

## DETC2008/DEC-49885

### RATIONALE AND METHODOLOGY FOR DEPLOYING AXIOMATIC DESIGN IN INTERDISCIPLINARY CAPSTONE DESIGN COURSES

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#### ABSTRACT

Capstone design courses require balanced attention to structured design processes as well as development of high quality design solutions. Process elements are commonly built into these courses through intermediate deliverables such as progress reports, design reviews, design reports, and forums for displaying prototypes as well as hardware. Despite this formal structure, steady evolution of design quality is not assured. Personal interaction with instructors, mentors, and clients is needed to evaluate intermediate designs and focus team efforts on design deficiencies as well as on promising design features. Clarification of functional requirements, determination of optimal design parameters, and implementation of viable solutions often requires considerable instructor and design team iteration. Design intent behind instructor feedback given at these junctures is not immediately obvious to many students. This paper outlines the rationale behind selecting and the methodology for deploying axiomatic design as a primary tool in an interdisciplinary design course. The selection of axiomatic design was based on 1) limited bandwidth for the introduction of new tools, 2) the desire to facilitate communication about design attributes between students and instructors, and 3) to provide continuity of application between various phases of the design process.

#### 1. INTRODUCTION

Axiomatic design provides a structured approach to design that adds value to multiple phases of the development process. Axiomatic design adds value to a process and the end product

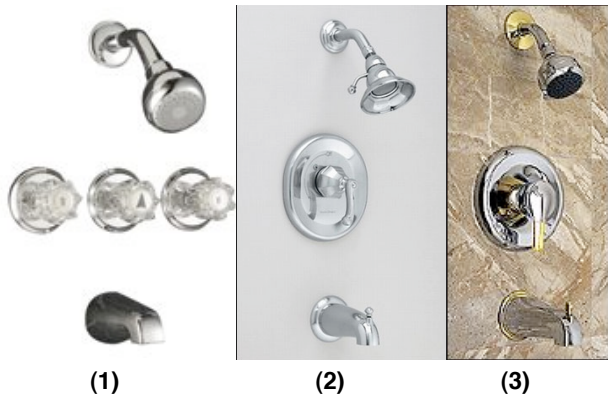
through two fundamental principles that challenge the designers to refine and clarify their thinking about the project. Additionally, modeling techniques exist as part of axiomatic design to represent and correlate domain information from customer input through variables that outline fabrication process. In an educational setting, axiomatic design is a valuable tool for students because it provides a consistent representation of relevant design data throughout the design process and requires relatively little overhead and training to use. This ease and efficiency of deployment is critical because of the limited lecture bandwidth available in a project-centric senior design course. An additional benefit of using axiomatic design in an educational setting is as a conduit through which the novice student designer can interact with the more experienced instructor/mentor. By exposing the design team's current understanding of the problem and progress towards creating solutions, instructors can better guide the student teams in a timely manner, ensuring a good level of quality.

In this paper, a subset of axiomatic design relevant to a capstone design setting is reviewed followed by a comparative analysis against alternative design methods for use in a project-focussed senior design course. Lastly, the necessary conditions for using axiomatic design in a capstone course to benefit the student design process, the student's design products, and the attendant instructor/team communication are outlined.

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## 2. PRINCIPLES OF AXIOMATIC DESIGN

Axiomatic Design was developed in the 1970s at MIT by Nam Suh [1]. Axiomatic theory assumes that high quality designs result from application of two axioms. These axioms, can't be proven but haven't yet been violated. The first axiom states that superior designs have functional independence between needs and components that address these needs. The second axiom states that ideal designs require and use a minimum set of information. An illustration of these axioms is shown in figure 1. Compare three different designs for a water faucet: 1) a knob faucet - two knobs that control hot and cold water, 2) a twist faucet - one knob that, when turned, changes temperature and volume of the water, and 3) a twist/pull faucet - one knob that is turned for temperature and pulled for volume. Using the first axiom, faucets (1) and (3) are equally independent. Faucet (2) is functionally inferior because adjusting volume also impacts the temperature value. Using the second axiom, faucets (2) and (3) become functionally superior because changing volume for a given temperature requires fiddling with knobs in faucet (1). Combining these axioms faucet (3) emerges as the superior design. This is the design that users instinctively select as the superior design because it is simple to use and easy to control.



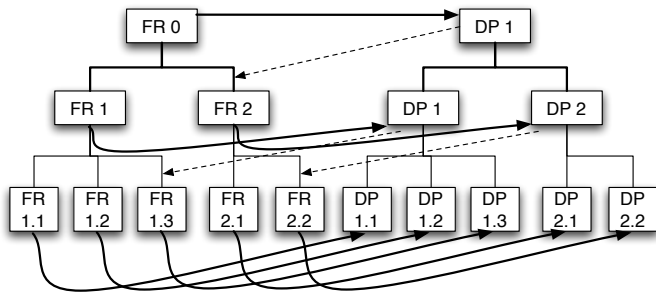
**Figure 1.** Three faucets with varying levels of independence and information content.

In more complex systems assessing the quality of a design becomes less apparent. To analyze a more complex system, the problem is decomposed into smaller segments in three categories: functional requirements (FRs), design parameters (DPs), and process variables (PVs). A functional requirement (FR) is an action that the design must perform and usually corresponds to a customer need. A design parameter (DP) is a feature of the design that performs a specific functional requirement and corresponds to a solution concept. A process variable (PV) is how the design parameter will be implemented; in capstone design often a purchase order or manufacturing plan. Distinctions between FRs, DPs, and PVs are further drawn in table 1.

**Table 1.** Relation and Usage of Axiomatic Design Concepts

	FUNCTIONAL REQUIREMENTS (FRs)	DESIGN PARAMETERS (DPs)	PROCESS VARIABLES (PVs)
Definition	Describes what the design should do	Describes what the design should look like	Describes how design should be implemented
Purpose	Satisfy customer needs	Satisfy FRs	Satisfy DPs
Word Usage	Start with verbs (imperative phrases inspire action)	Start with nouns (declarative phrases prescribe solutions)	Start with verbs (imperative phrases that inform actions)
Tolerancing	Functional tolerances	Physical tolerances e.g., $x = +/- .05$ mm	Time/money tolerances e.g. 3-5 days, \$40-60
Uniqueness	Independent from other FRs	One selected to satisfy each FR	One selected to satisfy each DP
Relation to Solution	Requires a DP	Specifies a purchased component, drawing, or a process	Plan for creating solution

To facilitate analysis of these categories, axiomatic design commonly utilizes two tools: 1) the symmetric tree and 2) the coupling matrix. The symmetric tree is a hierarchical mapping of customer needs (functional requirements) to design concepts (design parameters) and to manufacturing/purchase plans (process variables). Traditional symmetric trees place customer needs (i.e. functional requirements) in a hierarchy and map these to solution concepts (i.e. design parameters). Figure 2 shows a hierarchy of functional requirements and associated design parameters. The primary functional requirement (FR 0) is decomposed into two sub-requirements (FR 1 and FR 2). These functional requirements are then further decomposed into several sub-requirements each. The solid lines represent the one to one correspondence between each functional requirement and the supporting design parameter. Each dashed line represents the connection between a design parameter and the more refined functional requirements that describe the performance of the specified solution. The functional requirement is only necessarily valid for the higher level design parameter to which is it connected by a dashed line.



**Figure 2.** A hierarchy of functional requirements mapped to the associated design parameters.

Expanded symmetric trees also align functional requirements and design parameters with implementation plans (i.e. process variables). The functional requirements should be broken down to the level where the quality and solution become as simple as the water faucets in the previous example. In the expanded symmetric tree there are hierarchal levels visible in the breakdown of the functional requirements, design parameters, and process variables.

The coupling matrix (figure 3) uses the symmetric tree to create two axis of comparison. Ideally, each of the functional hierarchies should be independent of each other. A completely independent design will have only diagonal boxes as each functional requirement is fulfilled by the corresponding design parameter. However, this is not always possible. Even if complete independence is not possible or desirable, the coupling matrix provides insights into potential trade-offs in realizing a design solution.

	DP 1	DP 2	DP 3
FR 1			
FR 2			
FR 3			

coupled	independent	unclear
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**Figure 3.** A sample coupling matrix. Dependencies between functional requirements and design parameters are visualized through a color coded scheme. This example shows no unnecessary coupling.

### 3. COMPARISON TO OTHER DESIGN METHODS

There is a selection of high quality design tools that can be used to facilitate project learning in a capstone design course or professional setting. Aspects of axiomatic design are similar to tools and methods such as the house of quality, affinity diagrams, morphological charts, decision matrices, and TRIZ. In choosing a tool to meet our capstone course needs, a

handful of tools were evaluated with respect to their applicability across the design process, ease of use in a capstone environment, and threats to validity. Our selection of design tools was restricted by the time available to provide instruction in use of the tool and the student composition of the class. Our senior design course is a project-focused course in which lecture bandwidth is limited. Because of the interdisciplinary nature of the course (which includes bio-agricultural, computer, electrical, and mechanical engineers), past student experience with design projects, methodology, and tools could not be relied upon as a basis for continued design instruction.

### 3.1. Morphological Charts

A morphological chart is a concept generation tool that is used to visualize and organize the possible solutions for each of the enumerated product functions. The morphological chart organizes product functions or features on the row header with each row containing solutions or means for achieving the function. The functional breakdown is typically a flat decomposition of the overall product function into multiple sub-functions. An alternative form of the morphological chart displays multiple levels of a hierarchical functional decomposition for which solutions are provided for the lowest level of function [2]. The presence of the hierarchy is helpful for visualizing the details and ‘big picture’ in terms of product function and provides similar benefits to the functional hierarchy in axiomatic design. Additionally, the simplicity of morphological charts enables student teams to apply them effectively to their projects with little time and effort in training. However, the fundamental application of morphological charts is during the conceptual and detail design phases of product development and is not as broadly applicable as axiomatic design.

### 3.2. Decision Matrices

A decision matrix is a very general tool that encourages objectivity during design selection by comparing design alternatives with metrics based on customer requirements [3]. The requirements are often weighted to allow consideration of function ranking. Each design alternative is given a score for each criterion either on an absolute scale or relative to a baseline. After a score is given to each design alternative for each criterion, the scores for each design alternative are totaled. By examining both the total and the individual scores, a designer can determine both the best current concept and examine the possibility of incorporating design features from other concepts into a central “best” design concept.

The methods of scoring in decision matrices vary. Some applications use symbols such as “+” and “-” while others use numbers such as 1, 3, or 5. The focus of the Pugh concept

selection matrix is not on the score of the design, but the score of the design relative to other designs. Using a Pugh concept selection matrix is very straightforward and requires very little training. While the primary applications of decision matrices is during conceptual and detailed design, a decision matrix can be used at any point during the design process for a multitude of different applications. There is, however, no inherent structure in decision matrices that connects together multiple uses of a decision matrix throughout the design process.

### 3.3. Affinity Diagrams

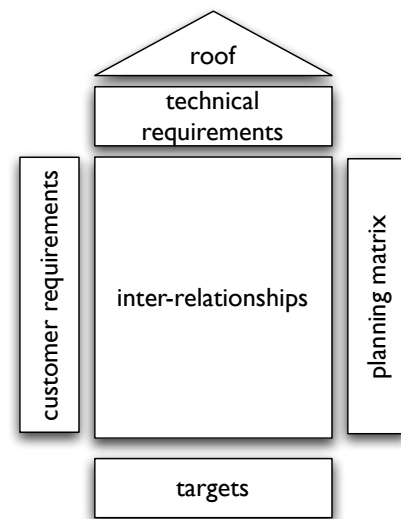
An affinity diagram is a useful tool for organizing large amounts of data into natural groupings based on related properties within the data [4]. Affinity diagrams can theoretically be used any time to address any type of problem, but their most practical application is in providing structure to an unwieldy amount of data. This type of situation frequently results from brainstorming, information gathering, or research activities. Hence, the most frequent applications in the design process are during problem understanding where large amounts of customer input are translated into a structured grouping of user needs. Again, affinity diagrams are broadly applicable in the design process, but each application is a discrete event that does not necessarily build upon or connect to past efforts. The affinity diagram is simple and direct to learn and implement.

### 3.4. TRIZ

TRIZ is a Russian acronym for the Theory of Inventive Problem Solving. TRIZ is a systematic approach to design which relies on a patterns, principles, and knowledge from past patents and designs [5]. The principle creator of TRIZ, performed extensive patent searches to discover the trends through which development typically progresses and to find the approaches that are commonly used to succeed. TRIZ and axiomatic design share the concept that fundamental principles exist through which design thinking can be filtered and improved. TRIZ even contains principles that map to the two basic axiomatic principles of information reduction and independence [6]. However, TRIZ goes further to list 40 total inventive principles and eight patterns of evolution. Additionally, TRIZ supplies analytical modeling tools through which the design problem and solutions are represented and refined with respect to the inventive principles. The modeling capabilities and broad applicability of TRIZ are very comparable to that of axiomatic design. However, teaching and learning TRIZ requires more time and effort than simply becoming proficient with axiomatic design. The benefits of this time spent may be justified, but this must be evaluated on a case-by-case basis.

### 3.5. House of Quality

A house of quality ranks and examines the relationship of customer needs and design features in a format similar to the coupling matrix of axiomatic design. With an extended house of quality, this analysis can be extended to include manufacturing considerations as well. An overview of the components of the house of quality is shown in figure 4 where the customer needs are captured in rows on the left side of the figure. In the upper triangular portion of the figure (the ‘roof’), the house of quality allows examination of interdependence of technical requirements which are listed in columns below. This analysis includes degrees (severe, mild) and type (good or bad) of dependence. The house of quality is an in-depth tool that gives very detailed information about a product such as design values, constraints and inter-relationships, and competitor benchmarking. However, there is no indication in the breakdown of customer requirements regarding hierarchy of function [7]. Consequently, a customer need will often interact with multiple design features as indicated in the central section of the figure. Along the bottom of the figure (labeled targets in figure 4), the designer indicates the relative importance of each design feature based on fulfillment of customer needs and relative cost of implementation. This section also contains target specification values for developing the new product and benchmark comparison to relevant competitive products.



**Figure 4.** The fundamental components of the house of quality.

Implementing a house of quality has the most impact in the conceptual design and detailed design phases. However, using the extended house of quality provides guidance throughout the project including mass production. Learning how to build a house of quality is straight forward, but time intensive due to the detailed information required.

### 3.6. Comparison Summary

It is clear that axiomatic design, extended house of quality, and TRIZ support the design process most completely from customer needs through process variables. The tools discussed in this section are summarized with respect to uses, applicability, and ease of use in table 2. Although, similar completeness can be achieved through applying a sequence of other tools, the continuity offered by of a single tool is appealing. Because of the breadth of application, axiomatic design, the house of quality, and TRIZ are the most difficult to implement and therefore require the most effort in training and practice. However, the benefits of using tools that are applicable to a substantial portion of the design process outweighs the extra effort required to train students and faculty.

An analysis of the decision making process inherent to axiomatic design and application of the house of quality was performed by Olewnik and Lewis [8]. The tools were evaluated according to their logic in application, use of meaningful and reliable information, and their tendency to bias designer decision making in an effort to validate their application. Olewnik and Lewis illustrate that the scoring mechanism used in the house of quality introduces arbitrary information into the model and therefore violates their validity principle of meaningful and reliable information. Additionally, Olewnik and Lewis argue that the fundamental principles of axiomatic design force the designer to be biased in terms of preference. In the case of axiomatic design the preference is for designs that minimize coupling and minimize information content. It could be argued that TRIZ also offers a biased perspective for the designer through its substantial number of principles, but TRIZ also has balanced this in many cases through well-conceived principles of contradiction. Despite the indicated weaknesses, Olewnik and Lewis support the notion that both axiomatic design and the house of quality are beneficial to the design process.

Given that outside validation and inquiries into completeness with respect to the design process did not substantially differentiate axiomatic design from house of quality or TRIZ in terms of applicability to capstone design, axiomatic design was chosen because of the simplicity of the fundamental axioms. The concept of evaluating functional requirements, design parameters, and process variables with regards to two fundamental principles that typically improve design quality is advantageous even if the modeling benefits are not fully realized. While the argument that it biases designers is valid, it is believed that students benefit from the application of a formal process. Coupled with the benefit of timely and useful teacher instruction, the use of axiomatic design was chosen for

use in the University of Idaho engineering capstone design course.

**Table 2.** Comparison of the design tools/methods.

TOOL	APPLICABLE PHASES	TYPE OF USE	DIFFICULTY
Axiomatic Design	<ul style="list-style-type: none"> <li>•Project Scoping</li> <li>•Problem Definition</li> <li>•Conceptual Design</li> <li>•System Integration</li> <li>•Detail Design</li> <li>•Fabrication</li> <li>•Testing/Validation</li> </ul>	<ul style="list-style-type: none"> <li>•Needs Analysis</li> <li>•Concept Selection</li> <li>•Project Management</li> <li>•Prototype Fabrication</li> <li>•Design Evaluation</li> </ul>	Medium
House of Quality	<ul style="list-style-type: none"> <li>•Project Scoping</li> <li>•Problem Definition</li> <li>•Conceptual Design</li> <li>•System Integration</li> <li>•Detail Design</li> <li>•Fabrication</li> <li>•Testing/Validation</li> <li>•Mass Production</li> </ul>	<ul style="list-style-type: none"> <li>•Needs Analysis</li> <li>•Concept Selection</li> <li>•Project Management</li> <li>•Prototype Fabrication</li> <li>•Design Evaluation</li> <li>•Fabrication for Production</li> <li>•Process Control</li> </ul>	High
Decision Matrix	<ul style="list-style-type: none"> <li>•Conceptual Design</li> <li>•System Integration</li> <li>•Detail Design</li> </ul>	<ul style="list-style-type: none"> <li>•Concept Selection</li> </ul>	Low
Affinity Diagram	<ul style="list-style-type: none"> <li>•Problem Definition</li> </ul>	<ul style="list-style-type: none"> <li>•Idea Generation</li> </ul>	Low
Morphological Chart	<ul style="list-style-type: none"> <li>•Conceptual Design</li> <li>•Detail Design</li> </ul>	<ul style="list-style-type: none"> <li>•Design Evaluation</li> </ul>	Low
TRIZ	<ul style="list-style-type: none"> <li>•Project Scoping</li> <li>•Problem Definition</li> <li>•Conceptual Design</li> <li>•System Integration</li> <li>•Detail Design</li> <li>•Fabrication</li> <li>•Testing/Validation</li> </ul>	<ul style="list-style-type: none"> <li>•Needs Analysis</li> <li>•Concept Selection</li> <li>•Project Management</li> <li>•Prototype Fabrication</li> <li>•Design Evaluation</li> </ul>	High

#### **4. CONDITIONS OF USE - AXIOMATIC DESIGN IN A CAPSTONE CURRICULUM**

Three benefits of using and teaching axiomatic design in a capstone design course have been identified: 1) as a reference for student-instructor interactions, 2) as a tool for instructors to monitor student team progress, and 3) as a structured approach for students to address design problems. In order to realize these benefits in the University of Idaho's capstone design course, three conditions for usage were identified and addressed. There was a need to structure the teaching of the principles of axiomatic design to best suit the diverse levels and types of knowledge in the University of Idaho interdisciplinary capstone course. Additionally, instructors recognized that there was a need for tools or templates to assist in the modeling aspects of axiomatic design. Finally, there was a need to provide students with a methodology to consistently apply the axiomatic principles during the design process. Each of these needs is addressed in the following subsections.

##### **4.1. Approach to Training Students and Faculty in the Principles of Axiomatic Design**

Effective training of students is crucial to making axiomatic design a useful methodology to supplement design instruction. However, instruction time is limited because capstone instructors are already pushed to include a full course of topics in capstone design. Given the time constraints, the wide variety of project types, and the benefits of a more interactive learning environment, a workshop approach was adopted for axiomatic design instruction. The workshop took place during lecture in parallel with other workshop sessions that may be more useful for particular projects and teams. Individual faculty mentors help guide the teams (and individuals) to attend the most relevant workshop session. The workshop is given several weeks into the semester after teams have had an opportunity to learn substantial details of their assigned problem. It is important to wait long enough for students to be able to work through at least a few levels of the hierarchy of functional requirements but still begin before conceptualization is well underway.

The workshop was planned using instructional design theory [9] with workshop goals aligned with course goals. The curricula included goals, assessment criteria, terminology, and questions to guide knowledge development. A presentation [10] was also developed to introduce axiomatic design in a context familiar to the students. During the workshop, the presentation was used to outline the basic principles and language of axiomatic design, using water faucets as the introductory example. Next, the workshop illustrated application of axiomatic design in the context of the Wright Flyer. The Wright Flyer example was used to introduce the

symmetric tree and coupling matrix in an applied context. The hierarchical decomposition of functional requirements and design parameters (figure 2) was shown in addition to template form (see section 4.2). Lastly, this workshop presented a methodology for the students to follow during the capstone project work to ensure use of the axioms. The final exercise in the workshop was to work on developing unique symmetric tree models focusing on specific capstone projects. This gave students the help needed to seed the high level representation of at least the functional requirements in their project. Additional development was then monitored and approved by each faculty mentor.

##### **4.2. Provide Tools to Model FRs, DVs, and PVs**

When axiomatic design was initially explored for use in the capstone course, a program called Acclaro [11] was used. The software was very effective for use and understanding; however, it required a yearly license fee. Consequently, the capstone instructors decided to develop a tool in Microsoft Excel that would perform the main functions of Acclaro. The Excel template [12] (figure 5) for the symmetric tree and coupling matrix was developed using native Excel functions and tools. The symmetric tree template allows breakdown of the FRs with alignment of the DPs and PVs using grouping with numerical annotation.

The template provides four main functional divisions and three levels of detail. The coupling matrix template utilized identical grouping organization and automatically grabs values for FRs and DPs from the symmetric tree worksheet. A color scheme is presented and explained within the coupling matrix template for annotating coupling or independence.

Using the Excel tools is intended to be a direct and uncomplicated experience. Learning a few key actions will alleviate many problems. First, the grouping is set-up with four main functional groups and three levels. This size is sufficient for most capstone projects. This level of detail was chosen as a guideline for students to provide sufficient detail without being overwhelmed with data. However, occasionally a project will require additional function groups or deeper details. These modifications can be made with the aid of a mentor. Additionally, if students create more than the default number of FRs, DPs, and PVs, the links between the symmetric tree and the coupling matrix must be formed.

##### **4.3. Provide a Methodology for Applying Axioms During Modeling**

The use of axiomatic principles in design is not ensured through the use of symmetric trees and coupling matrices. A methodology was required for the students to follow to ensure that the axioms are consistently applied while developing the

1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24
A	B	C	D	E	F																		
1	FR 0	Measure adolescent muscle strength	DP 0	Isometric Adolescent Leg Exertion Gauge System	PV 0	Assembly and Purchasing																	
2	FR 1	Isolate extremity movement	DP 1	Transducer/arm/seat system	PV 1	Process 1																	
3	FR 1.1	mount transducer	DP 1.1	transducer on moveable plate	PV 1.1	Guide pins and holes																	
4	FR 1.1.1	quick angular positioning	DP 1.1.1	indexed arm	PV 1.1.1	threaded knob and bullet-nose indicator																	
5	FR 1.1.2	quick changeover	DP 1.1.2	removable plate	PV 1.1.2	toggle clamps																	
6	FR 1.1.3		DP 1.1.3		PV 1.1.3																		
7	FR 1.1.4		DP 1.1.4		PV 1.1.4																		
8	FR 1.2	position subject	DP 1.2	seat adjustments	PV 1.2																		
13	FR 1.3	stabilize subject	DP 1.3	restraints	PV 1.3																		
18	FR 1.4	position attachment arm	DP 1.4	specific angle based on flange attachment	PV 1.4																		
19	FR 1.4.1	height	DP 1.4.1	slide on pad	PV 1.4.1																		
20	FR 1.4.2	length	DP 1.4.2	slide on arm	PV 1.4.2																		
21	FR 1.4.3	angle of arm	DP 1.4.3	indexed flange attachment	PV 1.4.3	threaded insert and bullet-nose indicators																	
22	FR 1.4.4	angle of pad	DP 1.4.4	circular pad	PV 1.4.4	rod with foam and upholstery																	
23	FR 2	Record measurements	DP 2	DataQ system	PV 2	Process 2																	
24	FR 2.1	measure muscle strength	DP 2.1	torque transducer	PV 2.1	honeywell transducer																	

Figure 5. The spreadsheet based symmetric tree template.

functional requirements, design parameters, and process variables. The methodology also guides students through the zigzagging process of developing FRs, DPs, and PVs (as seen in figure 2). The methodology was presented to students during the axiomatic design workshop and then used in the workshop to build the initial portion of the students' symmetric trees.

Table 3 presents a method for applying the axioms and using the structures to establish a hierarchy of FRs and DPs. This was originally created to accompany the Acclaro software, but also proved applicable to the symmetric tree and coupling matrix spreadsheets. The outcome from this process should be a clear definition and prioritization of customer needs, a list of realistic constraints, functional requirements (complete, decoupled, measurable, and organized in hierarchy), and tentative design parameters that are vectors for further research and refinement.

The zigzagging process for creating the FR-DP hierarchy is shown in figure 2. The FRs at the highest level are formulated first in a solution neutral environment. The corresponding DPs are then chosen and checked with their generating FRs against the axioms. Next, the FRs at the next level down are formulated within the constraints supplied by the DPs at the higher levels, then the corresponding DPs are chosen. In this way, zigzagging between the functional and physical domains, the FR-DP hierarchy is developed.

Frequently, especially at the highest levels, the DPs will be stated in a general or generic way, as systems for fulfilling the FRs. The components of the system and the specific nature of

the physical system are often only evident as the lower levels are reached. At the lower levels the components of the systems and sub-systems may frequently be mechanisms or devices. The nature of the system, mechanism or device can be revealed in modifiers, such as: mechanical, pneumatic or electrical. Competing DPs can be tested based on their ability to satisfy the FRs and fulfill the axioms.

Table 3. Method to Determine FRs & DPs.

STEP 1	Write top level functional requirements (FRs)
STEP 2	Select top level design parameters (DPs)
STEP 3	Check Axiom 1 (minimize coupling)
STEP 4	Check Axiom 2 (maximize chances of success)
STEP 5	Verify that constraints are not violated (Cs)
STEP 6	Go to the next level down (writing FRs and selecting DPs)
STEP 7	Go to step 3, repeating until the solution is obvious
STEP 8	Visualize solution by showing DPs on system diagram

**Table 4.** Tips for developing FRs.

Top level FRs should be customer needs expressed in engineering language.
Upper level FRs should capture all essential functionality, even if this must be stated in very general terms. In other words, lower level FRs should not introduce new requirements, although they may clarify or expand on existing requirements.
Lower level FRs (children) should be derived by appropriately decomposing upper level FRs (parents). Note that children FRs may be different depending on the DP corresponding to the parent FR, since the DP explains how the parent FR will be met.
Upper level FRs (parents) should either have no children or more than two children.
At all levels, FRs should be (i) collectively exhaustive, (ii) mutually exclusive, (iii) equal in size/reducibility, (iv) a minimum set, and (v) bounded in magnitude.

**Table 5.** Tips for developing DPs.

DPs should focus on equipment/solutions.
Select alternative DPs that are simplest to implement.
If you have too many DPs, consider making some of them constants.

**Table 6.** Tips applying the first axiom.

In examining interaction between DPs and FRs, ask yourself whether that DP could compromise each FR you have listed. If so, note this.
Be wary of fundamental coupling due to relationships based on physics, chemistry, mechanics, or electronics. These are not easily resolved.
During the decomposition phase do not be overly concerned about integration coupling resulting from physical connection of components, this should be considered during system integration rather than conceptual design.
Use sequential coupling (relationships resulting from steps or stages in a process) to establish a logical order for addressing FRs and DPs.

Three collections of tips were developed to help students in building symmetric trees and complying with the first axiom. The tips in table 4 are helpful in writing functional requirements (FRs), the tips in table 5 are helpful for writing design parameters, and the tips in table 6 are helpful for

checking the first axiom. These tips are provided to students in the workshop and reinforced by faculty mentors.

## 5. APPLICATION HISTORY

Piloting with capstone design teams at the University of Idaho began during the 2004-2005 school year<sup>13</sup>. Periodically, two teams met with a group of capstone mentors and instructors learning about Axiomatic Design as part of a class. Each of the two teams developed a symmetric tree and coupling matrix using Acclaro, the commercial software program. At this stage axiomatic design served mostly as a communication tool among team members and customers. Significant time in instructor/team/mentor meetings was spent discussing and learning about principles of axiomatic design and their application in capstone projects. This initial pilot served as the basis for expanded the application of axiomatic design in the following years.

Beginning in the summer of 2005, teams were given a formal introduction to axiomatic design and shown the Excel tools. The teams initially responded to using the tools as extra work and put very little effort into implementing them into the projects. Teams were again introduced to axiomatic Design at the beginning of the Fall 2005 projects with slightly better results. Several teams used the symmetric tree and coupling matrix to track the progress of the project. With the summer 2006 project teams, the current version of the workshop was developed with more refined axiomatic modeling tools. In instructor/team meetings the symmetric tree was used more frequently as a method of tracking the projects and to communicate project direction and understanding.

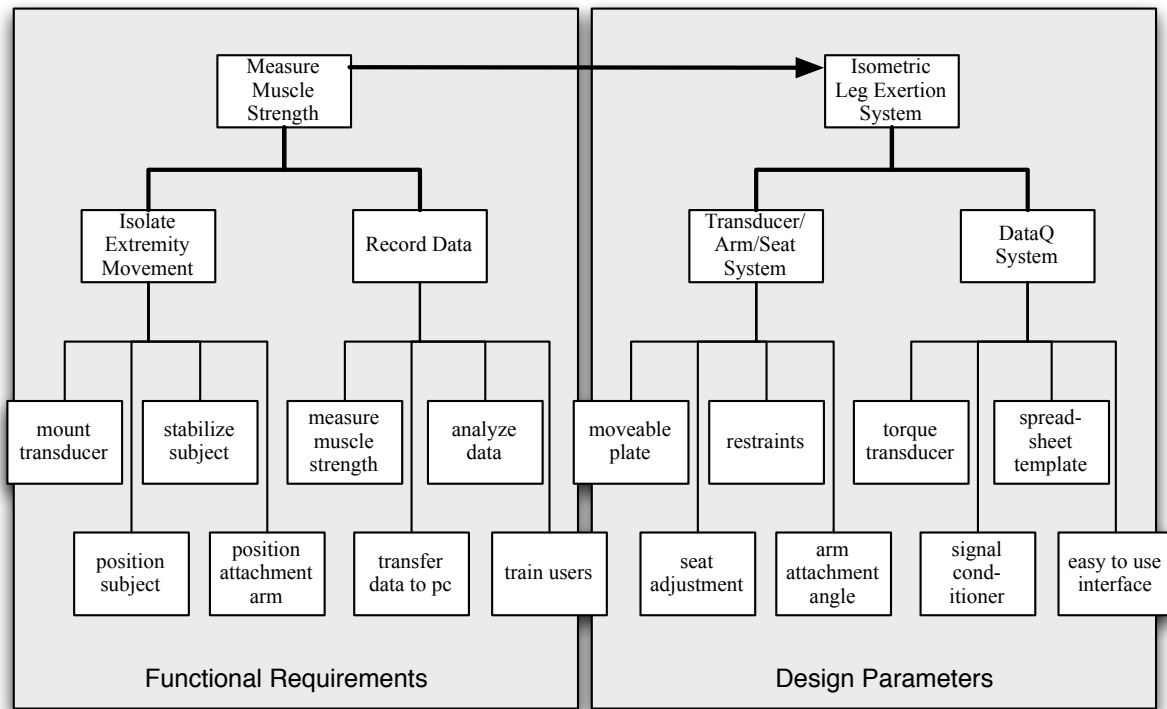
A study was performed with the 2006-2007 projects to evaluate the completion dates for different phases of the design process. This study was conducted to provided insights into the effectiveness of axiomatic design for tracking project progress. During this period, project teams attended the workshop and had access to the modeling tools and methodology that were presented. Examples of the student work are found on the capstone website [14].

One example of the student's progression is the Adolescent Leg Strength Measurement Device. The objective of this project was to create a station capable of measuring net isometric muscle torques for the lower extremities in children. The system was designed for the Human Performance Laboratory in the Department of HPERD (Health, Physical Education, Recreation, and Dance). After receiving initial instruction with regards to axiomatic design, the students identified the functional requirements and design parameters that were subsequently refined by working with their mentors. The refined results of the zigzagging approach to developing

FR and DP hierarchies are shown in figure 6 and the students' spreadsheet model is shown in figure 5.

Informally, teams reported that maintaining symmetric trees helped them to track areas that required more focus, thus producing a more even development of the project solution. Communication was enhanced in instructor meetings as the team discussed the projected future actions of the team and how it fulfilled customer requirements. In particular, graduate student mentors reported that use of axiomatic design aided communication by forcing the involved parties to think about

In order to realize the application of axiomatic design to capstone design projects, support must be provided in terms of lectures, tools, and a methodology. At the University of Idaho, a workshop approach was adopted to deliver axiomatic design instruction to those student teams that would benefit most. The workshops introduced 1) a subset of axiomatic design principles, 2) tools and templates for modeling symmetric trees, and 3) a methodology and tips for applying the principles in a capstone setting. Our solutions were effective, but clearly others may be effective too.



**Figure 6.** Hierarchical representation of functional requirements and design parameters from the Adolescent Leg Strength Measurement Device student project.

specific goals and the detailed design to realize those goals. Axiomatic design's benefits in terms of time management were also cited by graduate student mentors as the process of building and maintaining the symmetric tree was a clear indication of the work that remained to be done.

## 6. CONCLUSIONS

Axiomatic design adds value to the capstone experience both in terms of providing a structured approach to design, but also as a tool for facilitating student-mentor communication. Axiomatic design was selected for use in the University of Idaho capstone design course because it is useful during a significant portion of the design process and provided benefits through its modeling and clear principles.

As a result of the studies performed during throughout the 2004-2007 academic years, a better understanding of the correct use of axiomatic design in a capstone context has been developed. Axiomatic design is now presented to the students in the proper context with the correct level of expectations in terms of applicability and value. It is a very efficient tool for organizing perceived functional requirements, communicating rationale for selecting design parameters, and realizing machining issues.

There remains substantial work to fully realize some benefits of axiomatic design. The coupling matrix received little attention in the capstone course as of now. This tool has the potential to help students avoid unanticipated and undesired dependencies in the development of their conceptual designs

and prototypes. Adding the ability to concurrently work with symmetric trees and coupling matrices is an important next step in refining the tools, methods, and instructional approach for using an axiomatic design in capstone engineering course.

## REFERENCES

- [1] Suh, N. 2001. *Axiomatic Design: Principles and Applications*. Oxford University Press, New York.
- [2] Ullman, D. 2002. *The Mechanical Design Process*, McGraw-Hill, New York.
- [3] Dym, C. and Little, P. 2003. *Engineering Design: A Project-Based Introduction*, Wiley and Sons,
- [4] Shiavi, R., Bourne, J. 1995. *Affinity Diagram*. <http://www.vanderbilt.edu/Engineering/CIS/Sloan/web/es130/quality/newtool.htm>
- [5] Otto, K. and Wood, K. 2001. *Product Design: Techniques in Reverse Engineering and New Product Development*, Prentice Hall, Inc, Upper Saddle River, NJ.
- [6] Yang, K. and Zhang, H. 2000. *A Comparison of TRIZ and Axiomatic Design*. First International Conference on Axiomatic Design, Cambridge, MA.
- [7] Mazur, G. 1993. *Quality Function Deployment for Service Organizations*. Glen Mazur.
- [8] Olewnik, A. and Lewis, K. 2003. *On Validating Design Decision Methodologies*, ASME 2003 Design Engineering Technical Conference, Chicago, IL
- [9] Dick, W., Carey, L., NS Carey, J. 2000. *The systematic design of instruction*. (3rd. Ed.) Addison Wesley, Illinois.
- [10] <http://seniordesign.engr.uidaho.edu/DocsF07/AxiomaticWorkshop.ppt>
- [11] <http://www.axiomaticdesign.com>
- [12] [http://seniordesign.engr.uidaho.edu/Course\\_Docs/Phase1/Axiomatic\\_Template.xls](http://seniordesign.engr.uidaho.edu/Course_Docs/Phase1/Axiomatic_Template.xls)
- [13] Odom, E., Beyerlein, S., Brown, C., Drew, D., Gallup, L., Zimmerman, S., and Olberding, J, 2005. *Role of Axiomatic Design in Teaching Capstone Courses*, Proceedings of the Annual Meeting of the American Society for Engineering Education, Portland, OR.
- [14] <http://seniordesign.engr.uidaho.edu>