications are limited to academic experimental settings as conducted by the research team as opposed to designers. As a result, the examination of methods adoptable by designers remains unexplored. Furthermore, while the importance of form-exploration during the early stage of the design process is addressed, usually a simplified geometry is adopted for proof of concept due to the limited flexibility of said precedents’ framework (Flager et al., 2009; Janssen, 2009). As a result, the relationship between designed form-exploration and energy-performance has been largely excluded.

In response, a MDO design framework entitled Evolutionary Energy-Performance Feedback for Design (EEPFD) was developed. The intent of EEPFD is for designer use during the conceptual stage of design where geometric components and massing have not been finalized. The development of EEPFD enables form-exploration with energy-performance feedback and has been previously validated against the needs of early stage design where time constraints and rapid form-exploration are essential (Lin and Gerber, 2013). The objective of this paper is to further examine the applicability of EEPFD during the early stage of design by conducting a studio setting case study. The interest of this experimental case study is to observe the time, skill and knowledge needed for a designer other than a research team to apply EEPFD during the design process. Observations are also made regarding how the generated data from EEPFD is utilized by the design to assist in the design decision-making process.

2 EVOLUTIONARY ENERGY-PERFORMANCE FEEDBACKS FOR DESIGN (EEPFD)

EEPFD incorporates both conceptual energy analysis and design exploration of simple to complex geometry in order to provide energy-performance feedback for early stage design decision-making. Included in the multi-objective optimization (MOO) process are the competing objective function of spatial programming and financial performances for consideration in performance trade-off studies. EEPFD utilizes a prototype plug-in of Autodesk® Revit® (Revit), entitled H.D.S. Beagle, to integrate design, energy, and financial domains into an automated optimization routine. The integrated platforms are Revit, Autodesk® Green Building Studio® (GBS) and Microsoft® Excel® (Excel) respectively. The searching algorithm utilizes a custom genetic algorithm (GA) based MOO with the competing objectives of maximizing spatial programming compliance (SPC), minimizing energy use intensity (EUI), and maximizing 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 can be described in the six steps 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 and a constraints file. At this point, the initial geometry, applicable parameters and ranges, site information, program requirements, and available financial information are provided manually by the user. The generation of the design alternatives is part of the automated process driven by the customized GA-based MOO in EEPFD. Once the initial design is inputted into the automated system, the following steps are then cycled through until the automation loop is interrupted 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 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).

3 THE DESIGN OF THE CASE STUDY

For the case study, a first year master of architecture student serves as the designer and sole decision maker for the design of a single family residence to be located along Wonderland Park Avenue in Los Angeles, CA. The EEPFD development and research team acts as both owner and consultant, providing all necessary project requirements and technical support as needed.

The program requirements for the single family residences are designated as including: four bedrooms, three full bathrooms, two car garage, and living, dining and kitchen areas not to exceed a total of 3,000 square feet. All room areas are subject to designer preference, with a maximum being placed on bedroom dimensions as not to exceed twenty by twenty feet. A ten foot set-back from all site boundaries is also specified. The overall design goals are defined to include all design requirements, combined with consideration for a maximum decrease in energy consumption.

For the purpose of evaluation, a benchmark model is provided by the research team based on existing site conditions and calibrated against the electric and gas bill of current residents. All material selections, space-type assignments and other financial construction oriented specifications are provided to the designer prior to the implementation of the case study and are instructed to remain consistent throughout the case study.

The design of the case study is divided into four stages: 1) Pre-parameterization; 2) Parameterization; 3) H.D.S. Beagle; and 4) Final Design Selection. The required tasks and activates of each stage are detailed in the following:

1) Pre-parameterization Stage: during this stage, the designer is asked to propose their design ideas according to the predetermined design requirements. The research team acts as both project owner and studio instructor to provide critics and recommendations for design modifications. After two iterations of discussion, the designer proceeds to finalize their conceptual design ideas and begin identifying parameters of interest regarding the exploration of their adjusted design. During this stage in the design process, the designer is allowed to utilize the platform of choice for conceptual design exploration. The designer is also asked to document their design process regarding how they develop their design ideas.

2) Parameterization Stage: during this stage, the designer is asked to develop the parametric conceptual mass in Revit according to the designer’s proposed parameterization method provided at the end of the last stage. The research team acts as a consultant to provide technical support for encountered problems.

3) H.D.S. Beagle Stage: a lecture session is scheduled to instruct in the application of H.D.S. Beagle and the process of EEPFD. The content of the lecture includes the concept behind the Beagle, building Beagle executable Revit models, setting up needed excel templates, and hands-on to execute H.D.S. Beagle on the designer’s own design. After the instructional session, the designer then uses H.D.S. Beagle to generate design alternatives for final selection.

4) Final Design Selection Stage: during this stage the designer is asked to select a final design based on all available information. The designer is provided all context regarding the evaluation means and ranking mechanisms of H.D.S. Beagle. However, as the sole decision maker, the designer is asked to make a final decision according to the designer’s own design strategy to accommodate both design goals and requirements.

During each stage of the case study, the process is documented via a semi-structured interview and diagrammatic illustrations. Table 1 summarizes the bullet points of the recorded information during this case study.

<table>
<thead>
<tr>
<th>Case Study Stage</th>
<th>Recorded Data</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pre-parameterization</td>
<td>1. Education background&lt;br&gt;2. Prior design experience&lt;br&gt;3. Prior environmental design knowledge&lt;br&gt;4. Design process documentation during the pre-parameterization process&lt;br&gt;5. Utilized platforms</td>
</tr>
<tr>
<td>Parameterization</td>
<td>1. Parameterization process&lt;br&gt;2. Time required for each iteration and number of iterations&lt;br&gt;3. Encountered challenges</td>
</tr>
<tr>
<td>H.D.S. Beagle Stage</td>
<td>1. Time required to be familiarized with necessary tools and systems&lt;br&gt;2. Observed learning curve of H.D.S. Beagle</td>
</tr>
<tr>
<td>Final Design Decision</td>
<td>1. Final design decision process&lt;br&gt;2. Determination of EEPFD’s relevance in assistance of design&lt;br&gt;3. Observed process challenges&lt;br&gt;4. Feedback regarding the case study design process</td>
</tr>
</tbody>
</table>

Table 1: Summary of the recorded data for the case study.
4 OBSERVED DESIGN PROCESS

The designer of the case study is a master architectural candidate with six 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 other environmental simulation tool use or as part of the design requirements.

During the pre-parameterization process, the designer’s preferred design platform is Rhino. Based on the designer’s design logic, and over the course of two weeks, a total of four major iterations were explored and presented for discussion with the client (i.e. research team), as illustrated in Figure 2. From this discussion a parameterization concept is proposed by the designer who proceeds with exploring shading, opening and the spacial composition of each space.
After the determination of intent for the parameterization 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 two and a half months. This recorded time includes the designer’s required time to familiarize themselves with the use of Revit for conceptual design through a trial and error period. While one of the secondary goals of this case study is to observe the ability of a designer to translate their intended design into a parametrically oriented mathematically defined form. As a result, 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 experience parameterization process. Another contributing factor can be identified in the trial-and-error period necessary to define the design’s constraints file so as to maintain both design intent and model robustness during the optimization process since the current version of H.D.S. Beagle will prematurely terminate if the geometry breaks. According to feedback from the designer, if a simplification of the North façade had been allowed the parameterization process could have been completed within two days with the designer’s prior level of Revit experience.

After the completion of the parameterization process, the H.D.S. Beagle instructional stage is documented as a four hour lecture session. During these four hours, the designer becomes familiar with the process of setting up the executable files necessary for engaging H.D.S. Beagle in a GA run. The designer is also informed as to the optimization mechanism of EEPFD and the significance of all generated data. While improved energy-performance in the

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**Table 1:**

<table>
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<th>Name</th>
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<tr>
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</tr>
</tbody>
</table>

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**Equation:**

\[ \text{RightWidth} = 0.532 \times (\text{OverallWidth} - 4) \]
\[ \text{LeftWidth} = 0.543 \times (\text{OverallWidth} - 4) \]
\[ \text{DiningWidth} = 0.203 \times (\text{OverallWidth} - 4) \]
\[ \text{LivingWidth} = 0.312 \times (\text{OverallWidth} - 4) \]
\[ \text{LivingWidth} = (\text{LivingWidth} / \cos(\text{RefAngle2}) \times 5 \times 128) \]
\[ \text{LivingHeight} = \text{LivingHeight} \times \text{DepthRatio} \]
\[ \text{KitchenWidth} = \text{KitchenWidth} / \cos(\text{RefAngle2} - \text{KitchenAngle}) \]
\[ \text{KitchenDepth} = \text{LivingHeight} \times 0.82 \]
\[ \text{BedroomWidth} = 0.215 \times (\text{OverallWidth} - 4) \]
\[ \text{BedroomDepth} = \text{BedroomWidth} \times \text{DepthRatio} \]
\[ \text{BedroomDepth} = 0.432 \times (\text{BedroomDepth - 11}) + 0.428 \times (\text{BedroomDepth - 11.5}) \]
\[ \text{BedroomDepth} = 0.75 \times \text{BedroomDepth1} \]
\[ \text{BedroomDepth} = 0.69 \times (\text{BedroomDepth - 11}) \]
\[ \text{BedroomAngle} = \text{BedroomAngle} \times \text{RefAngle2} - \text{RefAngle3} \]
\[ \text{BWD} = (\text{BedroomDepth} - 0.4 \times (\text{BedroomHeight}) / 2) \]
\[ \text{H1} = 1.8 \]
\[ \text{H2} = 0.4 \times (\text{BedroomHeight} / 2) \]
\[ \text{ovhD2} = \text{ovhD1} \times \text{SkyLightHeight} / \text{H2} \]
\[ \text{ovhH} = (\text{ovhH} - \text{ovhD2}) / \text{tan(ovhH)} \\ \text{ovhD2} = \text{H2} \times \tan(\text{ovhH}) \\ \text{ovhH} = \text{ovhD2} \times \text{H2} \]

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**Figure 3:**

The final parametric model is illustrated in Figure 3 and was generated over the course of two and a half months. This recorded time includes the designer’s required time to familiarize themselves with the use of Revit for conceptual design through a trial and error period.
design is one designated design goal, the designer is given absolute discretion in the organizing of design priorities and balancing of design objectives.

For the final model selection, the data sets from two GA runs were provided to the designer for decision-making purposes, as illustrated in Figure 4. One GA run maintained a fixed glazing configuration along the north and south façades, thereby only allowing exploration for varying amounts of glazing along the east and west façades. The second GA run included an exploration of varied glazing percentages applied consistently across all four façades. It should be noted that in both of these GA runs the ability to explore the percent glazing of each façade independent of the other façades was not enabled. Both data sets provided solution pools with an improved performance when compared to the benchmarked initial design.

Although the ranking of each design alternative for the design scenario were provided, the designer did not limit their analysis to the design alternatives receiving the highest ranking from the provided data set. Instead, all resulting design alternatives were considered in the context of the generated solution pool. The final design decision process is provided in the following based on the description received from the designer for this case study.

The initial decision made by the designer was to discard the data set resulting from Data Set I with the fixed North and South façades. This was done in response to a consistently observed increase in the EUI for the overall data set when compared to the solution pool for Dataset II. Secondly, the designer deemed the overall NPV range as acceptable, therefore indicating that primary decision-making was based on EUI and SPC results.

From the overall Data Set II the designer observed that the best EUI performance of the solution pool was EUI = 43.82 kBtu/sqft/yr. Therefore, the designer narrowed the desired solution pool to design alternatives with an EUI performance between 43 kBtu/sqft/yr and 45 kBtu/sqft/yr. The solution pool was then further narrowed to only include design alternatives with an SPC score larger than ninety-five. The designer also included the only design alternative to receive the highest available SPC score, regardless of the EUI, in this final solution pool. From this narrowed solution pool the final design was selected based on aesthetic properties through the designer’s analysis of the provided three-dimensional images of each design alternative. The designer’s decision-making process is illustrated in Figure 5. The objective scores of the final selected design are: NPV = -2.38 million dollars; EUI = 52.04 kBtu/sqft/yr; and SPC = 99.29. It should be noted that while the final design was not within the initially designated EUI range, the final design did have an improved performance across all three objectives over the initial benchmark design. Once this final selection was made, the designer proceeded to next stage in design development with the generated Revit massing model.
5 DISCUSSIONS & CONCLUSIONS

This case study is the first documented attempt to integrate MDO into the design process through a designer user as opposed to prior case studies with engineers or researcher team members as the primary users. As such, this case study provides initial observations as to the impact of MDO on the early design process when implemented by a designer. This observed design process in this case study demonstrated how EEPFD can support informed decision-making despite the volatile subjective nature of the design process. By providing a context in which design alternatives can be evaluated, EEPFD allows designers to organize their priorities based on individual preference or project requirements. 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. Aside from aesthetic exploration, the designer indicated that EEPFD provided an opportunity to learn through previously inaccessible performance feedback about relationships between design elements and their impact on the resulting design performance. Therefore, in this case study, EEPFD succeeded in providing a “designing-in-performance” environment where a design with an improved performance was achieved. In addition, while this case study indicates that familiarization with EEPFD does not require an extended learning period, a prior familiarity with parametric design concepts and processes is a necessary prerequisite.

One challenge expressed by the designer in this case study was that, since EEPFD possesses neither aesthetic preference nor prejudice when generating design alternatives, consideration must be made when formulating the parametric model regarding whether the maintaining of design intent or an exhaustive exploration of design alternatives is desired. In this case study it was discovered by the designer that design alternatives with a reduced ceiling height were not of interest according to the designer’s aesthetic preference. In response, all design alternatives generated with a reduced ceiling height, regardless of performance scores, were automatically discarded. While it can be argued that time spent on generating design alternatives with a reduced ceiling height in this case was a waste of time, it can also be argued that without these alternatives the designer may not have recognized this element as essential to the final desired design configuration. It can be noted that EEPFD is adaptable to either scenario, broad or specific, dependent on designer preference.

While this case study is limited to the observation of only one user, it can be considered as a preliminary experiment to a more extensive field study regarding the impact of EEPFD on the early stage design process when implemented through the designer. As the workability of the case study format was confirmed by the designer, it should be considered as eligible for future research through 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 stems from an observation made during the parameterization process. It was noted that due to the specific design concept used for this project there was a possibility that a simplified geometry that still reflected the design intent could potentially have been used without compromising the integrity of the energy-performance analysis. If true, then a simplified geometry would have allowed for a reduction in the necessary time for the parameterization process. This possibility is a subject of future research to determine the appropriate degree of simplification and the resulting impact on the energy-performance analysis as part of the best practices necessary for the relevant use of engagement for EEPFD.
ACKNOWLEDGEMENTS
The work was in part supported by funding from the USC School of Architecture Junior Faculty Research Fund and in part by Autodesk, Inc. The authors thank the USC Dean of Architecture Qingsyun Ma and the junior faculty research grant program; Ms. Bei “Penny” Pan our initial lead software developer; Junwen Chen, Ke Lu, Shitian Shen, Yunshan Zhu for their continued software development.

WORKS CITED

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