Designing-In Performance:
A case study of a net zero energy school design

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ABSTRACT: Researching the potential of multidisciplinary design optimization (MDO) for overcoming current obstacles between the design and energy simulation domains, a MDO design centric framework, titled Evolutionary Energy Performance Feedback for Design (EEPFD) was developed to explore the applicability of this design framework to the early stage design process. EEPFD incorporates both conceptual energy analysis and the exploration of complex geometry for the purpose of providing early stage design performance feedback. This paper presents a practice based case study through a design competition project for a net zero energy school design with the purpose of evaluating the applicability and impact of EEPFD on the early stage design process. The research then compares three approaches used to obtain energy performance feedback during the case study; including in-house energy analysis, collaboration with MEP consultants, and the use of EEPFD. Through a comparative study EEPFD demonstrates the ability to generate performance feedback more rapidly than the industry standard alternatives. Challenges and suggestions for improvement of EEPFD are then presented and discussed.
Keywords: conceptual energy analysis, early stage design decision making, performance-based design, multidisciplinary design optimization

INTRODUCTION+BACKGROUND

Buildings account for a significant portion of energy consumption. In the United States, buildings consume almost 41% of primary energy usage and approximately 71% of electricity [1]. It is also projected that this demand for energy will continue to rise until a change in the design of buildings and incorporation of new building technology reaches the ability to offset increasing demand in the building sector amid expanded development [2]. In response to these predictions the concept of net zero energy building (ZEB) comes to the forefront as a primary visionary goal for new construction from public and private organizations, such as the Net-Zero Energy Commercial Building Initiative of the U.S. Department of Energy (DOE), the 2030 Challenge of the Architecture 2030, and the ASHRAE Vision 2020 report [3].

ZEB can be more strictly defined in the context of site energy, source energy, energy cost or energy emissions [2]. However, regardless of the definition or metric used, the design concept of a net ZEB is to design a building which maximizes energy efficiency to minimize overall energy demands which are then met through renewable energy resources. Therefore the maximum reduction in energy demand achievable through building design can be considered a fundamental first priority design criterion for ZEB projects. For this reason, the potential significant contribution of energy analysis tools takes on a more prominent role in the process of designing a net ZEB [4] and therefore should be integrated early on in the process where design decisions have the greatest impact on the overall expected building performance. In this way maximizing efficiency opportunities can be developed prior to the exploration of renewable energy plans. However, design professionals are often unable to adequately explore design alternatives and subsequent impact on energy consumption upfront due to time limitations, interoperability issues among software and necessary domain expertise [5-7]. Consequently, performance assessments are typically made after the initial design phase for design evaluation, not as iterative feedback to support early stage design decision making. In addition, it is suggested that trade-off studies are necessary in order to provide adequate feedback for design decision making since design often involves the balancing and synthesizing of competing objectives [8]. However, none of the conventional energy simulation tools are able to support this need.

The motivation of this research stems from the potential of multidisciplinary design optimization (MDO) methods to alleviate issues currently existing between the design and energy simulation domains [9-11]. MDO is a general term used by this research in reference to the method of coupling parametric design and optimization algorithms. MDO approaches have been successfully adopted by the aerospace industry and other engineering fields. Adoption by the building design industry has demonstrated the ability to mitigate issues of interoperability between varying platforms. In addition the benefits of automating the design exploration process have been shown through the inclusion of increased feedback results and performance evaluations of design alternatives with trade-off study of competing design criteria to support design decision making. 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, most of the 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 [12, 13]. While the importance of form exploration during the early stages of the design process is occasionally addressed, typically a simplified geometry is adopted for proof of concept due to the limited flexibility of existing frameworks [11, 14]. Furthermore, there are limited documented MDO applications that have been fashioned and explored through a designer’s perspective or with an emphasis on examining the applicability of the framework to the early stage design process [14-16]. As a result, the impact of applying MDO methods by designers during the early stage design process remains largely unexplored. In response to this existing gap, a MDO design framework, titled Evolutionary Energy Performance Feedback for Design (EEPFD), along with a prototype tool, H.D.S. Beagle, were developed to incorporate both conceptual energy analysis and the exploration of complex geometry for the purpose of providing early stage design performance feedback.

This paper presents a practice based case study of a design competition project for a net zero energy school design. During the competition the designers utilized three approaches to acquire energy performance feedback for the purposes of assisting in their design decisions. The three approaches employed by the designers were; in-house energy analysis, collaboration with MEP consultants, and the use of EEPFD. Through a comparative study of these three approaches adopted by the designers, the applicability and impact of EEPFD during the early stage of the design process is presented.

EVOLUTIONARY ENERGY PERFORMANCE FEEDBACK FOR DESIGN (EEPFD)

The development of EEPFD is for designer use during the conceptual design stage where overall building form has not been finalized. EEPFD incorporates both conceptual energy analysis and design exploration of simple to complex geometry in order to provide energy performance feedback. Also included in the provided feedback are spatial programing and financial performance for consideration in performance trade-off studies. EEPFD utilizes a prototype plug-in for Autodesk® Revit® (Revit), titled 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. H.D.S. Beagle also contains a custom genetic algorithm (GA) based multi-objective-optimization (MOO) algorithm as the driver to automate the searching and optimization routine. The three competing objectives in the algorithm are to maximize spatial programing 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 [17].

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 and a constraints file. At this point the initial geometry, 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 modelled 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 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 [18].

DESIGN PROJECT BRIEF

This case study is based on the detailed analysis of an architectural practice’s process regarding an educational project. The initial outlined design requirements were to provide 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. While a specific site was still designated as the intended project site, flexibility was insisted upon not just to allow for multiple site adaptability but to allow for future reconfiguration for various educational uses, such as library, media centre, open education space, multi-purpose room and food services. In addition to these requirements the designers decided to expand upon the provided sustainability considerations to pursue a net ZEB configuration for each site.

Based on the designers' time line, the development of the project spanned through two successive competition entries that can be separated into three major stages: I) schematic conceptual proposal; II) schematic design to design development; and III) design enhancement, as illustrated in Figure 1. The first two stages of the design development were to meet the requirements of the initial competition as previously outlined. The third stage of the design development was to refine the design for entry to a global competition. During design stage I, the designers proposed a concept of assembling a building with pre-engineered readymade kit-of-parts core and shell components to provide the flexibility necessary to accommodate different site conditions or space requirements. After being selected as a finalist the designers proceeded to advance their design towards achieving net ZEB. At this point in the design development energy performance simulation was introduced as part of the design process. As illustrated in Figure 1, three approaches were adopted by the designers to acquire energy performance feedback regarding the design's overall energy consumption through an estimated energy use intensity calculation. Other building environmental performance components, such as natural daylighting and thermal comfort, were included for consideration as part of the final design evaluation in pursuit of the net ZEB goal. The first two approaches, in-house analysis and MEP consultant collaboration, were conducted at this time during design stage II. The last approach implementing EEPFD was applied later during design stage III.

ENERGY SIMULATION FEEDBACK APPROACHES & COMPARISON

Despite the introduction of energy performance feedback during the schematic phase of design, the incorporation of energy simulation feedback was not utilized to explore form configuration. Instead energy performance feedback was limited to assisting in façade configuration through designating desirable kit-of-parts components such as skylights, solar screens, light shelves, etc. along with optimal compositions of these components for varying site conditions. As a result, all three energy performance feedback approaches focused on one standard classroom unit as the analysis target instead of including the whole building analysis as part of the exploration process. The whole building energy analysis was conducted at the end of the design stage to ensure code compliance and to evaluate whether the final design met design goals.

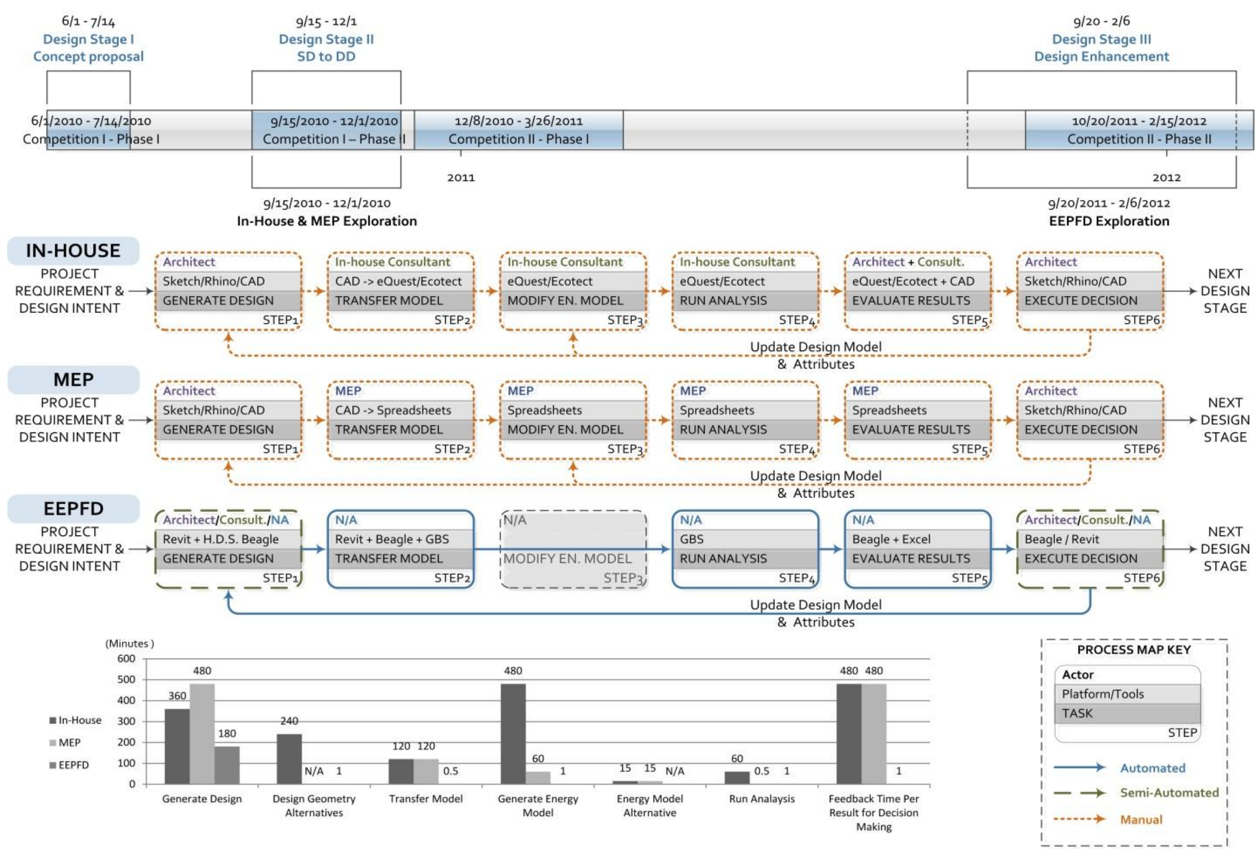

Figure 1: Overall project timeline & comparative process maps with initial observations.

During this comparative study the energy simulation process was broken down into six steps used by all three approached to provide a consistent basis for comparison. For qualitative and quantitative analysis data regarding the design problem, process, and product was collected and compiled into an established metrics. Table 1 summarizes the recorded data during these exploration processes.

Table 1: Summary of collected data for the case study.

	Recorded Data	Data Type
Design Problem Measurement		
Project Complexity	1. Project size	Sqft
	2. 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. Time to transfer to energy model	Minutes
	3. Time spent to clean up energy model	Minutes
	4. Time spent to run energy analysis	Minutes
	Performance feedback time per result	Minutes
Design Product Measurement		
Feedback method	1. Feedback number per day	Numbers
	2. Feedback information	Descriptive
Actor		
Actor Experience	1. Parametric model experience	Descriptive
	2. Energy simulation domain experience	Descriptive

In-House Analysis Process

During the in-house analysis process, the designers explored design ideas through varying mediums and platforms including hand sketches, Rhino, and CAD. During this design stage the authors provided in-house building performance analysis of various design scenarios as provided by the designers. After obtaining a design scenario from the designers, the authors created a gbXML format energy model through Revit, and imported the model into Autodesk® Ecotect® for lighting analysis followed by eQuest for energy analysis. This initial energy model required manual rebuilding of necessary building components in Revit from scratch and required manual input of energy simulation attributes in both Ecotect and eQuest individually since there is no interoperability between the utilized design platforms and the energy simulation platforms. This process required approximately 6 hours to complete an initial analysis. Once the initial analysis was obtained the design was manually altered in both design and energy simulation platforms according to designers' directions. Once adjustments were made another analysis was run in order to determine any measurable differences between the designs. The time required to generate design alternatives and their energy models was dependant on the type of modifications to the initial design requested by the designers. According to the recorded data the modification process averaged approximately 4 hours per design alternative. Due to the time consuming nature of this process, only four scenarios were fully analysed. As a result the in-house process was unable to keep up with the pace of design or provide the ability to isolate direct cause and effect of design changes to the expected performance in order to assist with design decision making. Therefore use of results from the in-house analysis was limited to validating design decisions as opposed to expanding the set of explored design alternatives.

MEP Consultant Collaboration Process

Following the in-house analysis process a MEP engineer was employed to assist in generating a more efficient design configuration using the designer proposed adaptable module. The assumption was that the MEP engineer would be able to provide a more efficient starting point for the design, be able to aid in providing suggestions for optimizing the design's geometric configuration, and finally provide the necessary HVAC strategies for achieving a ZEB design. During the process, the MEP consultant was provided only one design scenario, including basic space layout and the schematic space programing composition from the designers. The MEP engineer then extracted relevant data before proceeding with the energy calculations through their proprietary spreadsheet system. This proprietary spreadsheet system was the MEP engineer's major design iteration tool in understanding the impact of design alternatives on energy performance and the relationship between different parameters, such as thermal comfort, solar heat gain, natural ventilation, and natural daylighting. In this case, the spreadsheet system served as the energy model with building geometry recorded in a text format. According to the engineer, the initial data transfer from the designers' given scenario to the spreadsheet with code-compliant energy property setup took approximately three hours. For subsequent design alternatives, the manipulation of the single classroom's energy related parameters in the spreadsheet, took about 15 to 20 minutes per iteration. After approximately 20 iterations were explored the MEP engineer, based on their accumulative experience, compiled their feedback for the designer in the form of design guidance regarding building components' thermal properties, window area ratio, shade depth, skylight placement, and HVAC systems.

During this collaboration process, the MEP engineer was able to provide suggestions for optimizing systems within a single design configuration and was able to provide this guidance based on designers' design strategies within a day. While the provided guidance was able to assist designers in meeting the design goal, it was not able to support the designers' understanding of the impact of their design decisions, especially when confronted with a new design configuration falling outside of the provided guidance coverage. Instead the new configuration required another round of iterations with the MEP engineer and another set of design guidance. Due to the level of detail provided in each set of design guidance and the inclusion of the expert domain of the MEP engineer, the designers were able to progress the design to the next stage of development. Therefore, in comparing the in-house analysis with that of the guidance and support from the MEP engineer, the MEP engineer collaboration process was observed to be more thorough and complete for achieving the net ZEB design goal.

EEPFD Process

The implementation of EEPFD was introduced to the designers during the third stage of their design development. 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.

Two experiments were implemented through EEPFD during this stage; 1) the overall façade configuration vs. orientation; and 2) the detail façade configuration of a standard classroom unit. For both explorations, the overall design form remains fixed. As a result, the optimization algorithm is used to find the best compromise between minimizing energy use intensity and maximizing the net present value.

The first experiment is conducted by the authors as an exemplary showcase to demonstrate the potential benefit of the tool to the designers. During this experiment, EEPFD was utilized to explore the optimal configuration of each building side's glazing area ratio, sill height and depth of shading devices for five different overall site orientations: 0, 22.5, 45, 67.5 and 90 degrees from true North. In this experiment, there were a minimum of 500 design configuration alternatives generated for each site orientation within 6 hours as opposed to the previous in-house's average analysis time of 4 hours per iteration.

Following the showcase experiment, the second experiment was to emulate the process of EEPFD's implementation by the designers to obtain optimal configurations of the kit-of-parts module for the project's future development. During this process, the designers were first required to formally define their design problem into a parametric model. As with the previous two approached, the design problem definition was limited to optimizing one standard classroom unit using the defined kit-of-parts. As parametric design has 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 modelling, 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 the façade configuration were regarding customized opening sizes, solar screen depth, density, and mounting distance from the building. 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 the guidelines provided by the MEP consultant.

A total of 12 GA runs were completed through EEPDF with varying parametric ranges, GA settings and stopping points. Through the 12 GA runs a total of 2,082 design alternatives were generated with a 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. After the completion of the runs, the authors provided the final trade-off analysis along with 3D design images to the designers for their final decision making. According to the generated data, while an improved quantity of feedback over the prior two approaches was made available, more guidance was requested from the designers regarding the ability to discern desirable results from the abundantly populated solution pool. 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 either the in-house analysis or through the MEP engineer. As a result, the designers were able to include aesthetic preference as part of their trade-off analysis when examining the generated results.

CONCLUSION

This paper presents a practice based case study of 3 approaches to include energy performance feedback during a prototypical school design with the goal of net ZEB. While these three approaches of in-house analysis, collaboration with a MEP engineer, and EEPFD cannot necessarily be considered as comparable based on the input/output of each approach, there are trends which can be identified. First is regarding the level of detail necessary for each approach which influences the applicability of each to the early stages of design and ability to support design decision making. The feedback received from the MEP engineer was considerably more detailed and narrow in scope than that of the in-house analysis or EEPFD. However, the feedback received from the MEP engineer was in the form of general design guidance rather than the performance of a specific design iteration. In this respect only EEPFD provided feedback specific to a particular design alternative in a manner enabling the designers to gauge the impact of their design decisions on the design's EUI. Secondly, the time necessary for the implementation of any of these approaches must be considered. The in-house analysis performed required approximately 4 hours per design alternative, while EEPFD required less than a minute per design alternative. MEP results were received from the engineer within a day but were only applicable to a single base design with limited available alternatives. Finally, only EEPFD provided an automated trade-off analysis among competing objectives. Despite the MEP engineer's guidance, the actual components of the design were left to the designer to optimize. EEPFD, however, provided the ability to analyse and explore various combinations of these components rapidly in order to isolate desirable configurations.

Despite this rapid exploration, EEPFD is currently limited in scope regarding the inclusion of performance considerations relevant to net ZEB design. For example, natural daylighting is not included in either the objectives or as contributing to the EUI calculation. However, if the prototype H.D.S. Beagle can be expanded to include these additional performance considerations then EEPFD's rapidly provided feedback could support design decision making in pursuit of net ZEB design.

It should be noted that EEPFD is intended to be implemented during the conceptual phase of design. However, in this practice based case study EEPFD was introduced during the design development stage where the range of exploration of interest had already been previously narrowed by the guidance of the MEP engineer. As a result the implementation of EEPFD is here in this case considered as a means of fine tuning a previously optimized design. A subject of future interest would be to observe the implementation of these three explored approaches for including energy performance feedback concurrently rather than consecutively so as to gauge the effect of each on the early stage design process and yielded design performance results.

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