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STRATEGIES FOR AXIOMATIC DESIGN EDUCATION

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ABSTRACT

This paper addresses the needs for teaching axiomatic design—for engineers in industry and regular and part-time graduate students. Axiomatic design consists of principles for making good design decisions, models for designs, and a process to follow, but how can these ideas be adopted and implemented within a company's product development process? There are several challenges in successful implementation and adoption of axiomatic design by companies and practicing engineers. The challenges are especially difficult when processes and established ways of doing things are to be changed. How can courses or training in axiomatic design be designed to equip engineers and students with the necessary skills and lead to sustained use of the theory? This paper addresses four educational contexts in answering this question: engineers who receive a short training course on the theory and methods, full-time graduate students, students who work full time while also pursuing graduate degrees, and finally students in international settings. The authors discuss the objectives in each case, the constraints, the requirements for the courses, and the strategies for satisfying them. Cases are drawn from several industries, experiences of various students, and from courses taught in the United States and China. A case study is presented of a graduate-level course for students working in industry.

Keywords: design theory, axioms, education and training, industrial application.

1 INTRODUCTION

Traditional approaches to engineering design education have been experience-based. A primary goal envisioned for axiomatic design is to overcome this bias by providing a scientific-basis for design practice. As Suh states, "the goal of education is to transmit systematic and generalizable knowledge, rather than experience to those initiated in the art and science." [1] The key is to teach both process and principles. "In design, we also need to do both. We need to teach both the process and the abstracted concept of what is a good design and how to develop good designs." [2] When considering application of axiomatic design to industrial projects and its implementation within companies' projects, this science base for design intersects with several other disciplines and considerations.

This paper is structured as follows: Section 2 outlines technology-driven changes in design processes and challenges in teaching and implementing axiomatic design. Section 3 presents course design including the contexts in which axiomatic design has been taught, system-level design, and detailed design of the courses. Section 4 presents a case-study of a modular course for part-time graduate students who are employed in industry—especially regarding the application of axiomatic design within the company's development process. Section 5 presents a summary and conclusions.

2 BACKGROUND

Having a fundamental understanding of design has become increasingly important as the pace of technological development has accelerated due to global competition and collaboration. Ertas describes the way that technology has driven changes in design and development processes. Products have become integrated systems, and design and production requirements have crossed discipline boundaries. This requires input from other disciplines in addition to science and engineering, such as business, social sciences, medicine, etc. Knowledge from many disciplines must be integrated into an effective system or product. As this process has continued to accelerate, the need has shifted from multidisciplinary or interdisciplinary design teams to cross-organization or even cross-continent work. [3]

Technology often has preceded and led to the establishment of scientific fields. [2] Today the need is for a "transdisciplinary" model for education and research that can transcend traditional disciplinary or organizational boundaries to enable the solution of large problems by teams of people from diverse backgrounds. [4] *Transdisciplinary* goes beyond *multidisciplinary* (involving several disciplines in examining a shared topic) and *interdisciplinary* (borrowing a research method from one discipline to another) to mutually share methods and subjects between disciplines. [5]

The essence of this transdisciplinary model will be "a foundation of design fundamentals and process development and management....This core is then surrounded by knowledge and skill 'tools' selected from various disciplines. These tools can be updated as needed to keep pace with developing technology. The learning environment offers instructor facilitated team projects and discussions rather than the traditional classroom lecture." [3]

Axiomatic design is an example of a transdisciplinary foundation. [6] and [2] show how axiomatic design can be applied to design tasks in many disciplines, including the semiconductor, automotive, aerospace, software, and financial-services industries. To create a scientific foundation for design, axiomatic design provides discipline-independent representations of designs, a general design process, and criteria for effective making.

Even though much research has been done on axiomatic design, and many courses in the subject have been taught, the number of researchers who have discussed the teaching of axiomatic design has been rather limited. In the previous two conferences focused on axiomatic design—[7, 8]—although "teaching and learning methods" was listed as a topic area of interest, there was only one paper presented in this category. [9]

However, in the literature there have been a few other papers that touched on teaching and training for axiomatic design: methods for technology transfer to industry [10], a capability maturity model for axiomatic design [11], growth of axiomatic design within industry and academia [12, 13], and axiomatic design education for concurrent engineering [14].

[11] present an axiomatic design capability maturity model. They list three factors as obstacles to technology transfer to industry: 1. Industry-sponsored research is directed at specific problems, and the methodology used to achieve the result is not captured and transferred. 2. It can be difficult to establish guidelines for a company's practice that are consistent with axiomatic design. 3. It is hard to extend from an individual engineer to an organization-wide methodology.

Suh says that "From [his] experience in teaching this subject to many engineers and students, it has become clear that axiomatic design is not an easy subject to learn, much less to master, without some effort—perhaps because of the conceptual nature of the subject. To truly understand axiomatic design, students must put theory into practice by applying the basic principles to many problems and many design tasks." [2 p. xvi]

This paper seeks to provide a foundation on which courses in axiomatic design can be constructed—with the intent that it would thereby be an easier subject for students to learn and for companies to adopt. At the least, it should provide a basis for further discussion.

3 COURSE DESIGN

Axiomatic design was originally taught as a graduate-level course at MIT by Prof. Suh starting in the 1987-88 academic year using a draft of his book *The Principles of Design* [1]. Next it was taught as a summer course at MIT during the 1990s. For a description of the outline of summer courses in axiomatic design at MIT, see [12]. In the late 1990s, Prof. Suh was writing his second book on axiomatic design, *Axiomatic Design: Advances and Applications* [2], and the organization of the class changed accordingly. (For other graduate-level courses in design as a subject for comparison, [15] and [16 especially the "Instructor Site"] presents a phase-based, topical approach to product design and development.)

This section asks, how can a new course in axiomatic design be designed? Three levels will be discussed, the customer environment, the system-level design, and the detailed design of specific content.

Sections 3.1, 3.2, and 3.3 outline the design of a course in axiomatic design. Axiomatic design itself is illustrated for designing the course. The principles and procedures illustrated here are the same regardless of the context for the course; however, specific customer needs will naturally lead to differing functional requirements, constraints, and ultimately different courses. The author will briefly address several of these contexts, but will only focus in detail on one.

3.1 CONTEXT/ENVIRONMENT

Step 1. Determine the customer needs and environment

In teaching axiomatic design, there are topics that must be covered no matter the audience. Other topics, however, are more or less important, depending on the background, interests, and objectives of the students. This section presents several different categories of students to which axiomatic design has been taught. Students have been taught axiomatic design in the following types of courses:

- <u>non-credit short courses</u> taught to groups of engineers in industry or groups of professors
- <u>full-semester graduate courses</u> for full-time graduate students
- <u>limited-time, "modular" graduate courses</u> for engineers in industry who are also part-time graduate students working towards a degree

Each group of students has their own customer needs in terms of objectives and environment. In section 4, a specific, modular course for industrial engineers pursuing master's degrees is presented.

Some customer needs are presented in the first column of table 1. The other two columns for the functional and physical domains are arranged systematically with a one-to-one correspondence between functional requirements (FRs) and design parameters (DPs). Note, however, that customer needs (CNs) are loosely structured without a one-to-one mapping.

3.2 SYSTEM-LEVEL DESIGN

Step 2. Define FRs and Constraints

The overall requirement is to teach axiomatic design. The DP to satisfy it can be a graduate course, non-credit short-course, modular course for practicing engineers, etc. as chosen to satisfy the FR according to the customer needs.

The next step is to determine the top-level functional requirements (FRs) in the functional domain. There can be many different possible sets of functional requirements (FRs). A minimum set of FRs must be chosen according to the definition of FRs. [1] The top-level FRs in solution-neutral language are

FR1 Teach concepts
FR2 Practice skills
FR3 Apply knowledge in regular practice
FR4 Coordinate with others/integrate into company's process
FR5 Transfer learning

The details of these FRs change depending on the customers. For practicing engineers, "regular practice" means projects within the company; for graduate students, it means thesis and research work. Likewise "transfer learning" can be within a company or between academia and industry.

Step 3. Map FRs to DPs

Depending on the customer needs and environment, the top-level DPs can be different. For regular graduate students, the focus is on integrating axiomatic design into their research. For short-courses, the focus is on their full-time work. For part-time graduate students, the focus falls in-between as will be shown below.

Some differences due to changed customer needs, environment, and functional requirements show up in alternate selections for DP3, DP4, and DP5. This can be approached following Suh's model for large system design, in which DPs are dynamically allocated as FRs change. [17]

For the modular, graduate-level course that will be considered in further detail, the top-level DPs are

DP1a Limited-time classroom instruction
DP2 Comprehensive project
DP3a Application to on-going projects
DP4a Project deliverables
DP5a Training and seminars

For a regular, semester-long graduate course in axiomatic design, the top-level DPs are

DP1b Semester-long classroom instruction
DP2 Comprehensive project
DP3b Application to student's research
DP4b Work with thesis committee members
DP5b Publish papers and thesis

Step 4. Determine the design matrix

The design matrix for the top-level design can be constructed once the top-level FRs and DPs have been established. An element in the design matrix, Aij, is considered to be non-zero—ie, have a strong relationship—if a change in DPj affects the student's ability to satisfy FRi. As can be seen in the design matrix, considerations of application of axiomatic design to regular practice are affected by material presented in the classroom and later practice on a comprehensive project.

The design matrix for the modular, graduate-level course is shown in equation 1. Equation 1 is seen to be decoupled.

$$\begin{Bmatrix} FR1 \\ FR2 \\ FR3 \\ FR4 \\ FR5 \end{Bmatrix} = \begin{bmatrix} X & 0 & 0 & 0 & 0 \\ X & X & 0 & 0 & 0 \\ X & X & X & 0 & 0 \\ X & 0 & X & X & 0 \\ X & 0 & X & X & X \end{bmatrix} \begin{Bmatrix} DP1a \\ DP2 \\ DP3a \\ DP4a \\ DP5a \end{Bmatrix} \tag{1}$$

3.3 DETAILED DESIGN

Once the system-level design for the course in axiomatic design is established, further decomposition can be carried out for the detailed contents of the course.

Step 5. Decompose FRs from first to second level by zigzagging

The design is decomposed into a second level once the design matrix is constructed for the first level, and independence is verified by an uncoupled or decoupled design matrix. The decomposition for FR1 "teach concepts" by means of DP1a "Limited-time classroom instruction" is given in table 2. The format of table 2 is inspired by Suh's "Four domains of an academic department". [2 p. 13]

Table 1. Example of FRs and DPs for a course in Axiomatic Design

Customer Domain (Customer needs: Objectives and environment)	Functional Domain (Functional Requirements)	Physical Domain (Design Paramters)
Part-time students (environment) limited time for course students have high motivation students have experience	**FR1 Teach concepts, theory, and methods** [See Table 2]	**DP1 Classroom instruction** [See Table 2]
Part-time students (objectives) relate to work become champion within company use on real projects	**FR2 Practice skills** 2.1 Choose topic 2.2 Gather data 2.3 Do analysis/carry design to several layers of decomposition 2.4 Integrate other skills and knowledge 2.5 Reflect on process, learning, and tools 2.6 Overall assessment	**DP2 Comprehensive project** 2.1 Student or other initiation with good scope 2.2 Talking with customers–depends on project 2.3 Individual or group work 2.4 Various–depending on company 2.5 Criteria 2.6 Three levels (teacher, individual perception, company)
Short courses (environment) no time to do in-depth projects hard to follow-up for projects saturation/overload in class participants may not be self-selected commitment level of company amount of prior familiarity of AD relevant to current process limited time available to students uneven distribution of AD knowledge within company	**FR3 Apply knowledge** 3.1 Select good topic (need specific objective) 3.2 Gather data 3.3 Perform synthesis and/or analysis 3.4 Implement result 3.5 Report	**DP3a Use in practice (within company)** 3.1 Criteria based on resources and value 3.2 Various sources 3.3 AD framework and axioms 3.4 Implementation plan 3.5 Written and oral presentation
	FR4 Coordinate with others/ integrate into company's process	**DP4a Strategy for implementation**
	FR5 Transfer learning between industry and academia 5.1 Feedback industry to academia 5.2 Within industry	**DP5a Meetings and publications** 5.1 Thesis, academic papers, and conferences 5.2 Symposia

Table 2. Detailed FRs, DPs, and Examples for skills in Axiomatic Design

Decomposition of FR1 "Teach concepts, theory, and methods" by means of DP1 "Limited-time classroom instruction"		
Functional Domain – Skills/Activities (Functional Requirements)	Physical Domain (Design Parameters)	Examples and Exercises
1 Introduce AD framework	**1 Change in thinking**	
1.1 Define concepts	1.1 Ask questions	1.1 Questions from [2] chapter 1
1.2 Separate into domains	1.2 Sorting exercise	1.2 business plan ([13] appendix 4), examples from [18, 19]
1.3 Illustrate independence	1.3 Everyday tangible example	1.3 Faucet ([2] example 3.3), slider [Excel sheet after 20]
1.4 Illustrate information content	1.4 Combination of diverse requirements	1.4 Local manuf or shipped part [18]
1.5 Introduce hierarchies	1.5 Tangible example	1.5 Tube bending ([2] example 1.6)
2 Determine CNs	**2 Data gathering and analysis**	
2.1 Collect data	2.1 Various methods (e.g., interviews)	2.1-4 Origami software project [os]
2.2 Translate customers' voice into CNs	2.2 Guidelines for writing CNs	
2.3 Group/abstract CNs	2.3 Affinity diagrams	
2.4 Prioritize/assess CNs	2.4 Various methods (e.g., Kano questionnaires)	
2.5 Form missions statement for project	2.5 Market analysis	2.5 Braille reader, cell phone market segment
2.6 Map to FRs	2.6 Vital CNs	2.6 Origami software project [os]
3 Define FRs (and define Cs)	**3 Functional analysis**	
3.1 Think functionally (and solution-neutral)	3.1 Guidelines for writing functions	3.1 Tablet PC [tpc]
3.2 Distinguish Cs from FRs	3.2 Rules for constraints	3.2 Constraints on wafer handing system [21]
3.3 Define sub-FRs	3.3 V model	3.3 Bicycle ([1] exercise 2.1)
4 Generate concepts	**Experience, knowledgebase, out of the box thinking**	Peeler (trends of technology evolution, effects database)
5 Analyze independence	**Design matrix**	
5.1 Reorder & recognize coupled/decoupled/uncoupled matrices	5.1 Skills for reordering	5.1 [1] exercises 3.10, 3.11
5.2 Create ideal design	5.2 Various theorems	5.2 Hitting a golf ball
5.3 Distinguish functional vs physical coupling	5.3 Theorems	5.3 Coke can ([2] example 1.3)
5.4 Mathematically determine coupling	5.4 Theorem 8	5.4 WPI scanning laser microscope [18], faucet ([2] example 3.3)
5.5 Integrate DM with existing mathematical models	5.5 Derive DM from existing model	5.5 sleeve and cylinder ([2] example 2.7), vacuum wheel ([2] example 3.6), naval ship design [22]
5.6 Model processes with design matrix	5.6 System architecture	5.6 Medical treatment guidelines [23]
5.7 Analyze/select concepts	5.7 Compare alternatives	5.7 xx
6 Integrate DPs	**6 V model**	
6.1 Consider ergonomics	6.1 Think about user operation and man-machine interface	6.1 Microscope workstation [24]
6.2 Consider industrial design	6.2 Visual equity and effect on costs	6.2 Laptop computers
6.3 Establish product architecture	6.3 Design matrix	6.3 AD of object-oriented software [25]
6.4 Design for manufacture/assembly	6.4 DFA guidelines	6.4 VHS tape manufacture or computer mouse [15, 16] chapter 11
7 Analyze existing designs	**7 AD model of existing design**	**Drift-pull [26]**
8 Decouple coupled designs	**8 Tools for decoupling (AD theorems su-field analysis, Altshuller's matrix)**	
8.1 Decouple through reordering matrix	8.1 Recognize decoupled matrix	8.1 Printing process [2] example 9.1, slider [Excel sheet after 20], Driver's compartment [24]
8.2 Decouple through adding DPs	8.2 Identify single DPs satisfying multiple FRs	8.2 Newcomen engine ([2] example 1.5), electric switch ([2] example 2.5)
8.3 Decouple through new concepts	8.3 Recognize need for new concepts	8.3 Disk sealing ([2] exercise 6.3)
9 Apply information axiom	**9 Data**	

Decomposition of FR1 "Teach concepts, theory, and methods" by means of DP1 "Limited-time classroom instruction"

Functional Domain – Skills/Activities (Functional Requirements)	Physical Domain (Design Parameters)	Examples and Exercises
9.1 Model design and system ranges	9.1 Model	9.1 House buying ([2] example 1.10)
9.2 Make design robust	9.2 Adjust bias and variance	9.2 Van seat ([2] example 2.6)
9.3 Meet desired range	9.3 Range of values needed	9.3 Microscope table [24]
9.4 Sum information content	9.4 Joint probability	9.4 [2] appendix 3-C, [27]
10 Manage project	**10 Project control tools**	
10.1 Check for consistency during decomposition	10.1 Master (full) matrix	10.1 Strategic planning [28]
10.2 Assign resources for project development	10.2 Project planning (Gantt chart from design matrices)	10.2 Donation software [29]

Step 6. Find the corresponding second-level DPs and design matrices

Table 2 includes

- a Customer Domain with customer needs (CNs) stated in terms of objectives and descriptions of the environment
- a Functional Domain with functional requirements (FRs)
- a Physical Domain with design parameters (DPs)
- Examples and exercises for implementing the DPs (The examples can be customized to the discipline of the students and company—in this case an aerospace company.)

4 CASE STUDY—GRADUATE COURSE FOR STUDENTS IN AN AEROSPACE COMPANY

The above approach represents the material used by the author to teach a graduate course in axiomatic design to engineers in industry. (Similar material has been used by the author in the other two contexts identified in section 3.1, for a regular graduate-level course and for short-courses for practicing engineers. However, due to space constraints, they are not presented here.)

For the past three years, the author has taught a graduate course as part of Texas Tech's Master of Engineering program in Transdisciplinary Design and Process. The course Fundamentals of Transdisciplinary Design and Process has been taught by the author a total of five times at two locations—at an aerospace company in Texas and at the main campus of the university in Lubbock.

Fundamentals of Transdisciplinary Design and Process is one of four core courses in the program—along with Systems Engineering Principles, Technical Management and Creativity, and Engineering Modeling and Analysis. The program offers two tracks: Design, Process, and Production and System Design and Integration. [30]

The bulk of the material presented by the author has been based on axiomatic design. In the program, the students at the aerospace company take one course per month, until they have accumulated the 36 units needed for the degree. The courses consist of class time on one weekend followed by projects and assignments completed over the rest of the month. In addition to the 11 courses for the degree, the students are required to complete a Master's Research Report, worth 3 credit hours.

As one of the core courses of the program, Fundamentals of Transdisciplinary Design and Process is intended to present "the fundamental aspects of design and process, which cut across the boundaries of all disciplines [and] provide a means for solving complex problems." [30] This objective is naturally met by presenting axiomatic design.

The next section will focus on the project assignments in the

4.1 PROJECT ASSIGNMENT

The course employs a project as part of the learning process. This is similar to the projects used in Suh's axiomatic design course at MIT. As Suh says in [2 p. xvi], "Nearly all the examples given in this book were generated during the course of teaching this subject and, in many cases, were solved by the students in the class or as term projects. They enriched [his] experience and enhanced his understanding of the subject matter."

One notable difference from Suh's course is that there is a constraint that the assignment for the course at Texas Tech be a group project. The instructions given to the students for the project are as follows:

> Please write a group report in which you apply axiomatic design to a project of your choice. Please provide a project description (in terms of its objective and scope). Determine a set of customer needs through interviewing appropriate customers. Produce a description of the design including at least three hierarchical levels of functional requirements, design parameters, and design matrices. Choose at least two other tools from those presented (or others that you know): KJs, Kano, Pugh concept selection, TRIZ, Taguchi methods, Gantt charts etc. and include the results of these tools in their appropriate places in the design process. Conclude with a discussion of the results of your project, the usefulness of the tools, and your view of how axiomatic design fits within your organization.
>
> So your outline would approximately look like:
>
> Introduction
> Project description
> Defining customer needs
> Design description
> Other tools considered
> Results
> Comments on usefulness of tools

Comments on applicability to your current design process
Conclusions

Table 3 shows a list of topics for the projects done by the students in the course.

Table 3. Axiomatic Design Projects

Topic	Authors	ref
2004		
The Design of a Firefighter's Thermal Imaging Heads-up Display	Christopher Adams, Kimberly Y. Ball, Mike Ballard, Missy Barnard	thd
Group Project for Axiomatic Design Module (Digital Image Viewer)	Terrence Chan, Schuyler Deitch, John Zanoff	dv
Origami Crease Pattern Generation Software Design	Brent Granstaff, Rich Koshak, Steve Reynolds, Todd Shipley	os
Axiomatic Design Principles (Design of a House)	Kent Bacon, Kent Bond, Angelito Cruz	dh
2003		
Axiomatic Design of Portable Personal Access Manager	Pete Polcari, Eric Martinson, Anthony Peterson, Larry Welch	pam
Applying the Principles of Axiomatic Design to the Development of a Tablet PC	Brandeis Marquette, Chris Rynas, T.J. Theodore, Matthew Zimmerman	tpc
Axiomatic Design Module Group Project (Home Entertainment System)	Jim Hart, Tim Smith, John Wright	hes
2002		
Axiomatic Design: Taking Systems Engineering to the Future	Jean Cathcart, Davinia Chism, Donna Maestas, Kurt Himmelreich	se
Axiomatic Design Module Group Project (House Design)	Sue Armitage, Clay Harden, Gary Irvin	hd
Retinal Scanning Identification Device	Julian Parker, Belinda Brown, Herbert Moore	rs
Integrated Home-theater Center	Jodi Morrison, Ming Nguyen, Marco Solano	htc

4.2 Implications for Axiomatic Design Use Within the Company's Development Process

This section presents the results of the projects regarding the use of axiomatic design within the company's development process.

Overview of process

The company has a well-established, formal process for integrated product teams to propose, develop, and execute solutions for customers composed of seven stages from customer needs to operations and support. The company follows a process that includes mapping and zigzagging activities. [os]

The standard methods for planning and systems engineering in all programs are defined by an overall integrated product development process, together with local directives, procedures, and plans. [thd] The students felt that the company's existing process already "possesses many Axiomatic Design concepts" especially in the early phases in which customer needs are defined and functional requirements are developed. [os] Axiomatic design concepts—domains and mapping, hierarchies, and zigzagging—are woven into the process. [os]

Customer needs ("customer requirements inputs") are solicited through "technical demonstrations; interface control working groups; technical control working groups; interim project reviews; questionnaires, interviews, and operational scenarios obtained from end users; operational analysis and end-user task analysis; prototypes and models; brainstorming; market surveys; beta testing; extraction from sources such as documents, standards, and specifications; observation of existing products and workflow patterns; use cases; business case analysis and reverse engineering". [hd]

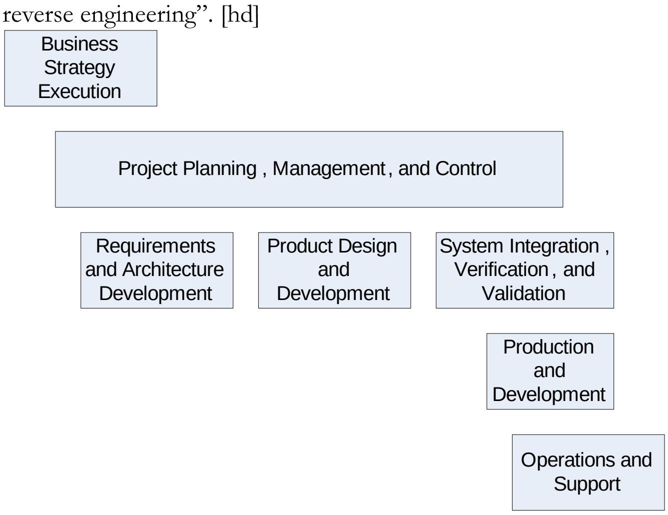

Figure 1. Outline of company's integrated product-development process [os]

In the next step, the engineers translate the customer needs into high-level functional requirements that are suitable for implementation and verification, which are recorded into a requirements management system. The requirement development procedure derives low-level requirements from high-level system requirements through a process of selecting among product and component solution alternatives. [thd] A hierarchy with three levels is constructed, composed of system, product, and component levels. Each level consists of three sets of functional, physical, and process requirements. The process is similar to zigzagging in axiomatic design, except that "DPs are not formally defined at this stage of development" and the goal is to provide sufficient coverage of customer needs, not uncoupled design. [thd]

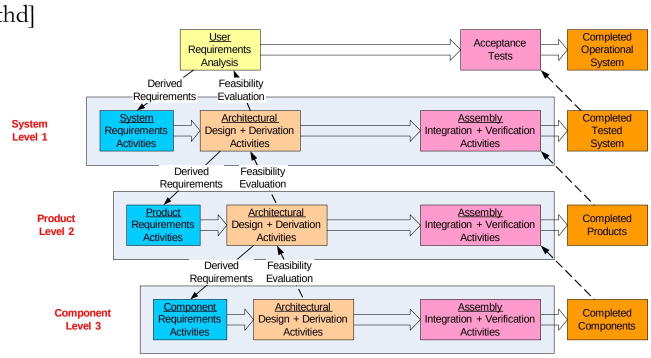

Figure 2. Levels of hierarchical design mapping and zigzagging [os]

Differences between current process and AD

Currently trade studies are used to explore many options at low cost. They are used to discover the effects of design options on performance parameters. They illustrate the strength of relationships between FRs and various design options, reveal the difficulty of creating certain design features, and indicate through sensitivity the technical difficulty of setting parameters in practice. While trade studies are most valuable when formalized and reported so that the reason for the choice of design options can be recalled, this is rarely done. [hd]

The current process places lots of attention on "what" is desired by emphasizing functional requirements and physical architectures. [se] Compared with axiomatic design, the obvious omissions in the current process are additional criteria for decision making, provided by the independence axiom and information axiom. [os, tpc] The reasons have been the complexity of the systems and lack of awareness and demonstrated benefits. [os]

The students say that while good requirements definition practices mostly capture the intent of independence, there has rarely been any formal analysis to ensure there are no relationships between the requirements. [se] Additionally, regarding one-to-one mapping, there is no specific effort or standard method to ensure there is a single design parameter for each functional requirement. [se]

One proposed solution is to insert into the process a "dependence analysis" at the "highest functional level" using design matrices and the independence axiom. This could be incorporated into future tool version releases. The goal would be to align the project approach with the customer needs and thereby drive value into the process at an early stage. The proposed analysis step would occur after creating a proposed architecture, but before cost estimation. [os]

Benefits to using axiomatic design

Overall, the company's engineers use mathematics and science to design and develop systems. AD provides a method to help focus on "the creative aspects of design" while also ensuring "functionality, performance, testability, and producibility of the system" through scientifically defining and formalizing aspects of design. [tpc] It assists the engineers to be "more creative, focused, discerning, and successful" in engineering design. [tpc] Moreover, it fostered "out of the box" thinking and "stretched the imagination of this group, but did so in a way that helped us to see new methods of achieving design excellence." [dp] The methods were easy to use and "provided a means to brainstorm ideas and to get our arms around the design challenge." [rs]

The outcome of using axiomatic design will be products with shorter time-to-market, fewer iterations, and more robust and scalable designs having "open" architectures that allow for expansion, upgrades, and technology insertion. [os]

Axiomatic design helped the students to jump start their projects and facilitated the quick progression of their projects from inception to the detail-design phase. [os]

Many groups of students reported that their natural tendency is to jump to solutions before fully appreciating the customers' needs. [os] This often leads to "over-design" or "under-design" which leads to cost issues in the design. Axiomatic design's most useful application will be during a new program's conceptual design and requirements flow-down phase. It focuses in on an often weak area of the design process—the complete understanding of functional requirements at all design levels. [hts] Axiomatic design challenges the students to be more careful with requirements decomposition and design decisions to ensure minimal coupling of functional requirements. [pam] Axiomatic design is unique from other tools that seek only to prevent design mistakes: it distances the engineer from his or her comfort zone and forces positive activity into the design process. For example, thorough evaluation of all requirements of the design and establishing their independence increases the likelihood of true top-down design that best satisfies customer needs. [se]

The tools provided by axiomatic design enabled them to elicit the customers' needs, organize them, and prioritize them, thereby effectively minimizing FRs and avoiding wasted time to satisfy FRs which were of no interest to their customers. They felt this was very important because "when it [comes] time to analyze the design matrix interdependencies and uncouple the functional requirements from the design parameters you want as few FRs and DPs as possible." [os]

Challenges to using axiomatic design

The students identified several clear challenges in incorporating axiomatic design in the company's development process.

First, while the current design process follows a framework that is consistent with axiomatic design, the quality and efficiency of the design are also affected by decisions driven by cost and schedule: [rs] "The axiomatic design concept fundamentally follows our current design process. Cost and schedule play a major role in our design and engineering development process, which may affect quality and efficiency of a design." [rs]

Second, the engineers have only partial control over the requirements: "The customer often gives the customer needs and high-level functional requirements to us at the beginning of the contract." [pam] Moreover, changes and recommendation for new requirements must be submitted to management with an "engineering change proposal (ECP)" when presented to the customer [hts]

Third, perhaps most importantly, axiomatic design concepts must reach people with the right positions in order to achieve the most beneficial results: "The application of the tool itself, spans areas that are usually delegated to distinct groups with different and differing levels of authority." [hts] For example, established requirements may be handed out to developers to implement, which limits the scope of application of axiomatic design, and limits the consideration of relationships between FRs and DPs among different branches of the design hierarchy. The full benefits of using axiomatic design can only be achieved through more widespread use and closer coordination among diverse groups.

Fourth, using axiomatic design may lead to a design that is not what the customer expected even though it may be more satisfying to his actual, overall needs. In this case, the designer needs to be careful not to "negatively surprise" the customer. Unexpected design features that are fleshed out during the process should be communicated to the customer and approved as early as possible. [hd]

Fifth, even though the great value for axiomatic design tools is clear in the context of new innovation, the need to create an uncoupled design when upgrading or improving an existing system can be overwhelmed by factors such as legacy implementation, limited budgets, etc. [hd] Nevertheless, application of axiomatic design to existing programs that have redesign phases would be beneficial to ensure that the redesign is not coupled.

These five challenges can be addressed by future work: 1) incorporating cost modeling into axiomatic design and by demonstrating the net cost and schedule benefits to axiomatic designs, 2) developing new ways for interacting with customers and new methods for working with customer needs, 3) strategically positioning axiomatic design skills within a company, 4) using axiomatic design to promote new customer interaction, and 5) having better analysis and focused decoupling of existing programs.

Questions about application of AD

In addition to the obvious challenges, there were other areas in which the students were unclear about the applicability or had questions about the use of axiomatic design. Some examples include the following:

The students would like to see examples applied to large systems with both hardware and software requirements. [pam]

They would like to compare the results of applying the axiomatic design process with the standard systems engineering processes for requirements definition and decomposition. [pam] They propose having two groups which could perform requirements and design starting with the same customer needs and comparing the resulting requirement sets and design decisions.

They are unsure about the application of axiomatic design to software engineering. The factors which are of particular interest are "real-time requirements, multi-tier architectures, heterogeneous environments, integration of multiple third-party products, [and] object-oriented design". [hts]

The students have questions about scability—including practical aspects of managing large matrices. [pam] Large, complex systems and embedded systems with many interfaces creates large design matrices which are more difficult to evaluate; however, the value and applicability for mechanical components and noncomplex systems is clear. [rs]

The students mentioned several other design tools that have been used within their company. Their comments indicated that the effort and utility in applying design tools is inconsistent among different parts of the company. For example, while six sigma is used "at management levels", overall, the implementation is "incongruous...to say the least". It is not used by the engineers actually designing and developing a system. [hts]

Additionally the students identified several other tools as being compatible with axiomatic design, including QFD and Gantt charts. QFD is identified as a tool for use with six sigma. However, some students show that they do not recognize the unique characteristics of the design matrix that differentiate it from QFD's House of Quality because they feel that if QFD is done at several hierarchical levels taking it to the lowest-tier of functional requirements, that it will provide the same value as the design matrix. [hd]

Summary

The projects done by the students in the course served several useful purposes: giving them opportunities to 1. practice the axiomatic design skills learned in the classroom, 2. think critically about how to integrate axiomatic design within their current work, and 3. provide feedback to shape the further development and teaching of axiomatic design theory.

5 CONCLUSIONS

This paper has addressed the need for strategies for axiomatic design education. This is especially true when considering the adoption and implementation of axiomatic design within a company's existing product development process. This paper draws upon experience from several educational contexts. The aim is to provide students with the skills and support that they need to sustainably use axiomatic design in their future work. Two things are very important to achieve this aim: show that the results from using axiomatic design are much greater than the overhead in applying it and show how axiomatic design applies in a wide variety of real-world contexts that the students will face, rather than being a tacked-on afterthought.

This paper proposes a list of skills which students must master in order to have a functional understanding of axiomatic design. These skills correspond to activities that the students will perform when engaged in design activities within their companies. A structure for teaching these skills is presented; exercises are identified for teaching these skills; and observations about their use are made.

Next different contexts are considered from the point of view of objectives. Different contexts have different functional requirements and constraints. The differences are identified and explained.

Finally a case-study is presented of a modular graduate-level course taught with students from an aerospace company. The application of axiomatic design within the context of the company's design and development process is presented.

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