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ON LEARNING AND EXECUTING AXIOMATIC DESIGN IN THE ENGINNERING INDUSTRY

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ABSTRACT

The principles of Axiomatic Design, although logical, often do not match conceptual design methods of engineering industry. Most engineering organizations try to inspect quality into the design process in the form of gate review processes with corrective change actions taken when problems observed. Iterative design cycles are common in industry. The Axiomatic design process attempts to form a rational design synthesis intended to eliminate iterations and produce the desired result in one design cycle. In order to fully take advantage of the organizational and analytical benefits of Axiomatic Design high level restructuring of an organization's design process can be required. This restructuring effort requires a large commitment of resources and energy. This process can be extremely difficult if the engineers involved have an incomplete understanding of the methods of applying Axiomatic Design. This paper draws on experience gained teaching Axiomatic Design principles to engineers in industry. It summarizes some of the problems engineers commonly have with the Axiomatic Design learning process and it also presents suggested methods for effectively conveying an understanding of Axiomatic Design. It includes ways in which functional requirements are often misunderstood by engineers in industry as well as what parts of the axiomatic approach are most important to be communicated and understood completely. This paper discuses how important it is for a student of Axiomatic Design to apply its principles to design examples relevant to the students current design activities and offers suggestions about how engineers can adapt their existing design systems to make them compatible with coupling analysis.

Keywords: education, learning, engineering industry

1 INTRODUCTION

The practical application of Axiomatic Design in the engineering industry presents many unique challenges. Axiomatic Design is a tool for communication, documentation, and evaluation of design ideas. It requires high level restructuring of the design process to take full advantage of the organizational and analytical benefits of using Axiomatic Design. Implementing or changing a design system in the engineering industry is a large undertaking that can be expensive and time consuming. This implementation can be even more difficult for large design teams, especially if a design organization scheme or requirements documentation system is already in place. Paradoxically the design teams that find it most difficult to adopt new design practices are often those designing systems with many functional interactions which would benefit most from an Axiomatic Design approach. Because of the commitment involved in completely integrating Axiomatic Design into a design structure it is important to fully understand how to apply Axiomatic Design, and what the benefits are, before the integration process is undertaken. This paper will attempt to outline ways in which some of the benefits of Axiomatic Design can be realized given the practical constraints that exist within a preexisting design organization. Section two of this paper focuses on some of the problems engineers commonly have with the Axiomatic Design learning process. This includes ways in which functional requirements are often misunderstood by engineers in industry as well as what parts of the axiomatic approach are most important to be communicated and understood completely. The third section of this paper discusses how Axiomatic Design can be learned through the practical application of its principles in industry. This section offers suggestions about how to best

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gain value from the Axiomatic Design principles without reorganizing design practices already in place. It presents ways in which engineers can adapt their existing systems to make them compatible with coupling analysis and therefore understand the potential benefits to their design activities that Axiomatic Design may provide. Once engineers understand how to state functional requirements, and how to build a decomposition that truly reflects their design intent, then they will then be prepared to implement these ideas in larger organizational structures and in the design of more complex systems.

2 COMMON PROBLEMS STATING FUNCTIONAL REQUIRMENTS

Engineers who have little or no experience with Axiomatic Design often find its principles difficult to incorporate into their design process. Many who have been working in industry have an established method of creative design that is difficult for them to change. It is essential that engineers learning Axiomatic Design understand their designs from a functional perspective and how functional requirements are different from customer needs and product specifications. One of the greatest challenges that face an engineer trying to apply Axiomatic Design for the first time is learning how to state the functional requirements (FRs) and design parameters (DPs) in the most useful way. The FRs and DPs of a system are the basis for the design evaluation and if they are not a clear, independent, and comprehensive reflection of the intended design functions then there will be little information provided by a coupling analysis. Furthermore, the language used in FR-DP statements is essential in communicating the design intent to other engineers. If logical and consistent language is chosen then Axiomatic Design provides a structure through which design intent can be communicated almost trivially. Ensuring that those studying Axiomatic Design can recognize and communicate the functional requirements of a system is a critical first step in enabling them to use Axiomatic Design.

The most basic rule Axiomatic Design teaches for deciding how to state functional requirements is the rule of orthogonality, or independence. If one functional requirement depends in any way on another then coupling will inevitably exist in the resulting design. This makes identifying and removing functional dependencies critical in obtaining a useful design evaluation. Therefore it is essential that students of Axiomatic Design understand how requirements can be functionally interdependent and how to remove these dependencies. Resolving these dependencies is a skill that improves with experience and at first it can be difficult to identify when a particular set of FRs has functional relationships. For example the partial list of functional requirements for a pencil in figure 1 appears to be a set of reasonable FRs.

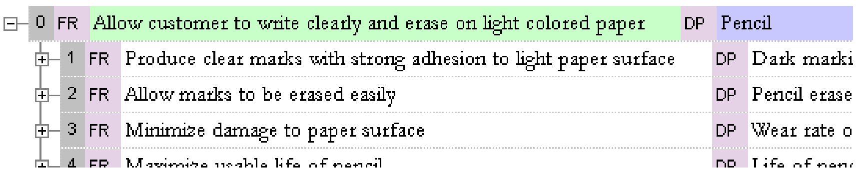

Figure 1. Functionally dependent FRs

However, these requirements are too specific and they cannot be independently satisfied. FR1 requires 'strong adhesion' between the paper and the pencil core material while FR2 requires that the core material be 'erased easily'. These requirements would not be an acceptable basis for a decomposition. One way of making a set of related requirements independent from each other is to closely reexamine a parent functional requirement that encompasses all the dependent requirements and then restate the requirements in a more general and independent way. In this case the parent FR does not included anything relating to the adhesion of the pencil core to the paper or how easy or difficult erasing should be. Therefore, one possible solution might look like this:

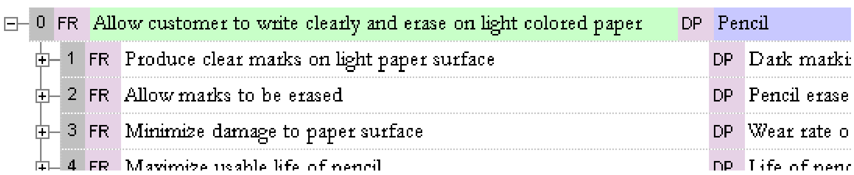

Figure 2. Functionally independent FRs

Another way to remove or minimize interactions between functional requirements is to impose constraints on the system that limit the flexibility of the functional requirements. It is preferable to have as few constraints as possible in order to allow flexibility during the design processes, however in some cases it may be necessary in order to ensure an independent design. An alternative solution to restating the functionally dependent FRs in figure 1 is to add a constraint to the system as shown in figure 3.

0	CON	Pencil Constraints
1	CON	Pencil core / paper surface adhesion force must be less than the pencil core / eraser surface adhesion force
2	CON	Pencil must not present any unnecessary safety risks

Figure 3. Constraining functional dependencies

This constraint bounds the dependent FRs so that it is clear what the design intent is. In order to ensure that the greatest possible number of design solutions are considered it is desirable to keep functional requirements stated as generally as possible and also to impose the minimum number of constraints. Therefore when functional requirements are dependent it is always preferable to restate them in a different way based on their common parent. Attempting to constrain their interactions should only be considered if restating the FRs is impossible.

Carefully wording functional requirements and design parameters is important for more than just controlling functional interactions. It is also important to be precise with the language used in the FR-DP statements to communicate design intent. The words used not only greatly affect the accessibility of the design to those who see the decomposition for the first time, but also help to guide the designer to clarify his design intent during the decomposition process. Many designers try to make sure each functional requirement is stated with a verb and each design parameter is stated with a noun. Using a verb to explain a functional requirement makes clear the task that the FR is intended to perform which can also expose interactions between FRs that violate the independence axiom. Similarly using a noun to describe a design parameter makes the object chosen to accomplish that task more obvious. This rule makes the entire design more transparent by imposing consistent language on the hierarchy. Figure 4 is a list of FRs and DPs stated as verb/noun pairs.

0	FR	Allow customer to write clearly and erase on light colored paper	DP	Pencil
1	FR	Produce clear marks on light paper surface	DP	Dark marking material core
2	FR	Allow marks to be erased	DP	Pencil eraser
3	FR	Minimize damage to paper surface	DP	Wear rate of paper
4	FR	Maximize usable life of pencil	DP	Life of pencil components
5	FR	Minimize possible dangers associated with pencil use	DP	Pencil safety characteristics
6	FR	Allow customer to use pencil comfortably	DP	Pencil human factors characteristics
7	FR	Prevent pencil form rolling	DP	Width of largest external flat surface
8	FR	Provide required esthetic	DP	Pencil appearance

Figure 4. Verb/noun FR/DP pairs

Stating functional requirements and design parameters carefully becomes increasingly important as the size of the design team grows. If FRs and DPs are stated with consistent, clear language the design intent becomes obvious and a lot of time normally lost in communication is saved. This is one of the greatest advantages of Axiomatic Design and it is often undermined because of unskilled formulation of FR/DP statements.

Another important factor to consider when stating functional requirements is the scope of the possible design solutions. When a designer is considering potential design solutions it is important that he consider as compressive a list of alternatives as possible to ensure the best possible solution. As discussed earlier this means that it is important to try and state functional requirements as generally and as solution neutral as possible. This will ensure that the child FRs will have a broad design space to cover and will therefore will form a completely exhaustive list of functional requirements. If the language describing a requirement is too specific, or implies one particular solution, it will eliminate potential design solutions that should be considered and could introduce functional interactions. For example, the language used for some of the functional requirements in figure 5 eliminates potential design solutions and ignores potentially important decomposition branches.

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0	FR	Allow customer to write clearly and erase on light colored paper	DP	Pencil
1	FR	Produce clear graphite marks	DP	Graphite core
2	FR	Allow marks to be erased by rubber eraser	DP	Pencil eraser
3	FR	Minimize sliding wear to paper surface	DP	Wear rate of paper
4	FR	Maximize usable life of pencil	DP	Life of pencil components
5	FR	Minimize possible dangers associated with pencil use	DP	Pencil safety characteristics
6	FR	Allow customer to use pencil comfortably	DP	Pencil human factors characteristics
7	FR	Incorporate flat outer surfaces	DP	Width of largest external flat surface
8	FR	Provide attractive bright yellow outer color	DP	Pencil appearance

Figure 5. Solution specific FRs

The more general the functional requirement is, the more design parameters are open for consideration. General requirements insure that branches of the design tree addressed and all solutions are considered.

A more subtitle problem with FR statements that is commonly encountered by engineers learning Axiomatic Design involves confusion about the difference between the functional requirements of the design or design process and the functional requirements of the object of the design process. Stating functional requirements correctly requires a detailed understanding of the system being designed, what it is supposed to do, and what is required to make that happen. Developing the required understanding of the system can be a difficult research process. It is tempting, therefore, when stating functional requirements to indicate a requirement of the process by which the correct functional requirement can be determined rather than actually stating a functional requirement of the design object. Some of the FRs in figure 6 are examples of vague requirements that indicate a lack of specific system knowledge.

0	FR	Allow customer to write clearly and erase on light colored paper	DP	Pencil
1	FR	Make appropriate marks on paper	DP	Dark marking material core
2	FR	Determine required eraser properties	DP	Pencil eraser
3	FR	Ensure correct paper wear rate	DP	Wear rate of paper
4	FR	Maximize usable life of pencil	DP	Life of pencil components
5	FR	Minimize possible dangers associated with pencil use	DP	Pencil safety characteristics
6	FR	Allow customer to use pencil comfortably	DP	Pencil human factors characteristics
7	FR	Prevent pencil form rolling	DP	Width of largest external flat surface
8	FR	Provide required esthetic	DP	Pencil appearance

Figure 6. Requirements of the design process rather than of the design

It is important that the purpose and scope of each functional requirement is clearly understood and documented for the decomposition process to provide useful design insights.

3 TEACHING AXIOMATIC DESIGN THROUGH FORMING DECOMPOSITIONS FROM THE STUDENTS OWN DESIGN EXPIERENCE

Fully integrating Axiomatic Design into an engineering design process requires changing the way in which requirements are documented and understood. Making these changes is problematic for many engineers. While most engineers have little trouble performing the coupling evaluation element of Axiomatic Design, often they find it difficult to construct a clear and comprehensive axiomatic FR-DP decomposition. For each engineer the learning process is different, as are the problems encountered. Learning Axiomatic Design well requires understanding the practical application of its axioms well enough to apply them to the new and different situations which are inevitable in innovative design. This learning process is made significantly easier if useful design decompositions can be developed for systems that the design students understand well and have invested time into. If an engineer can form a decomposition of one of his own designs then he can begin to formulate an understanding of Axiomatic Design as it relates to his way of thinking about design. In order to accelerate the process of understanding Axiomatic Design engineers must see the benefits of adopting Axiomatic Design by forming a design hierarchy

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from their own design experience. In some cases this can be accomplished by constructing an Axiomatic Design decomposition from existing requirements documentation. However, this is only feasible if the functional requirements are stated clearly and independently. If the requirements are not documented well, or are not sufficiently independent, work must be done to remove the functional interactions before a decomposition can created. Alternatively, rough decompositions can always be formed by working backwards from an existing design embodiment. Clearly working backwards makes producing a new or innovative design impossible. However, it can still be a useful learning tool. Understanding the design motivation that is behind the FR/DP decomposition enables engineers to see how design goals are reflected within Axiomatic Design and enables them to construct decompositions more easily.

One method for forming a decomposition with which a student can relate is to draw upon existing requirements documentation. Translating requirements from an existing design documentation system into an Axiomatic Design hierarchy requires separating FRs into single, independent requirements to which a single design parameter can be paired. It is important that the students not be caught up attempting to reproduce a system/subsystem or design hierarchy. The hierarchy of a design decomposition is an arbitrary choice of the designer; correct parent/child/sibling relationships are not required. Parent/child relationships are intended as tool of design organization that should not affect the leaf level FRs. Instead the design hierarchy should be used to simplify coupling analysis by grouping functionally related FRs together. Separating functional requirements into single FR-DP pairs is not difficult and often this exercise alone provides useful design insights. Some engineering firms have a method of recording the requirements of the systems they design though requirements documentation methods used in the engineering industry rarely have the level of precision that is necessary to perform a rigorous coupling evaluation. In some cases, when the pre-existing design requirement structure does not satisfy axiom 1, independence can be established by restating the requirements or imposing constraints as previously discussed. In order for independence to be possible the functional interactions between requirements must be small and limited, otherwise the work to make them independent will be unwieldy. As long as independence is assured and FRs and DPs can be roughly determined a cursory coupling evaluation is possible. Often this is all that is necessary to communicate an understanding of how to form a good design decomposition.

Other ways to provide Axiomatic Design students with a clear tangible decomposition that they can learn from are to construct FR-DP decompositions either based on previous design efforts or in parallel with their ongoing design process. If their design process is continued without Axiomatic Design while at the same time the students try and construct an axiomatic decomposition then they will be able to see how there own design process can be altered to become compatible with Axiomatic Design. Likewise reviewing old designs and using them as a basis for building decompositions can allow designers to relate their own design strategies to the Axiomatic process. Constructing flat decompositions, or decompositions of only one level of hierarchy, can be a useful way to apply Axiomatic Design to small pieces of a system design. This can simplify the decomposition process and provide an easy way to execute Axiomatic Design in parallel with other design activities. Because the hierarchy organization is arbitrary, removing all hierarchal distinctions and putting the entire decomposition on one level has no effect on the resulting design and it can be a good way to communicate the concept of independence as well as conduct coupling evaluation. This can only be done for small pieces of a design because flat enumeration of functional requirements can be unwieldy for large complex systems. Another useful technique is to build a list of DPs from the existing design solution; this can be much easier than determining FRs for systems that are already designed. Once this list is compiled determining the functional requirements for each DP is easier. The important thing to remember when using this method is that the generated list of DPs is only a tool for determining the correct FRs. The design should still be functionally driven. Whatever method is chosen it is important that the student work on constructing an Axiomatic Design decomposition that draws upon his own design experience in order to really formulate an understanding of the Axiomatic Design process.

4 CONCLUSION

Changing design practices that may have been in place for years can be complicated and hard work. Learning how to state functional requirements in the most useful way and make sure that their language is clear to everyone is rarely intuitive or obvious. Engineers must be able to form independent requirements that are precise and clear while remaining as general as possible. Removing functional dependencies through restating requirements or adding constraints is an important skill to practice before attempting to apply Axiomatic Design on a large scale. Engineers must also learn to focus their requirements on the object being designed and not allow FRs to reflect the design process rather than the actual design intent. Furthermore, an engineer must be able to relate Axiomatic Design to his own designs and design experience and then he can begin to see his own design experience reflected in his decompositions and design matrices. This enables him to understand how to use Axiomatic Design as a tool, and how it can be most useful for him in new design situations. Creating decompositions from existing requirements documents or design embodiments, or decomposing in parallel with another design activity are the best ways to bring about this understanding. If these tools can be used to establish a bases for relating existing engineering experience to Axiomatic Design methods, then what will result are designs that are easy to evaluate and communicate, and therefore easy ensure quality.

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