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Teaching Axiomatic Design to Engineers – Theory, Applications, and Software

Christopher A. Brown, PhD, PE, Professor of Mechanical Engineering
Surface Metrology Laboratory Director
Haas Technical Center for CNC Machining Director
Worcester Polytechnic Institute, Worcester, Massachusetts 01609
e-mail: brown@wpi.edu, phone 508 831-5627

ABSTRACT

Axiomatic design (Suh 1990, 2001) shows that the engineering of good designs can be taught as a science. There is a simple set of underlying rules, or design axioms, on which good designs are based. The design axioms provide the opportunity for teaching design as a science, in that it is based on some simple underlying principles. Taking advantage of this opportunity a systematic approach to teaching how to engineer and critically evaluate good designs has been developed.

Three steps are used in introducing axiomatic design. First is providing motivation, which is attempted by observing that design is fundamental to all engineering. The purpose of traditional engineering analysis, which is emphasized in engineering studies, is to support design. Second is developing the concept that there are two simple axioms, independence and information, that govern design, just as Newton's laws govern mechanics. Third is observing that in order to apply the axioms designs must be decomposed into a hierarchical structure. This leads to stating that there are three essential elements to engineering design: the axioms, the structure, and the process for creating that structure.

A barrier to teaching, and using this scientific, axiomatic approach to design, has been the difficulty of creating, modifying, managing, and communicating anything beyond relatively simple design hierarchies. Any design with more than a few functional requirements was difficult to manage. Recently introduced design software (Acclaro, www.axiomaticdesign.com), has overcome this barrier. It can easily handle many hundreds of functional requirements and facilitates the application of the independence axiom. The impact on the teaching process is that the students learn to construct large design hierarchies quickly, and spend more time on mastering applications.

1. INTRODUCTION

The objective of this paper is to present a simple, straightforward approach for teaching engineers the theory and applications of axiomatic design in less than a full course. Axiomatic design is especially worthwhile because the design axioms elevate engineering design to a science, governed by a few basic rules, from what has been a kind of an art integrated with engineering analysis. The importance of the effectiveness of teaching essential methods in engineering design has a broad and significant impact on adding value to the practice of engineering.

In 1997, Campbell and Colbeck published an insightful critical literature review on teaching and assessing engineering design. They note that there are no articles about how to assess students' designs and that the literature on teaching engineering design is relatively new, begun about 1987. Campbell and Colbeck point out that the approach to teaching engineering involves practice solving open-ended problems, creativity, teamwork, teaching by coaching, and experience for offering evaluation of student work. They stress the need for more education on teamwork.

Evaluation of engineering designs in the absence of an underlying science is problematic. Love in 1980 showed how design evaluation could be based on the degree of achieving objectives, or functions. Pugh in 1991, taking a broad view, which incorporates marketing and selling, as well as traditional engineering design functions, also bases evaluation on a student's level of success in achieving design objectives.

The University of Maryland has made notable contributions to the literature on teaching engineering design including Dieter's book (1991) which emphasizes an algorithmic approach to design, and discusses evolution, iteration, trial-and-error, art and intuition in optimization of designs. Dieter also shows a method for evaluating designs based on the degree of achieving the functions. Parcover and McCuen (1995) cite the need for curricular improvements. They focused on the constructive learning method, the content of which is process oriented, focusing on individual problem solving. They emphasize experience, and iteration with prototypes and testing for evaluating designs. Zhang (1999) discussed a product driven approach to teaching design to hundreds of first year students, at the University of Maryland which emphasizes experience, one-on-one instruction, and is resource intensive.

Decomposition can be a useful approach for a variety of engineering problems. Frindley et al. (1992) discuss the use of a kind of lateral decomposition, or product dissection, divided into three segments: function, performance, and manufacture. The purpose was to facilitate the use of benchmarking in the design process, rather than assisting the design process itself. In that work, it was enabling the application of benchmarking that provided the motivation for product dissection or decomposition. Their paper focuses on development and applications of the benchmarking process for classroom use.

In a landmark book for advancing a scientific approach to design, Suh (1990) put forth a proposition that good engineering design is governed by two axioms: axiom one - maximizing independence (or minimizing coupling), and axiom two - minimizing information (or maximizing the probability of success). This approach is refined and further illustrated with expanded applications of axiomatic design in a second book (Suh 2001). In Suh's axiomatic approach, designs are evaluated according to their compliance with the axioms, which inherently incorporates the degree of achieving the functional requirements. The design structure of lateral decomposition into design domains and vertical decomposition into hierarchies defines the necessary parts of applying the axioms. Suh also defines the process of creating the hierarchy, by zigzagging between the domains at progressively more detailed levels of the hierarchy, as well as by a process of physical integration of the components. These are excellent books (Suh 1990, 2001),

although they may be challenging for any teaching situation other than a graduate or advanced undergraduate course dedicated to axiomatic design.

For teaching axiomatic design, Bathurst (2004), in a paper given at the third international conference on axiomatic design and intended for those already familiar with axiomatic design, emphasizes the importance of examples and adapting existing design practices to independence analysis. He cites the strength of axiomatic design in promoting a hierarchical representation that facilitates communication, documentation, and evaluation. He also notes that high-level restructuring of the design process in industry is required to implement axiomatic design.

An axiomatic approach to design allows engineering design to be taught as a science. As in other sciences, basic underlying principles with broad applications can be taught... These principles are applied to solving design problems and are used for evaluation. This approach has clear and important advantages over the traditional approaches, which rely on compliance with sometimes abstract algorithms to attempt to ensure good results. These approaches often include intuition, innate creativity, and evaluation by experience, teaching by one-on-one coaching, and a process based on time-intensive iterations of trial-and-error work. A good design method should be self-consistent and could therefore be used to design the content as well as the best approach for teaching engineering design.

2. METHODS

The basic premise in designing the class is that people learn best by doing. Therefore, the basics of the principal [elements of axiomatic design are covered quickly and in just enough depth so that they can be used at the beginning of the course. Thereafter, the principal elements are elaborated, decomposed, and expanded and used with greater sophistication.

This teaching method for axiomatic design has evolved over a decade and a half, in the first part of a graduate course at WPI on the design and analysis of manufacturing processes. The class meets once for three hours one evening a week and includes twenty to thirty students. About half the people in the class are working full time as engineers in industry. One objective of the class is to have some of these full-time engineers use axiomatic design within a month, at least qualitatively, and do it because they believe axiomatic design will help them to do their jobs better.

All the basic elements of axiomatic design and the process to implement it are presented in the first lecture so that the students can do an initial simple design exercise. In the second and third weeks, the basic elements are covered again, decomposed, and reinforced and expanded with more detail and applications. The students are given increasingly more sophisticated exercises to verify their understanding of the material. The students then work in groups to do a larger design project on a manufacturing process as part of the rest of the course.

The objective of the evaluation of the students' work in the first month is not to find ways to differentiate the students according to their abilities but to verify that they have achieved a minimum level of competency, and to assist those who have not. The homework grading is done in a way to show students where they may be lacking basic

competencies. Errors are noted, with appropriate points deducted. Students are encouraged to redo homework exercises for full credit in order to verify their competency.

Class time is used for a combination of lecture and discussion, along with presentations of homework. The lectures are based on modules, which are introduced by discussion questions. The class discusses a question, such as how can you tell a good design from a bad one. A lecture module follows the discussion, so that essential points that are missed will be covered. Examples of the students' homework efforts are presented and discussed.

2.1 Motivation

Motivation in students is essential for effective teaching. The motivation for learning axiomatic design is presented along the following arguments. The basic function of engineers is to design, that is, to create devices and systems that never existed before. Nearly every aspect of the industrialized, modern world is designed. The process by which we design things influences everything. The design process is arguably the singular most important process in the modern world, yet the key components have often been left up to intuition and inspiration. Design courses that are intended to teach something beyond drafting or analysis tend to try to coach some kind of process, often abstract, for creative intuition or inspiration. Many engineers leave engineering school knowing little more about how to create a new design than they did in high school. Axiomatic design lifts engineering design from an iterative, abstract, intuitive process, which relies on inspiration to achieve creativity, to a science with clear and simple underlying principles. Effective use of axiomatic design will produce better designs in less time than any of the other earlier educational design methods.

2.2 Basic elements of axiomatic design

There are three basic elements that need to be understood to get started teaching axiomatic design; they are: the design axioms, structures, and processes (Table 1). The axioms are decomposed into the rules or grammar that governs design, i.e., the two axioms, already mentioned above and the corollaries and theorems (Suh 1990, 2001). The structures are decomposed laterally (Fig. 1) into the design domains and vertically (Fig. 2) into the design hierarchies (Suh 1990, 2001). The processes consist of decomposition, by zigzagging between the design domains (Fig. 3) down to the "leaf levels" or "nitty-gritty," i.e., the most detailed or fundamental level of the design hierarchy, and physical integration or composition of the final design (Suh 1990, 2001).

Table 1. The three basic Elements of Engineering Design

<i>Elements</i>	<i>Components</i>	<i>Details</i>	<i>Notes</i>
Axioms	Maximize Independence	Decouple functional elements	Provides Adjustability and controllability
	Minimize Information	Max. probability of success	Provides robustness & high yield
Structures	Lateral	Design domains	Customer-Functional-Physical-Process
	Vertical	Hierarchies in the	Decomposition from

		Domains	General to Specific
Processes	Zigzagging	Between functional & physical domains	Generation of the vertical hierarchies
	Physical integration	Recomposition	Construction into physical systems

The lateral decomposition (Fig. 1) has been called the playing field for design, and the axioms, corollaries, and theorems called the rules. While the domains are usually presented with the customer domain (not shown in Fig. 1) and the process domain, the design exercises concentrate on the relationships between the Functional Requirements (FRs) and the Design Parameters (DPs) in the functional and physical domains. The process domain is used as a check to see if a reasonable manufacturing process and process variables exist. This helps with concurrent or simultaneous engineering. Manufacturing process and tool design are recast as product design problems aligned with the appropriate customer FRs and DPs.

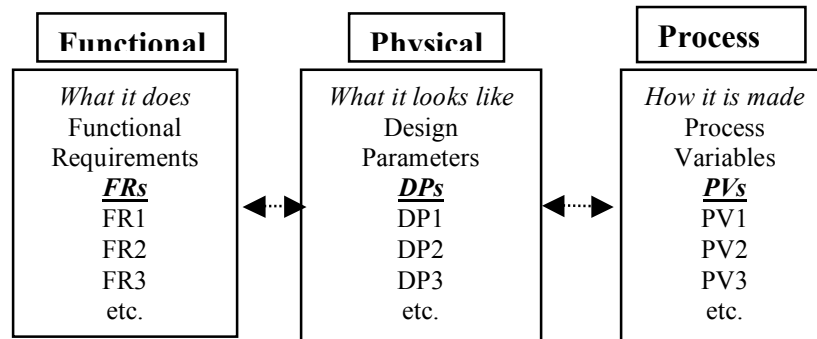


Fig.1 Lateral decomposition of the design structure into design domains. The arrows represent mapping between the domains. Understanding the nature of the mapping is the objective of engineering analysis and experimentation (Suh 1990, 2001).

Defining the FRs properly is essential for a good design. The final design cannot be better than the FRs. Engineers have a tendency to jump immediately to physical embodiments, DPs, in addressing design problems. The result, frequently, is that the FRs are not well defined. Understanding the difference between FRs and Constraints (Cs) is also essential. Guidelines for these requirements are shown in Table 2.

Table 2. Guides for formulating Functional requirements FRs, Design parameters DPs, and Constraints Cs

Functional Requirements (FRs)	Design Parameters (DPs)	Constraints (Cs) (e.g., cost, time, weight)
List of what the design should do	List of what it should look like (e.g., prints)	List of what it must conform to
Start with verbs	Start with nouns	
Satisfy customer needs	Satisfy FRs	Define boundaries
Independent from other FRs	One selected for each FR	May be linked to several FRs
Have functional tolerances	Have physical tolerances	Have limits

Requires a DP		Must not have a DP
Minimum list		
Avoid conjunctions		

The objective of the first homework exercise is to verify the students' ability to create the vertical decomposition in the functional and physical domains, as shown in Fig 2. (The design matrix is discussed below.) This requires following the process shown in Fig. 3. In the zigzagging process, the DPs at one level supply a context, if not a constraint, on the FRs and DPs at the lower levels.

2.3 Software

The Acclaro software (Axiomatic Design Solutions, Inc, Brighton MA, www.axiomaticdesign.com) has raised this first exercise to a level where significant designs can be considered. Without the software, it is cumbersome to impossible to represent designs with a significant number of FRs. About fifteen FRs and three levels of the hierarchy are about the maximum that can be manipulated reasonably without software. Especially important is the ability to hide levels of the hierarchy, so that the designer can focus on only the current level of interest. The first assignment, using the software, is to create a design with at least fifteen FRs and three levels in the hierarchy. Deficiencies that are commonly found initially are formulating good FRs, understanding the difference between FRs and constraints, and performing reasonable decompositions.

2.4 Decompositions

At each level of the hierarchy the FRs must be collectively exhaustive and mutually exclusive (CEME). This means that the required functions are covered without overlap between the FRs. The overlap would result in coupling and violate the independence axiom. Also, the decompositions must logically flow from one level to the next. If an FR at one level, say FR1, is to guard against mechanical impacts, then it might be decomposed in one of several logical ways. One way would be to decompose it into guarding against mechanical impacts from different directions, so that, for example, FR1.1 guards against vertical impacts, FR1.2 is to guard against frontal impacts, and FR1.3 is to guard against lateral impacts. Another decomposition scheme would be to guard against impacts of different duration. This could substitute for the above decomposition or be useful in the next level of decomposition. In the case of guarding against shocks from different directions, while three lower level FRs for guarding against impacts from three different orthogonal directions appears to be decoupled, i.e., mutually exclusive, it is not clear if oblique impacts would be included; therefore, the exercise would require some checking to be sure that these lower level FRs are collectively exhaustive.

In the initial decompositions, a common mistake is to decompose an FR into only one other FR. This results in either an incomplete decomposition, i.e., the lower level FR is not collectively exhaustive, or else it makes the lower level FR redundant, just a re-definition of the higher level FR. In the FR decomposition structure each parent must have at least two children, unlike the biological metaphor.

The second homework is to apply axiom one, the independence axiom, using a design matrix, as shown in Fig. 2, and to indicate with Xs and Os where the coupling is. The most desirable result is a diagonal matrix, where each FR has its own DP, and each DP influences only FR. If this is not possible, then a triangular matrix is workable. Either in class or as homework, the problems in 3.10 at the end of chapter 3 in *Principles of Design* (Suh 1990) are worked out. This exercise shows that design interactions can be represented compactly and manipulated symbolically, according to simple rules, just as there are mathematical representations in the areas of mechanics, thermodynamics, or electrical circuits.

Fig. 2. Vertical Decomposition and design matrix – Acclaro screen shot. One decomposition branch has been expanded to illustrate the hierarchical nature of the decomposition. The Xs in the matrix indicate interactions. This design is quasi-coupled, in that there are off-diagonal Xs, but only in one half, i.e., one triangle of the matrix.

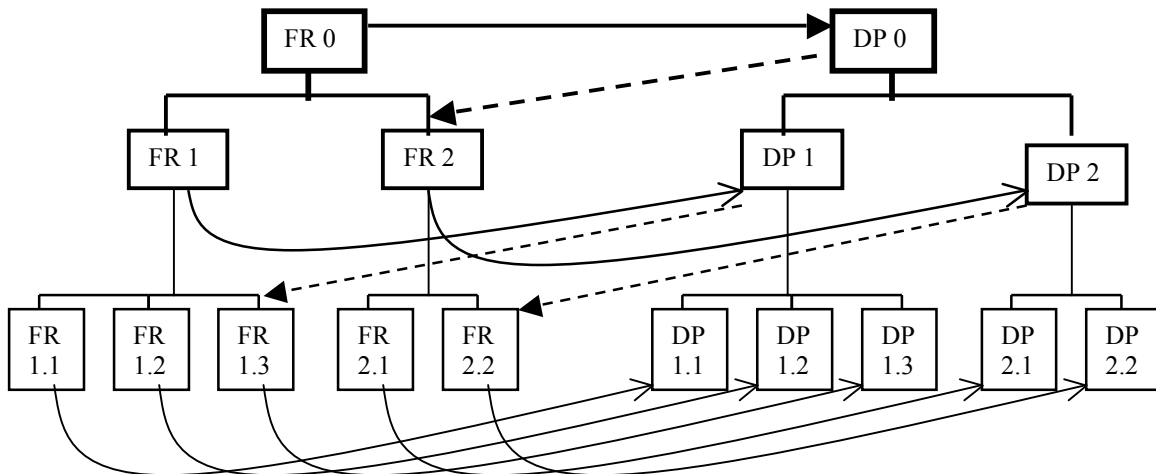


Fig. 3. The process of zigzagging between FRs and DPs. At each level, one DP is selected to satisfy one FR. Subsequently, that DP imposes a constraint on the FR at the next level down. The process stops when the next level is obvious (Suh 1990 2001).

2.5 Information Content

The third homework addresses the second axiom, information. Without some historical and disciplinary perspective, it may not be fully appreciated why the information content (I) is used and represented as the log of the reciprocal of the probabilities of success (p_i).

$$I = \log(1/p_1) + \log(1/p_2) + \log(1/p_3) \dots \quad [1]$$

The similarity with statistical thermodynamics ($S = k \ln(w)$) only helps those who understand Boltzman's work. In any event, it may be easier to minimize a summing function that goes to zero, as the information content does, than to maximize the probability of a multiplicative function. The information content is discussed in the context of manufacturing tolerances, so that the probability of success is the ratio of the common range (the manufactured parts complying with the design tolerance) to the system range (the total manufactured parts). It is shown how the information content can accommodate manufacturing capabilities similar to the C_{pk} parameter and, in addition, include the information associated with a missed delivery.

2.6 Term Project

Subsequent homework assignments contribute to the components of a term project, where the students seek references from the archival literature to understand the elements of the design matrix that were represented by Xs and Os in the second exercise. These matrix elements can be formulae, tables, rules or graphs that explain the relation between the FRs and DPs. The students select a problem in the design of manufacturing processes, and they need to be able to construct a design in FRs and DPs, represent it in a design matrix, and interpret the literature to explain the matrix elements.

3. RESULTS AND DISCUSSION

The results of this approach have been overwhelmingly positive. Every time this approach has been used, for over ten years, students have reported using axiomatic design to some extent at work within the first month. A survey was done of former students who could be contacted by email. Comments from former students who responded are in appendix A. All who responded appear to be using axiomatic design qualitatively, primarily the axioms and secondarily the structure. In one instance a former student stressed its value in communication.

In one spectacularly successful case, a student applied axiomatic design to a redesign of the production system he was responsible for, and it resulted in savings of \$2.4 million before the course finished. The student was subsequently promoted, from tool designer to manager of manufacturing engineering to VP for engineering.

The introduction of Acclaro software has facilitated the teaching of axiomatic design, resulting in significantly more sophisticated designs and deeper understanding of the decomposition process and hierarchical structure. There is currently potential to sell software to former students' companies.

Teamwork is facilitated by the structure required in axiomatic design. This has been observed in two ways. Communication for mutual understanding is essential for good teamwork and is enhanced by practicing axiomatic design, through the use of evaluation rules and the imposition of a structure on the design. Teamwork is also facilitated by the decoupled decomposition, in that different members of the team can more easily and clearly divide the tasks and work on them more independently when they are decoupled.

Using axiomatic design requires greater investment in the higher levels of the design than is the practice historically. Engineers are often uncomfortable with investing so much time in design work, without producing drawings. Managers need to realize the value of design effort at the higher levels. For example, definitions need to be formulated to facilitate exclusivity and decomposition. The goals of the design need to be clearly and succinctly stated. Often it is clear from the homework efforts that there is confusion between designing the product and creating the design process for designing the product. Both exercises can have value, but they should be distinct. Also there is sometimes confusion between designing the process and designing the tools to accomplish the process. These kinds of confusions may be only apparent when a clear, systematic, and scientifically rigorous design approach is used.

The design axioms, like Newton's Laws, cannot be proven. Their legitimacy is derived from the fact that they have never been observed to be violated, at least within some domains of applicability. Students are challenged to find exceptions to the axioms. Over the years, all the challenges to the axioms have been resolved to the satisfaction of everyone in the class, through a careful consideration of the principles of axiomatic design. In most cases, there is a misunderstanding of a definition or a poor statement of the functional requirements. Of course, these resolutions of alleged violations of the axioms are taking place in a classroom under the guidance of a professor, who the students know has yet to record their grades.

For teaching large design courses, such as have been reported in the literature, it is possible that the scientific, axiomatic approach to design will reduce some of the resource demands. It should be possible to formulate more general, universal instructions to lead students through the design process, eliminating the need for some individual coaching. In addition, axiomatic design provides clear and simple rules for evaluating the results of students' work, eliminating the need to get experienced designers to legitimate the evaluations.

5. CONCLUSIONS

1. Many of the difficulties with teaching traditional design are avoided with axiomatic design.
2. Practicing engineers are able to use axiomatic design on the job after four classes of three hours each.
3. The use of specially designed software facilitates the process of teaching the decomposition of FR and DP hierarchies in axiomatic design.

6. ACKNOWLEDGEMENTS

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APPENDIX A

"Axiomatic design takes you from argument to analysis when evaluating designs."

"...used at preliminary stages of concept selection/evaluation and high-level system design to identify fundamental high-level coupling."

"Always, it comes down to seeing coupling and getting rid of it. I've done it at the system level, at the sub-system level, and the component level. Each has resulted in a better design. One change in particular has resulted in improved dimensional stability of our latest torch design. The simple change (let the insulator insulate and not position/align) has fundamentally changed the performance of the torch. The locating features do not change dimensionally over the life of the torch. We have the data to prove it. Another change was stated: "let the insulator insulate and not align/position." Another was "let the water tube carry the water and not align itself. (We added an alignment feature to align and another to position axially.) One feature, one function."

"We use structured designs of experiments (one form is Taguchi - robustness) to verify the stiffness of important interactions, and we use the experiments to choose an O or X if there is disagreement about whether there is an interaction at all (O or X) . We first use our tribal knowledge and analysis to decide if it's an O or X. We revert to experimentation when we can't choose AND we think a strong interaction could be troublesome."

E.M.Shipulski, PhD
VP of Engineering

"The axioms have had a profound affect on my ability to design effective code and in problem solving."

Wm. S. Johnsen, PhD
Sr. Software Engineer

"This changes the way I think about everything."

Owner, president, manager of a fabrication shop

"I have found that I have used the overall structure of Ax [axiomatic design] mostly to outline what the problem is and what the main components for the design are going to need to be. I also used it for brainstorming possible solutions to problems.

One example is the development of a new method to articulate an endoscope for my previous employer (Optim, Inc, Sturbridge, MA). By reviewing what the doctors needed (CAs) along with what the doctors complain about when using endoscopes, I was able to identify the functional aspects of a new design. From this, I was then able to brainstorm physical designs that would meet those requirements. Without getting into great detail, the new design will allow doctors to easily articulate an endoscope in 4-axis environment, with tactile feedback, using only one hand, which will then allow doctors to operate other tools to do biopsies or other procedures through the endoscope. The new design was purely mechanical to eliminate the complexity of motorized systems. The previous method for operating an endoscope [required the use of] both hands and an assistant and was nonintuitive. The new design has resulted in my first patent. The strong point [of the course] was doing our own test example and seeing other students' work.”

Ralph Tillinghast, MS
Engineer

We use axiomatic design for creating FRs and DPs to ensure the incorporation of all necessary elements of a design and to start narrowing down possible solutions.

[We] created FR and DP lists with constraints. Used for being sure all req's[requirements] are accounted for and to help narrow down [choices] from many possibilities of designs.

[We] used axiomatic design also to show robustness of a particular solution after the narrowing-down of solutions is complete. We have used [axiomatic design] only for new designs and concept generation. We have not used it much for rework, or design improvement, or other possible applications.

Michael Rufo
Project Engineer
Foster Miller Inc

“Two examples [from my previous job] come to mind. The first was a design of a process line for a low production sensor system used on a US Navy Submarine.

...by considering a “decoupling of operations” approach, we were able to optimize the man usage and layout of the sensors for concurrent assemblies (up to 3 at a time, as opposed to the original plan from start to finish). This also allowed us to speed up our overall time from 8 weeks to 4.5 weeks (which we held or beat consistently from the first unit on). The tools all worked for their specific purpose, and although at first it was a hard sell to go from the original 5 “specialized hand tools” up to ~12, once the workers had the “right tool for the job” it went quickly, painlessly, and easily made back the additional money spent on the tooling.

...we developed a conceptual tool design that met all the requirements individually (again, decoupled). ...This tool saved 1 full week of our schedule in itself. And due to the simplicity of the design, ...the cost of the part stayed low, the maintenance is easy and inexpensive, and it performed flawlessly....”

Michael Malchiodi
Currently: Mechanical Engineer, Associate Professional Staff
Johns Hopkins University Applied Physics Laboratory

“I have used the concepts to talk to strategic suppliers overseas and domestic to alert them to what is important in the design process and to make sure they can streamline their internal design process and give careful thought during their NPI stage, in order to pass on the cost savings to us.

The group projects presentation enabled me to hear from other professionals and students their point of view when designing a new product.” Po Tse

“I use axiomatic design... primarily in developing processes in electro-mechanical assembly. Most recently to decompose an existing process to diagnose the "WHY" of the root cause of a problem.

The strength is the simplicity of the concepts; the weakness is the language used to communicate them, particularly axiom 2, referred to as the "information content" and using a logarithm calculation. It may be technically the best; however, if one of the functional requirements is communicating the results to nontechnical people (management), then the term "information content" and the log calculation are not the best DP.”

John Scanlan,
Manufacturing Engineer, Teradyne

Students from first course to use Acclaro

“I typically use the elements of the design concept when designing machines and fixtures. I may not take the time to write out the list or use Acclaro, but I have the process in the back of my mind and try to keep components and key elements decoupled as often as possible.

My first big project was a degating system to separate two pieces post-shot that were connected by a runner. I knew that I needed to move the pieces into position, cut them, contain the pieces after cutting, and then bring the pieces back to the operator. So, I designed a nest to hold the pieces that were on a slide (all it did was slide the nest, so, no coupling there), a piston to bring the cutter into position, a slide on the end of the piston to adjust for width variations, and the cutters. So, I broke down what needed to be done at each step, and designed stand-alone (or semi-independent) components for each step.

A strong point [of the course] was that it showed us a new and simple manner to begin the design process. A weak point could be that you have to stay with it in order to fully use its potential. If you miss a couple of steps when designing and get lazy, then it doesn't help you in the end because you could miss those small aspects. If you do keep up with it though, you're sure not to leave out any necessary design parameters.”

Timothy Baird
Project Engineer

“its teachings definitely affect my thinking, planning and engineering. Being self employed, my engineering time must be optimized to the maximum, and I really don't have time to write down my customer restraints, functional requirements, and design

parameters (must have learned something there), but I live by the rules. It's like a Zen rule of life."

Jason Long

CEO, President and Head Janitor of NextGenAVD (They are all coupled)