A COMPARISON OF MULTIDISCIPLINARY DESIGN, ANALYSIS AND OPTIMIZATION PROCESSES IN THE BUILDING CONSTRUCTION AND AEROSPACE INDUSTRIES

Forest Flager, John Haymaker

Department of Civil and Environmental Engineering, Terman Engineering Center, Stanford, USA

ABSTRACT: Advancement in computer-based product modeling and analysis tools now allows diverse disciplines to simulate product performance in the early stages of Architecture, Engineering and Construction (AEC) projects. However, the capability of this technology to permit AEC professionals to quickly create, represent and rigorously analyze design options from the perspective of multiple disciplines has not been fully realized compared to other industries such as Aerospace. This paper compares Multidisciplinary Design, Analysis (MDA) and Optimization (MDO) processes in the AEC and aerospace industries based upon case data gathered on recent projects in each industry. Case study results are then generalized by industry to highlight the respective strengths and limitations of current practice in each industry to support effective MDA and MDO. Finally, the appropriateness of adapting methods and technology developed in the aerospace on AEC projects is discussed.

1 INTRODUCTION

Advancements in computer-based product modeling or Building Information Modeling and analysis methods now allow architects and engineers to simulate building performance in a virtual environment. The number of performance criteria which can be analyzed from product models now includes to some extent architectural, structural, mechanical (energy), acoustical, lighting and an expanding list of other concerns [Fischer 2006]. Consequently, performance-based design supported by product models is becoming state-of-the-art practice [Hänninen 2006].

Building orientation, massing and systems selection (e.g. structural, mechanical) are typically determined early in the design process and have a significant impact on the life-cycle economic and environmental performance of a facility [Smith 2003]. However, the potential of this technology to inform the early stages of the design process not been fully realized because current tools and processes do not support the rapid generation and evaluation of alternatives.

The amount of time required to generate and evaluate a design option using model-based methods means that very few, if any, options can be adequately studied during the conceptual design phase before a decision must be taken. Often engineers resort to using model-based methods only to validate a chosen design option, rather than to explore multiple alternatives. The inability to quickly generate multiple options and to rigorously analyze them from the perspective of multiple disciplines invariably leaves a broad area of the design space unexplored. The uncharted regions of the design space - different building orientations, massing, internal layouts and combinations of systems (i.e. structural and mechanical) - potentially may contain better performing building solutions than anything previously considered [Shea et. al. 2005].

The aerospace industry faces similar design challenges due to the close integration required between vehicle components to achieve stringent performance requirements. The tight performance coupling between system components challenges conventional design paradigms [Bowcutt 2003]. To address this problem, the aerospace industry has developed and successfully employed unconventional approaches, among them parametric geometry definition, automated discipline analysis and multidisciplinary optimization (MDO) [Bowcutt 2004].

This paper compares MDA and MDO processes in the AEC and aerospace industries based on case study data gathered from each industry. First, we present the limitations of current AEC practice based on a series of directed interviews with architects and engineers from a leading firm. Next, we discuss methods for Design Space Exploration (DSE) and MDO that have been developed and are currently being utilized by the aerospace industry based on case study data gathered through a similar set of directed interviews. Finally, we consider the appropriateness of adapting methods and technology developed in the aerospace industry to AEC projects.

2 BENCHMARKING THE CURRENT BUILDING DESIGN PROCESS

2.1 *Process description*

The conceptual building design process is characterized by the collaboration of architects and engineers who collectively define their performance goals and then generate and evaluate design alternatives to find a solution that best meets the these goals [Rosenman and Gero 1985, Haymaker and Chachere 2006]. This process can be characterized by three iterative steps (Fig. 1): (A) the architect creates a design option based on perceived stakeholder requirements and, depending on the project, engineering heuristics. The architectural team represents the option in the form of sketches, 2-D drawing and/or a 3-D CAD model to communicate with the project team. (B) The engineering team then spends a significant amount of time integrating this information in order to construct discipline-specific analysis models to simulate the behavior of a particular building system. The representation of the option required for a particular analysis varies depending on the system to be modeled, the requirements of the analysis tool, the particular behavior to be studied, and level of accuracy required. The analytic results are then used by the engineering team to complete the initial design of their respective building systems which are each, in turn, communicated to the rest of the design team in the form of sketches, 2-D architectural drawing and/or a 3-D CAD model. (C) Finally, the design team conducts meetings to ensure that the building systems are coordinated and are consistent with the architectural concept. The coordination process is also labor intensive and typically focuses on resolving conflicts so as to reach a feasible design option rather than optimizing the performance of the building as a whole.

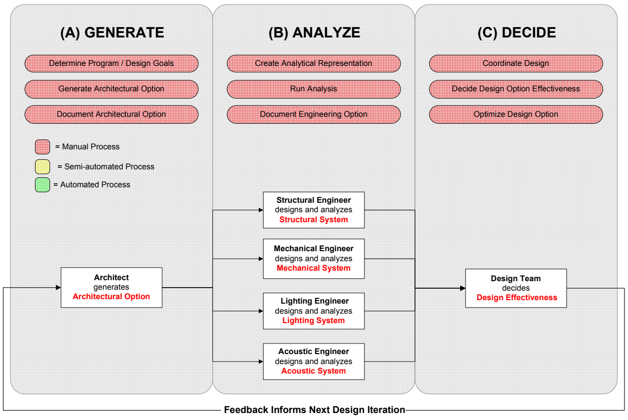

Figure 1. The current building design process.

2.2 *Process metrics*

To assess the effectiveness of the current process and provide a baseline for future research using time as the unit of analysis, a survey of architects and multidisciplinary engineers at a leading practice[1] was conducted. The goal of the survey was to determine (1) approximately how many design iterations are possible within a standard project timeline and how long iteration customarily takes as well as (2) the relative amount of time spent on key process tasks. Based on an information-processing view of design teams [March 1956, Galbraith 1977, Jin and Levitt 1996], these tasks were then classified into four categories based on their relationship to design information – specification, execution, management, and reasoning – which are defined in Figure 2.

The following working definitions were given to those surveyed:

- *Design option:* A particular configuration of the following variables: building orientation, massing and system types (e.g. structural – steel framing, mechanical – radiant floor system). Changes to one of more of these variables constitute a distinct design option.
- *Design iteration:* The generation and analysis of a single design option using model-based methods (Figure 1: steps A-D). The level of information required to demonstrate the feasibility of an option was set to a common industry milestone known as "25% Design Development (DD)", which includes the preparation of architectural drawings, the selection of building systems and the preliminary positioning and sizing of system components.

The results of the survey are shown in Figure 2. These results suggest that architects and engineers spend the majority of their time managing design information (54%) and relatively less time executing (36%), reasoning (8%) and specifying (6%) this information.

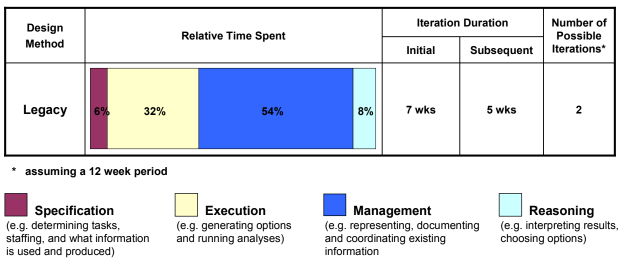

Figure 2. Building design process metrics.

2.3 *Summary of limitations*

Conceptual design decisions have a significant impact of the life-cycle economic and environmental performance of buildings. Performance-based analysis methods supported by product models have little opportunity to influence these early stage design decisions due to schedule limitations. According to the initial survey it takes architects and engineers over one month to generate and analyze a design option using product models and, typically, less than three such iterations are completed during the conceptual design phase.

This appears to be due to a collection of tool and process limitations. Part of the problem is that designers' tools are intended to generate static design options rather than help them define and explore solution spaces. Another problem is that when information is produced, little consideration is given as to how to represent that information to facilitate multidisciplinary analysis. Many have written about the difficulties of tools used by different disciplines to share data effectively [i.e., Gallaher 2004]. As a result, design professionals appear to be spending less than half of their time doing work directly related to design and analysis. The majority of this time is spent managing design information, including manually integrating and representing this information in their task-specific format, and coordinating their solutions (Fig. 2). These limitations

[1] Survey results were obtained in February, 2007 from 50 design professionals (5 architects, 45 multidisciplinary engineers) working at Ove Arup and Partners (www.arup.com) in San Francisco, USA and London, England.

prevent a more complete and systematic exploration of the design space based on multidisciplinary model-based performance analysis.

The aerospace industry is in the process of overcoming a similar set of limitations by adopting a suite of technologies and methodologies to support multidisciplinary analysis (MDA) using product models, among them parametric geometry definition, integrated design schemas, automated discipline analysis and multidisciplinary optimization leading to improved process and product performance. Our intuition is that these methods and technologies can be adopted by AEC design teams to significantly reduce the time required to generate and analyze a design option using model-based methods. Reducing the design iteration time will allow architects and engineers to formally investigate the performance of many more design alternatives within the current project timeline than is currently possible. This work has the potential to improve building performance in terms of initial cost, energy performance and overall quality.

3 CURRENT AEROSPACE PRACTICE

3.1 *Background*

Aircraft design is typically broken down into three phases [Nicolai 1975]: (1) concept design, where the mission's requirements are defined and the vehicle topology is identified based on those requirements; (2) preliminary design, where the external shape and positioning of major components (e.g. engines, fuel tanks, cockpit) are determined and approximately sized; and (3) detailed design, where the remainder of the vehicle components are specified. Generally, the external shape directly influences flight performance while structural characteristics are substantially determined by the layout of internal components [Vandenbrande et. al. 2006].

In 1998 Boeing began a project to design a hypersonic vehicle as part of the National Aero-Space Plane (NASP) program. The mission requirement was for the vehicle to take off from a commercial airport and deliver a payload into the upper stratosphere. Preliminary design was critical to this project as close integration between the vehicle components and the external shape were required in order to achieve the desired performance level (Fig. 3).

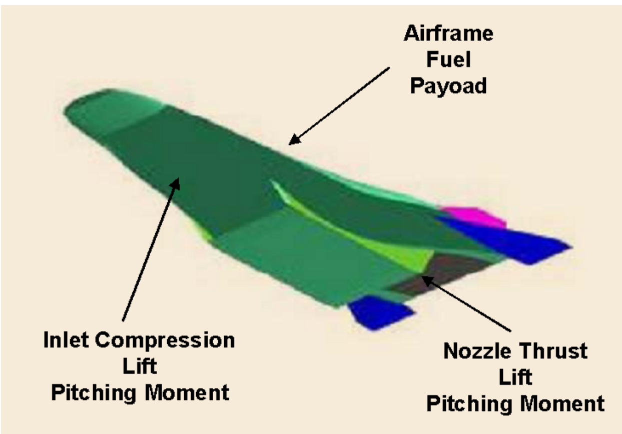

Figure 3. Close integration of vehicle components is required to achieve hypersonic performance.

After six years of project work using legacy design methods similar to those used in the AEC industry (Fig. 1), the design team was unable to produce a design that was capable of meeting the mission requirements. In 2002, Boeing began to adopt a suite of technologies and methodologies to support multidisciplinary analysis (MDA) using product models, among them parametric geometry definition, integrated design schemas, automated discipline analysis and multidisciplinary optimization leading to improved process and product performance.

3.2 *Process description*

Boeing's Multidisciplinary Optimization (MDO) process is organized fundamentally differently than traditional design processes. Figure 4 shows the main components: (A) the design team defines the design space by creating a parametric vehicle topology and then selects the parameters to be varied and their associated ranges. A new geometry model is created for each point in the design space corresponding to a particular parameter configuration using a parametric CAD tool. (B) Each discipline then analyzes the design represented by this geometric model and produces analysis results (e.g. lift, drag, heating, and mass properties). These parameters are used to compute the flight trajectory and corresponding fuel requirements. (C) A Design Explorer controls the selection of new parameter configurations using statistical methods based on the need to explore the entire design space. The optimizer, in turn, uses the performance feedback to find the most promising areas in the space. The implementation of this process is explained in more detail below.

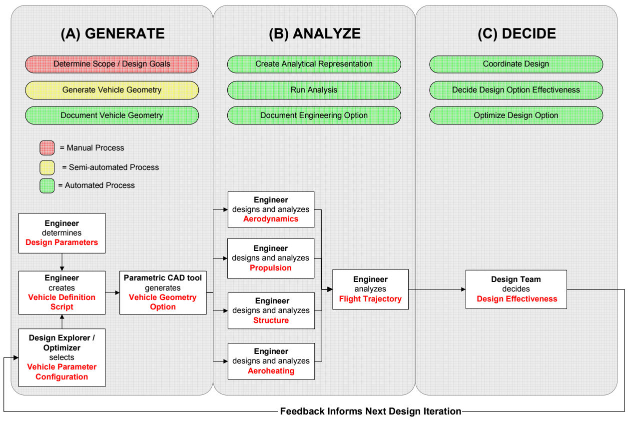

Figure 4. A systematic design space exploration process for aerospace vehicle design [based on Vandenbrande et. al. 2006, Fig.7].

(A) *Vehicle topology definition and parameterization:* The structure of the design space and the parametric model are both defined with each other in mind. One of the most challenging aspects of the process was determining suitable parameters to control the desired shape change behavior and the necessary rules for vehicle definition such that any combination of parameters produces a sensible configuration. The vehicle was parameterized using 12 global independent variables that are illustrated notionally in Figure 5.

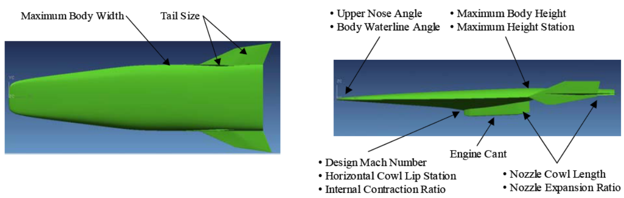

Figure 5. Design variables selected for vehicle optimization[2].

(A) *Geometry creation:* The ability to automatically create vehicle geometry based on parametric variations and to produce discipline-specific geometry data for analysis is a key element of the MDO process. This was achieved using an internally developed geometry generation tool called the General Geometry Generator (GGG). The basic requirements of this tool are the following [Vandenbrande et. al. 2006]: continuous function of the input parameters – ideally the geometry should morph differentially, enabling the calculation of partial derivatives of the computed performance characteristics with respect to the design parameters; explicit shape control to ensure any combination of parameter values produces a valid vehicle geometry for analysis; and, finally, the capability to embed engineering knowledge into the geometry generation to support the necessary analysis codes.

(B) *Analysis:* Disciplines included in the MDO were aerodynamics, propulsion, structure (mass properties) and aeroheating. The tools used for analysis ranged from spreadsheet models based upon geometric scaling relationships to full 3-D computational fluid dynamics (CFD) simulations. Each vehicle configuration was analyzed over a range of speeds, altitudes and angles of attack. The results, including lift, drag, mass properties and heating, were then input into a performance module to analyze vehicle flight trajectory in order to determine the fuel required to meet a user specified mission.

(A-C) *Process integration:* Phoenix integration's ModelCenter® and AnalysisServer® [Ng and Malone 2003] provide the underlying framework for integrating the hypersonic vehicle MDO process. Analysis server allows legacy codes to be "wrapped" and published on a computing network. This allows disciplines to keep ownership of their codes, maintain and upgrade them, and serve them from their preferred computing platform. ModelCenter provides a graphical environment which permits users to select published components and graphically link their inputs and outputs as required to create an integrated MDA model (Fig. 6). Tool integration using ModelCenter required significant set-up time as "wrappers" were custom written between tools on a point-to-point basis. Once the integrated process is in place, however, the time and labor expended in exchanging data between each discipline's design and analysis codes (which are often on different computer systems) were almost completely eliminated.

(A) *Design explorer and optimizer:* The optimization problem was defined as finding the set of 12 independent design parameters (Fig. 5) that minimized the vehicle's Take-Off Gross Weight (TOGW) subject to the following three constraints: available propellant being greater than that required to accomplish the mission; temperature being maintained within prescribed limits; and finally, tail surfaces sized to meet preliminary stability and control requirements. The tool used to define Design of Experiments (DOE) matrices, build Response Surface Models (RSM), and perform the optimization was Boeing's Design Explorer [Cramer and Gablonski 2004]. A key tool in this kit is the Design and Analysis of Computer Experiments Package (DACEPAC) [Booker 1998], which provides a means for exploring the relationship between simulation input variables and output values by constructing surrogate models. A sequential optimizer is then used to find the optimal surrogate model.

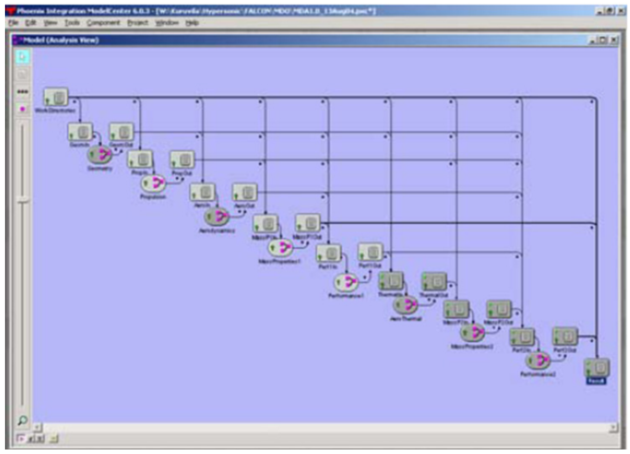

Figure 6. Sample ModelCenter interface for hypersonic vehicle MDO process [Bowcut et. al. 2004].

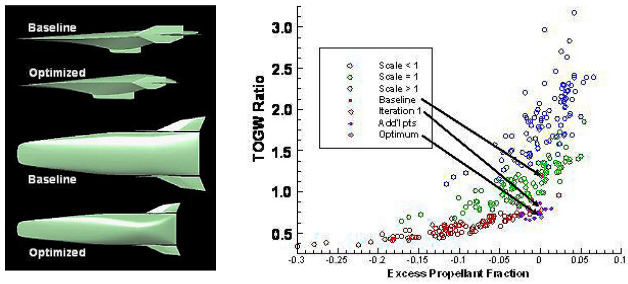

Figure 7. Hypersonic baseline vehicle versus optimized shape. Each point in the graph represents a unique design option. The desirable designs have a relatively low TOGW and a positive excess propellant fraction[3].

3.3 *Process results*

The aim of the study was to minimize vehicle take-off gross weight (TOGW) while satisfying the mission requirements. The MDO process described above produced 98 different vehicle configurations and analyzed 3900 engine inlet flow paths (including 3-D CFD analysis) in a fully automated loop over the course of six days. In contrast, in the previous eight years of the project using legacy methods, only 12 vehicle configurations and 116 engine inlet flow paths were analyzed by a dedicated team of people to reach a baseline design [Bowcutt et. al. 2004]. The MDO process improved baseline TOGW by a

[2] Image courtesy of Geojoe Kuruvila, Associate Technical Fellow, The Boeing Company

[3] Image courtesy of Geojoe Kuruvila, Associate Technical Fellow, The Boeing Company

39% margin (Fig. 7) despite an increase in drag. This dramatic improvement resulted from non-intuitive changes in the vehicle configuration. The vehicle is shorter and narrower, yet taller; the engine is longer; and the tail control surfaces are smaller.

3.4 *Process metrics*

To assess the effectiveness of the current process and provide a baseline for future research using time as the unit of analysis, a survey of multidisciplinary engineers at Boeing that had worked on the project before and after the implementation of the MDO method was conducted. The guidelines for the survey were designed to be comparable to the AEC survey described in Section 2.2.

Design Method	Relative Time Spent	Iteration Duration		Number of Possible Iterations*
		Initial	Subsequent	
Legacy	8% / 32% / 50% / 10%	6 wks	4 wks	2.5
MDO	26% / 18% / 8% / 48%	14 wks	1.5 hrs	>1,000**

* assuming a 12 week period
** after process set-up has been completed

Specification (e.g. determining tasks, staffing, and what information is used and produced)
Execution (e.g. generating options and running analyses)
Management (e.g. representing, documenting and coordinating existing information)
Reasoning (e.g. interpreting results, choosing options)

Table 2. Comparison of legacy and MDO process metrics for the design of a hypersonic vehicle.

The results of the survey indicate that the design iteration duration using legacy methods on this project is similar in duration to the results for a typical project in the AEC industry. It is also apparent that although the MDO process requires significantly longer setup time when compared to legacy processes, it was dramatically more efficient once in place. The distribution of how engineers spent their time varied significantly between the legacy and MDO method. Using the legacy design process, engineers spent half their time managing design information (55%) and relatively less time executing and reasoning with this information (42%). These results are similar to the distribution observed in the AEC industry. Using the MDO process, engineers spent only 8% of their managing design information. Once the process had be specified and automated, the rest of the time was spent on the more "value-added" activities of executing and reasoning with this information (66%).

3.5 *Lessons learned*

One of the major challenges of the project was to define the vehicle's topology and parameters. The design team invested a significant amount of time in determining the suitable parameters to control the desired shape change behavior and identifying rules for vehicle definition such that any combination of parameters produced a sensible design option for analysis. Frequently the rules and key parametric relationships were only discovered by trial and error during the development of the vehicle's configuration.

The time required both to create the parameterized model and to integrate the necessary software challenged the patience of the design team. The team had to wait nearly four times as long as they were accustomed to before reviewing analytical results for a design option. This being the first implementation of a large-scale MDO process at Boeing, it required a great amount of faith in the MDO process on the part of the team. Now that the process is better understood, expectations can be managed more effectively. The team felt that the integrated software platform that was developed could be reused for subsequent design processes with minor modifications.

Finally, the MDO process drastically changes the role of the engineer. Instead of applying expertise to manipulate a set of parameters for a given vehicle configuration, the MDO process requires the engineer to help determine the parameters and rules that define the design space without a specific configuration in mind. Once the process is implemented, engineers spend a great deal more time interpreting results, deciding between options and reconfiguring the design space towards more promising areas. For example, in the legacy process a designer might be expected to review analytical results for a single option in a day. In the MDO process, designers were frequently asked to review results from over 20 options in a day. At the same time, the workload for other tasks decreased sharply. The MDO process therefore requires a different design philosophy and team skill set than legacy methods.

4 SUMMARY AND CONCLUSIONS

Decisions made early in the design process have a significant impact on the life-cycle economic and environmental performance of buildings. Engineering simulation supported by product models is becoming state-of-the-art practice in the AEC industry. However, the potential of this technology to inform early-stage design decisions has not been fully realized because current tools and processes do not support the rapid generation and evaluation of design alternatives.

Boeing has developed and successfully implemented an MDO process to address similar problems in the aerospace industry leading to significant improvements in process and product performance. The requirements of this MDO process, including a parametric geometry generation system, software integration tools to automate the exchange of model-based information, and methods and tools for design optimization will now be discussed in regard to their potential application within the AEC industry:

- *Parametric geometry generation system:* A few academics and practitioners [Burry 2003] are utilizing parametric design representations in their research and practice. Norman Foster's practice, for example, utilizes parametric methods to explore and refine design solutions. However, the extent to which these generative systems are driven by engineering performance criteria has been limited by a lack of integration with analysis tools and processes. Further work is needed to determine if the necessary analysis representations can be defined in advance for a range of options and if geometric dependencies can be identified and captured within a parametric model.

- *Software integration tools:* The integrated software platform developed for the Boeing MDO process required a significant investment in time and resources to automate data exchange between a specific set of tools. It is unlikely that a single AEC firm would make a similar investment given the relative number of different firms involved in a typical project and the variability of software tools compared to aerospace projects. A significant amount of work has been done to develop information exchange standards in the AEC industry [Karola et. al. 2002, Lee et. al. 2003, Eastman et. al. 2005]. Further work needs to be done if this area to simplify these standards and document the benefits of such an approach in order to encourage industry-wide adoption.
- *Multidisciplinary design optimization:* MDO requires the capability to quantify system effectiveness in terms of a global objective function and constraints. Further work is needed to determine if is beneficial to quantify the conceptual design of an AEC project in such a fashion.

Based on the success of Boeing's implementation of the MDO process in the context of the aerospace industry, this process holds great promise for improving the AEC design process. After reviewing the requirements for MDO, however, it is apparent that there is considerable work to be done to make such a process feasible in an AEC context. However, incremental benefits can be gained through parallel research in each of the above areas. It is useful to examine work done in other industries throughout this process to see what insights might be gained to improve performance-based design processes for the early phases of AEC projects.

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