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Teaching Design Optioneering: A Method for Multidisciplinary Design Optimization

By

David Gerber and Forest Flager

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David Jason Gerber[1] and Forest Flager[2]

[1] Assistant Professor, School of Architecture, University of Southern California, CA 90089; email: dgerber@usc.edu
[2] Ph.D. Candidate, Department of Civil and Environmental Engineering, Stanford University, CA 94305; email: forest@stanford.edu

ABSTRACT

This paper describes a Design Optioneering methodology that is intended to offer multidisciplinary design teams the potential to systematically explore a large number of design options much more rapidly than currently possible using conventional methods. Design Optioneering involves first defining a range of design options using associative parametric design tools; then coupling this model with integrated simulation-based analysis; and, finally, using computational design optimization methods to systematically search though the defined range of alternatives in search of design options that best achieve the problem objectives while satisfying any constraints. The Design Optioneering method was tested by students as part of a parametric design course at Stanford University in the spring of 2010. The performance of the method are discussed in terms of the student's ability to capture the design intent using parametric modeling, integrate expert analysis domains, and select a preferred option among a large number of alternatives. Finally, the potential of Design Optioneering to reduce latency, further domain integration, and enable the evaluation of more design alternatives in practice is discussed.

INTRODUCTION

Current Computer-Aided Design and Engineering (CAD/CAE) tools allow architects and engineers to simulate many different aspects of building performance (e.g. financial, structure, energy, lighting) (Fischer 2006). However, designers are often not able to leverage simulation tools early in the design process because of the time required to complete a design cycle involving the generation and analysis of a design option using model-based CAD/CAE tools. It often takes multidisciplinary design teams longer than a month to complete a single design cycle (Flager and Haymaker 2007). High design cycle latency in current practice has been attributed to software interoperability (Gallaher, O'Connor et al. 2004), lack of collaboration between design disciplines (Akin 2002; Zhao and Jin 2003; Holzer, Tengono et al. 2007), among other issues.

Associative parametric CAD tools have been shown to reduce latency associated with the generation of design options (Sacks, Eastman et al. 2005) as well as to manage greater project complexity (Gerber 2009). A parameter in this context is a design variable that can be associated or related to other parameters to define

883

particular design logic. The designer can then manipulate a single parameter or set of parameters to rapidly generate many unique design configurations (Szalapaj 2001). Parametric modeling as a concept and mathematical construct (e.g. parametric curves and surfaces), has been around for years with the first parametric CAD tools emerging in 1989 (Eastman, McCracken et al. 2001). However, providing tools that enable designers to readily develop these robust and rigorous input models that describe their design intent in order to guide design generation remains a challenge (Shea, Aish et al. 2005; Gerber 2007).

The use of associative parametric tools to reduce design cycle latency in current AEC practice has been limited by two primary factors. First, there are inherent differences in the way architects and engineers iteratively define and represent design problems (Akin 2002). Therefore, it is often difficult for these different disciplines to agree on a common parametric representation of the design, particularly when opportunities for collaboration are limited by organizational and/or geographic boundaries (Burry and Kolarevic 2003; Holzer, Tengono et al. 2007). Few methods have been developed to instruct practitioners on how to use parametric methods in collaborative, multidisciplinary environments, and those developed have not been pervasively disseminated. Second, there is limited interoperability between parametric CAD tools commonly used by architects and CAE tools commonly used for engineering analysis. With a few exceptions (Shea, Aish et al. 2005; Holzer, Hough et al. 2007; Flager, Welle et al. 2009), engineers are not able to provide timely simulation-based performance feedback on the parametric variations generated by the design team.

This paper introduces the Design Optioneering methodology that aims to address the limitations associated with parametric modeling discussed above. The paper is presented in the following structure. First, a Design Optioneering method is described. Second, the context of initial use of the method by students in a parametric design course at Stanford University is described and the findings of the use-case are presented. Finally, the potential and implications of Design Optioneering to reduce latency and enable the evaluation of more design alternatives in practice is discussed.

THE DESIGN OPTIONEERING METHODOLOGY

The Design Optioneering methodology for Multidisciplinary Design Optimization (MDO) consists of three primary activities which are described in more detail below: problem formulation, process integration, and design exploration / optimization.

Problem Formulation

The first step is to formally define the design problem including the design objective, variables and constraints. The design objective is the goal of the optimization exercise and generally involves maximizing or minimizing a real function (e.g. cost, energy consumption, etc.). The constraints are the criteria that a design option must satisfy to be considered feasible. Finally, the variables are the parameters of the design that the can be manipulated within a defined range to achieve the objectives and satisfy the constraints.

Definition of the problem objective, constraints and variables are then used to

inform the creation of an associative parametric digital model. This involves creating a parametric representation of the project in CAD that is driven by the design variables specified. Designers can then test the parametric model by modifying the variable values and observing the resulting design configuration to ensure that it is consistent with design intent. This process is often iterative; observations made from variable testing can lead to the selection of new variables and/or ranges as well as the refinement of parametric model logic.

Process Integration

The goal of this activity is to create an integrated process model that includes the parametric CAD model created in the previous activity as well as any CAE models used to assess design objectives and constraints. Process integration involves first defining the information dependencies between all of the CAD/CAE tools used in the design process. Next, the data flow between the tools is automated to reduce design cycle latency that is pervasive in current practice. Finally, the integrity of the data flow and the analysis representation is checked by modifying the variables in the parametric CAD model and ensuring the necessary analysis configurations update correctly to ensure rapid evaluation of all design domains.

Design Exploration / Optimization

Once the design problem is formalized and an integrated process model has been created, the designer is capable of completing a design cycle much more rapidly than conventional processes. However, exploring the design space using manual trial and error methods is still often impractical due to the large number of possible alternatives (Flager, Aadya et al. 2009). In this case, computational techniques such as Design of Experiments or optimization algorithms can be applied to systematically explore the design space in an automated fashion.

COURSE BACKGROUND

The course "CEE 135A/235A: Parametrics - Applications in Architecture and Product Design" was originally conceived by the authors in 2008 to explore how to capture and communicate design intent using parametric methods at both an architectural and a product scale. The course was first offered in the fall term of 2008 to undergraduates and graduates in product design, architectural design and engineering disciplines at Stanford University. The course evolved through two quarter offerings at Stanford University's Civil and Environmental Engineering (CEE) Department. The more recent course offered in the spring of 2010 included the addition of the Design Exploration module which involved coupling the parametric model with integrated simulation-based analysis and using computational design exploration and optimization techniques. For this course which is described in more details below, author Flager developed the curriculum and served as the primary instructor and author Gerber participated as a guest lecturer.

Objectives

The pedagogical goals for the course are as follows: (1) be proficient with parametric modeling methods and understand the strengths and limitations of these

methods with regard to capturing design intent; (2) learn to communicate design intent to others in a multidisciplinary team; (3) understand how to integrate parametric CAD tools with CAE tools; (4) be able to critically assess a given design logic/process and its impact on the range of possible solutions, emphasizing the value of solution space thinking; and, (5) hear from leading design practitioners about how they are applying parametric design concepts to their own work.

The primary research goal for the course was to get user feedback on the Design Optioneering method in the following areas: (1) effectiveness in capturing design intent; (2) quality of performance feedback provided; (3) ability to systematically search through the design space in search of preferred designs; and (4) ease of use. A second research goal was to document how multidisciplinary design teams collaborate using the Design Optioneering method and to compare these observations to conventional design methods.

Structure

The course was organized in two modules (1) defining the design space and (2) exploring the design space. The former module provided instruction related to parametric modeling methods and communicating and abstracting design intent into computable and shareable constructs. The later module dealt with methods for integrating parametric CAD with CAE tools as well as computational optimization and sampling methods to systematically search the design space for high performance solutions. Class time was divided approximately equally between lecture and studio / workshop components. The lectures are structured to give students a background in parametric design and its applications. Topics include design theory, precedents in architecture and product design, as well as methods for mapping design intent to parametric logic and design exploration. Workshops are designed to provide students with hands-on experience with parametric modeling and simulation software that will be used to complete the design exercises. The workshop time is also used to mentor individuals and teams on their design projects.

Assignments

The primary assignments for the course were the completion of three design projects: (1) beverage container, (2) building façade, and (3) tall building (final project). The first two design exercises are described below and the final project is explained in the following section.

The objective of the first assignment was to introduce the class to associative parametric modeling methods. The brief was to select a single factor to drive the physical form of a beverage container (e.g. ambient temperature, user age, etc). Students began by sketching what they thought would make a good beverage container for the extreme cases given the chosen driver and then identified at least three geometric dimensions that responded to the customer needs identified from their driving concept. Next, students described the dependencies between the design driver, the customer needs, and the geometric parameters using a logic diagram. Finally, the students created a 3-D parametric CAD model of the beverage container and documented the possible geometric variations.

The second assignment was to design a façade system for a series of rail

station canopies to be built in various Chinese cities. The functional requirements for the façade were to provide shading from direct sunlight during the summer and to allow solar penetration and maximum day lighting during the winter. The design challenge was to create a single parametric façade panel that could satisfy the requirements above for the specified canopy geometries and geographic locations. The second project instructed students in the value of developing and prototyping a design logic for repeatable deployment, where each instance was topologically identical but geometrically unique given the varying context of the panel. As with the first assignment, the deliverables were a parametric logic diagram and 3-D parametric CAD model that could be reconfigured to each of the specified station locations.

COURSE FINAL PROJECT

For the final project, the students worked in teams of three to apply the Design Optioneering Methodology to group design project. The project brief was the design of a tall building for a pseudo corporate client to be located in the Middle East. Each student played the role of a specialist and was responsible for the design of a particular subsystem of the tower: architecture, structure, and façade. The assignment was divided into two parts: (1) subsystem design involving the optimization of the tower form considering only a single design discipline; and, (2) system design involving the optimization of the tower form considering all of the design disciplines simultaneously. The application of the Design Optioneering method to address the final project brief is discussed below.

Problem Formulation

The objectives and constraints for each subsystem were included in the design brief as described below:

Architecture	Structure	Facade
GOALS • Appropriateness to site context • Symbolize commitment to sustainable design • Maximize IRR over a 10 year period CONSTRAINTS • Net Leasable Area (NLA)	GOALS • Minimize cost of structure CONSTRAINTS • Material stress • Global tower deflection • Net Leasable Area (NLA)	GOALS • Maximize daylight factor CONSTRAINTS • Solar gain • Façade cost • Net Leasable Area (NLA)

Based on the design brief, each multidisciplinary student team collaboratively developed a design scheme through charettes and then created a digital parametric model of the tower design concept. The parametric model was driven by a set of variables that the design team planned to vary to optimize the performance of the tall building concept.

The construction of the parametric model was one of the most challenging aspects of the assignment. Student teams generally took one of two approaches to parametric model creation: the first approach was to create the parametric model collaboratively, essentially all team members participating concurrently in the modeling process. Teams that used this approach were generally satisfied with the quality of the parametric model, but felt that having all team members participating concurrently in the modeling process limited the productivity of the team.

Alternatively, some teams assigned the architect role to create the parametric model with relatively little input from others. In this scenario, the architect found it difficult to communicate the parametric logic to the rest of the design team. In addition, the other team members often found the parametric model deficient in that it did not afford them enough flexibility to explore desired design variations that were significant for their particular discipline.

Process Integration

A variety of analysis tools were required to assess the performance of a given design option with respect to the design objectives and constraints defined above. The software tools used and their purpose are described below.

Software Name	DIGITAL PROJECT	OASYS GSA	MICROSOFT EXCEL
Description	Parametric CAD	Structural Finite Element Analysis (FEA)	Spreadsheet
Parameters Calculated	• IRR • NLA • Daylight Factor • Solar Gain	• Material Stress • Global tower deflection	• Construction Cost • IRR

Phoenix Integration's ModelCenter® software was used to automate the execution of the commercial software tools described above and to integrate data between the different domain specific CAD/CAE applications into a single common environment.

In general, students were able to successfully create integrated process models. Many students found it difficult initially to create analysis models that were robust for all possible configurations of the parametric model, but felt that they became more stilled in this area as the assignment progressed. Students also commented that while these models enabled significant reductions in design cycle time compared to conventional methods, they are required substantially more time to set up. As a result, students had to wait much longer than expected to receive preliminary feedback on the performance of their design concept and, therefore, had relatively little time to revise the model parameterization if they were not satisfied with the initial iteration.

Design Exploration / Optimization

Once the students had created and tested integrated process models for each

subsystem as described above, computational methods were applied to iterate analyses of the design across the range of design variables to best achieve the specified objectives while satisfying the constraint(s). In this case, students used Design of Experiments techniques (Booker 1998) and the SEQOPT optimization algorithm (Booker, Dennis et al. 1999; Audet, Dennis Jr et al. 2000) to explore the design space. Sample results of the optimization process for two tower design concepts are shown below.
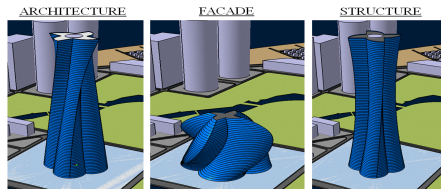

Figure 1: Sample final project results showing optimal tall building forms from the perspective of each subsystem (courtesy of John Basbagill, Spandana Nakka and Jieun Cha)

The students found the computational techniques provided to be extremely valuable to the design exploration process for three reasons: (1) it allowed them to evaluate many more design alternatives than otherwise possible; (2) it lead them to counterintuitive design solutions can they otherwise would not have discovered; and, (3) The large sample size provided the design team with piece of mind that they had indeed found the best performing design configuration given the set of variables considered. Suggestions to improve the usability of these tools included making the optimization process more interactive by making the results viewable in real time. In addition, the students would have appreciated more formal training in computational optimization techniques before beginning the design project.

CONCLUSIONS

The Design Optioneering methodology was presented and applied by students to a multidisciplinary design project involving the optimization of a tall building massing considering architectural, structural, and façade performance. In general, the students felt that Design Optioneering enabled them to substantially reduce design cycle latency, and enable the evaluation of more design than conventional design methods. It was observed that the method required a substantially different approach to the design that the students were accustomed to. Perhaps the most significant changes involved the requirement to define the complete range of design alternatives at the beginning of the process and the relatively long set up time required to create the integrated process models. At the beginning of the class, students struggled to understand how a given design parameterization might impact the range of design forms and performance, but the students became much more skilled in this area with practice. Further research is underway to make Design Optioneering more collaborative and interactive as well as to understand what types of design problems are best suited for this method.

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