Proceedings of ICAD2009
The Fifth International Conference on Axiomatic Design
Campus de Caparica – March 25-27, 2009
ICAD-2009-30

DESIGN AND DEPLOYMENT OF AXIOMATIC DESIGN

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ABSTRACT

The objective of this work is to further the understanding of how to design and institute the practice of axiomatic design at a company. This includes designing the design process. This work goes beyond previously published papers on teaching axiomatic design. Teaching axiomatic design is one thing; instituting it as a practice in a company is another.

Both the institution of axiomatic design and the designing of the design process itself can be addressed using axiomatic design. The paper discusses how to formulate Functional Requirements (FRs) for providing an effective design environment. The upper level FRs include: manage value addition, costs and investments. Fulfilling the FRs requires developing appropriate metrics for engineering design work, including how to measure the value of progress during design work. Teaching axiomatic design to engineers is considered as part of the investment FR. In order to gain maximum corporate benefit from axiomatic design training, careful consideration must be given to deployment aspects such as pre-training preparation, effective training, and post-training project coaching. The paper includes tips on coaching teams, as well as maintaining momentum in a large organization with competing initiatives.

Keywords: value, design, teaching, deployment, product development

1 INTRODUCTION

The objective of this work is to further the understanding of how to design and institute axiomatic design at a company. Part of this furtherance is a discussion of a procedure for designing the design process.

This work is important because it goes beyond previously published papers on teaching axiomatic design [Odem et al.,2005; Brown, 2005a; Brown, 2005b]. Teaching axiomatic design is one thing; instituting it as a practice in a company is another. Axiomatic design can increase the value of engineering work only if it is used.

Others have written about deployment issues in axiomatic design [Yang and El-Haik, 2003; Dickinson, 2006]. Axiomatic design has become a significant element of Design for Six Sigma (DFSS) in many corporate deployments. DFSS is seen by many companies as a value-added tool to facilitate the development of design concepts that satisfy customer requirements and are robust to sources of variation, as shown in Figure 1. The first steps of DFSS are designed to help the engineer "Get the Right Product" (concept design). The core methodology of "Get the Right Product" is axiomatic design and it is imperative that a DFSS deployment program adequately trains engineers in its principles.

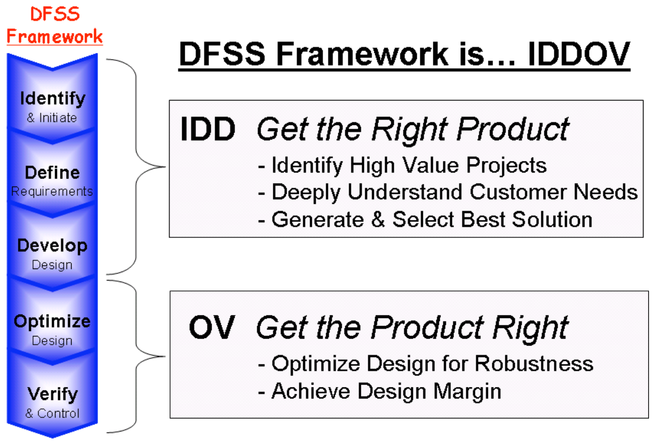

Figure 1. DFSS Process: Concept Design and Design Optimization.

The paper reviews deployment considerations, such as, pre-training project selection, effective instruction, and post-training project coaching. Good deployment of axiomatic design will include a method of measuring its use. A saying that is apropos here is "you get what you inspect, not what you expect" (author unknown). A couple of approaches to "inspect" axiomatic design will be reviewed.

Both the institution of axiomatic design and the designing of the design process itself can be addressed using axiomatic design. FRs (Functional Requirements) must be formulated appropriately to provide an effective design environment. This is essential as no design can be better than its FRs [Suh, 1990].

The following section (2) on theoretical design discusses creating a system that will improve the return on investment in design. Coupling is considered in the context of designing the system. Therefore the order of design of the elements, rather than in the sequence of their use, dictates the influences completing the design matrix. Consequently the decision on the order of adjustment of the Design Parameters (DPs) in order to satisfy the FRs is based on the influences the design of each element has on the others. The themes in the decomposition are based on the design of the system, including its deployment. In principle this context for the consideration of coupling should eliminate the need for iteration in the process of designing the deployment system.

The section that follows on deployment (3) describes how the deployment was executed and what was learned in implementing axiomatic design at Delphi Steering. In the discussion section (4) the results of this actual deployment are compared with the theoretical design.

2 THEORETICAL DESIGN

The highest level FR (0) is to improve the return on investment in engineering design. This could be decomposed (equation 1) into FR1 manage value in order to increase it, FR2 manage cost in order to reduce it, and FR3 manage investment in order to allocate it appropriately to support the process of adding value and reducing cost.

$$ROI = \frac{value - cost}{investment} \quad (1)$$

These three management FRs can be addressed by specifically designed management systems (DPs). See Figure 2.

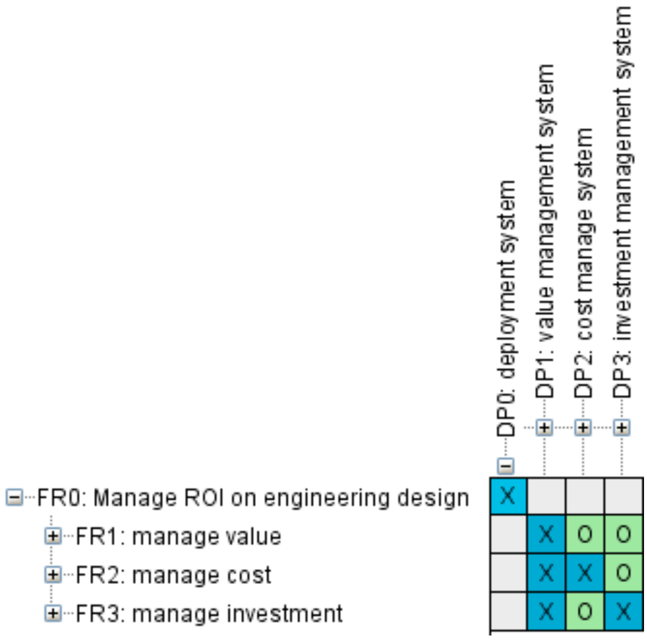

Figure 2. Improving the return on investment in engineering design.

Value is what the customer is willing to pay for – the product that is being designed. Because the company's customer could be well removed from the engineer, the design process itself needs to be developed to efficiently create designs that are responsive to the customer's needs. The design system needs to be able to recognize value creation during the process. It also needs to be able to recognize value to the company of the design knowledge, which, when properly managed, can be used to decrease design times and improve ROI in the future. The value added to the company in the improved capabilities of engineers from learning a more productive and profitable design system is considered under the investment branch. The value of the investment in effective training, like the value in the design knowledge, is intrinsic to the company. The cost branch considers managing the cost of the design process, apart from the cost of the investment. That is, the costs of the training and the knowledge management systems are considered investments, as they increase the value of the company, and are not something that the customer of the product being designed is willing to pay for. The cost branch and the investment branch are independent, but are each dependent on the value adding system. Therefore, following axiom one, the value adding system should be designed first.

2.1 VALUE ADDITION SYSTEM

The first FR, manage value creation, could be decomposed into: FR1.1 evaluate designs, FR1.2 manage design knowledge, and FR1.3 create designs (Figure 3). Through the evaluation branch this decomposition should be able to recognize and quantify the value of the design activities in two parts: 1) the value to the customer in the form of product performance, and 2) the value to the company in the form of the product design knowledge. Although this division is not the theme selected for the decomposition it should, nonetheless be covered.

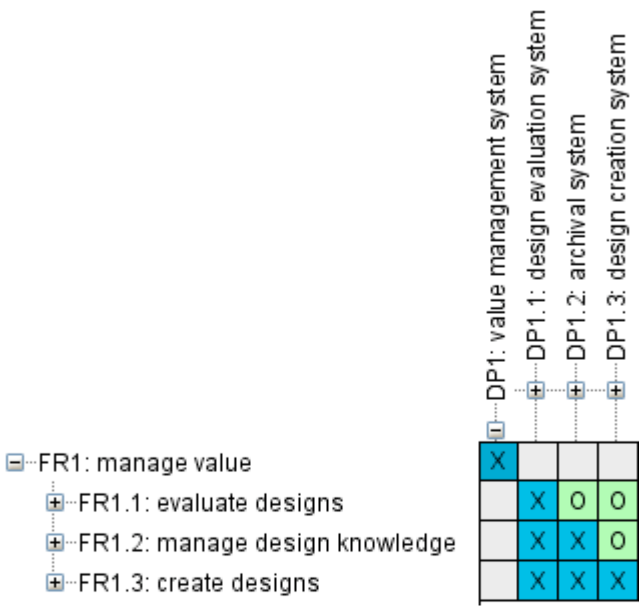

Figure 3. Top-level decomposition of "manage value" (FR1).

Three DPs for the value branch are three separate systems addressing each of the FRs. The design matrix would be lower triangular, as all the FRs depend on the assessment system. That is, knowledge management depends on the assessment system. Whether a lesson learned in a design activity is judged to be of value and retained for future reference depends on how designs are assessed in the first place. Additionally, product development assessment systems will evaluate how well new designs leverage previously acquired design knowledge as a measure of design efficiency. And design creation depends on both the assessment and the knowledge management systems. A design team will know in advance how their design will be evaluated, and thus their work would reflect how they will be measured ("you get what you inspect, not what you expect"). Therefore the assessment and knowledge systems utilize the products of the creation system and dictate the design of the design creation system.

The design evaluation system (DP1.1) needs to be able to place a value on the design and on the progress of an in-process design. These tasks can be combined to utilize the same system. Evaluation of the design could be decomposed into: evaluate the FR-constraint (FR-CON) system (FR1.1.1) and evaluate the DPs (FR1.1.2). Evaluating the FRs is the most important part of the assessment. The FR-CON system must be a collectively exhaustive response (FR1.1.1.2) to the customer's needs (CNs) (FR1.1.1.1), mutually exclusive (FR1.1.1.3), and the smallest number (FR1.1.1.4) (Figure 4). The DPs must satisfy axioms one and two. The evaluation system needs to be able to place value on a good design matrix. This would include making the method of determination of the matrix elements clear.

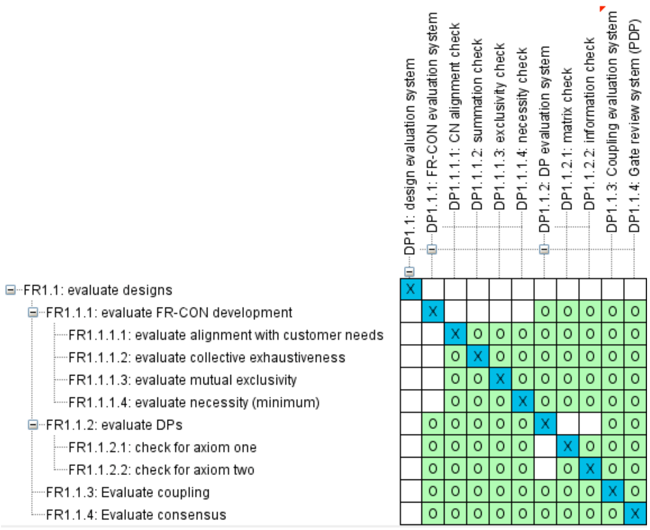

Figure 4. Decomposition of "evaluate designs" (FR1.1).

Knowledge (FR1.2) is an important part of the value to the company that is created during design activities [Kennedy, 2003]. The management of design knowledge is responsive to the efficiency in creating designs. It is an investment in future designs. The knowledge must be archived in such a way that it is retrieved when it is needed during design activities [Brown, 2007]. Axiomatic design provides a clear way to accomplish this through linking across the domains, e.g., customer needs with FRs and the CONs, and the FRs with DPs.

The design creation system needs to define the project (FR1.3.1), generate ideas (FR1.3.2), build consensus (FR1.3.3), establish design robustness (FR1.3.4) and communicate the design (FR1.3.5). See Figure 5.

Defining the project (FR1.3.1) includes developing a project charter that will elucidate alignment with corporate goals and indentify stakeholders. Idea generation (FR1.3.2) includes development of a system of FRs and CONs (constraints) to meet the customer needs (CNs) and selecting the DPs that will satisfy the FRs. Innovation is part of both of these steps. To do this generation the customer needs (CNs) must be assessed so that the FRs and the constraints are developed appropriately.

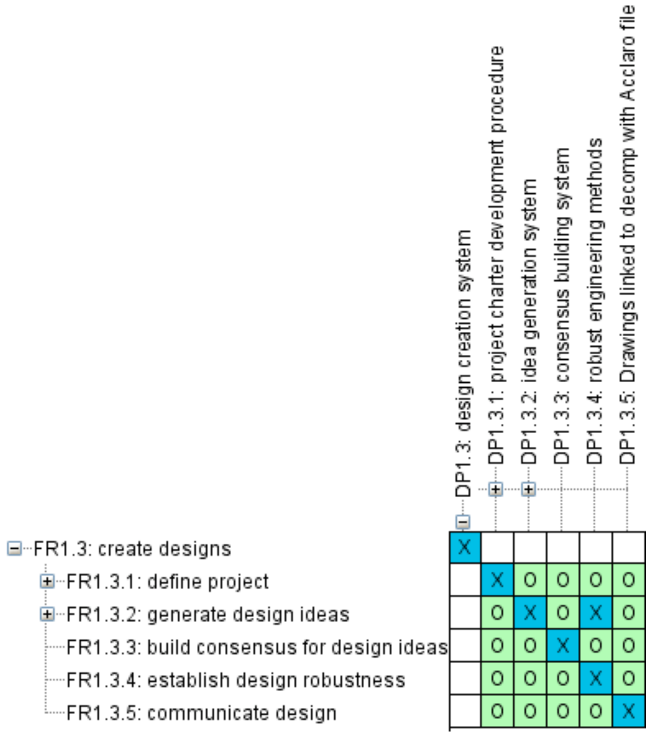

Figure 5. Decomposition of "create designs" (FR1.3).

The most important part of a design is selecting the best FRs. The design generation should also utilize previous lessons learned embedded in the knowledge management system. And the generation should utilize the assessments from the in-process evaluation system, during the current design cycle. These utilizations are coupled with the evaluation and knowledge archival systems. Design creation is valued in the context of the evaluation system.

Consensus (FR1.3.3) could be considered as part of the evaluation. This construction, with an FR to build consensus in the creation branch, recognizes that the evaluation is active, continuous, and hierarchal in nature, and that consensus is built at one level, before evaluation at a higher level. In the spirit of concurrent engineering, good consensus building will include the voice of manufacturing.

Establishing design robustness (FR1.3.4) will leverage Taguchi's robust engineering process (or similar) whereby the design is made insensitive to sources of variation (manufacturing, customer use, environmental conditions, and internal wear) [Taguchi et al., 1999]. In large part, achieving design robustness is a result of proper application of axiom 1 (resulting in an uncoupled or decoupled design). Additionally, application of axiom 2 will drive capability to design tolerances [Suh, 1990]. Robust design supplements axiomatic design, as it has been amply demonstrated that design optimization that comprehends subjecting the design to variation during development will result in a more robust, durable product or process design.

Communication of the design ideas (FR1.3.4) is important to assessment, building consensus and to the utilization of the products of the design work – building the product. Ideally, the communication should include a decomposition of the FRs/CONs to DPs integrated onto drawings with the features linked to the corresponding elements in the decomposition.

Robust engineering methods (DP1.3.4) influences generate ideas (FR1.3.2), since parameter optimization will clearly depend on the DPs. Referring back to Figure 1, this is simply stating that a design team must first "Get the Right Product" (concept design) before moving to "Get the Product Right" (optimization). The result of this dependency of generation ideas on robust engineering methods is a matrix with an off diagonal element, demonstrating a decoupled design, as shown in Figure 5.

2.2 COST

The tasks of managing the costs can be decomposed into: FR2.1 identifying the cost drivers, FR2.2 identifying the value adding activities, and FR2.3 eliminating the non-value adding activities (Figure 6).

The cost drivers can be identified by evaluating the activities of the engineers during the design process. Many companies use value stream mapping or process mapping to accomplish this goal [George, 2002]. In identifying the value adding activities both extrinsic and intrinsic values should be identified and evaluated appropriately.

Eliminating non-value adding activities requires redesign of the design process at some level. The level depends on the activity. For example, non-value adding iterations in building consensus with a small group of designers at a low level drives costs unnecessarily and delays the design process. Note that consensus building will be accomplished easier if proper leverage is made of past lessons learned, i.e., knowledge is well managed and actively pursued as part of the consensus building.

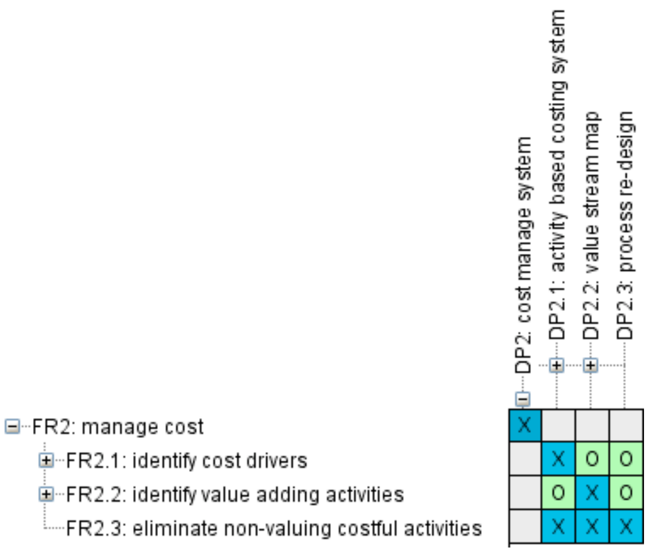

Figure 6. Decomposition of "manage cost" (FR2).

2.3 INVESTMENT

The investment provides the means to manage the resources that add value to the design. Because the cost management is concerned with direct operating costs it is decoupled from the investment. The investment is designed based on the needs for value management. There are clearly various investments that could be considered to improve ROI from engineering design. This decomposition focuses on the investment made in developing competency in applying axiomatic design. The management of the investment provides the means for deployment of axiomatic design. And in order to gain maximum corporate benefit from axiomatic design training, careful consideration must be given to pre-training preparation, effective training, and post-training project coaching.

Managing the investment could be decomposed into: FR 3.1 prepare engineers, FR 3.2 manage acquisitions, and F3.3 build management support. The DPs are training activities for the engineers, an acquisition management system, and support building activities for management (Figure 7).

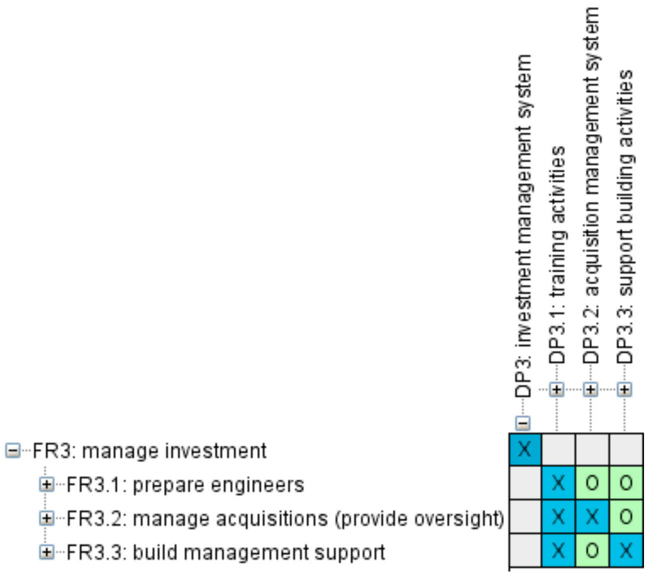

Figure 7. Decomposition of "manage investment" (FR3).

Preparing the management depends on how the engineers are prepared. The system for preparing the engineers should be designed first to meet the needs of value creation. The system for preparing the managers will be deployed first, although designed third. The management of acquisitions depends on the preparation of the engineers and would be designed second. However, the preparation of engineers is independent of the systems for managing acquisitions.

Managing acquisitions (FR3.2) provides review and keeps the cost management branch (FR2) independent from the investment branch (Figure 2). Through managing the acquisitions the investment branch oversees and coordinates the investments. The cost branch is concerned with the direct costs of the engineering activities. The acquisitions should include software for axiomatic design (e.g., Acclaro) as well as software for knowledge management, which would interface with the design software. The authors are not aware of any such knowledge management software. Included in the personnel could be consultants to help with the training and the design of the systems.

Preparing the engineers can be decomposed into supplying motivation (FR3.1.1) and coaches (FR3.1.2), and training for developing FRs (FR3.1.3) and DPs (FR3.1.4), for design reviews (FR3.1.5) and for effectiveness (FR3.1.6). The effectiveness training system is responsive to the need for creating designs as quickly as possible, something that engineers frequently ask for. The motivation, coaches and training for FRs, DPs and design reviews all impact the design of the effectiveness training system. The effectiveness needs to be responsive to all the other elements of the preparation. Effectiveness is where the rate of value creation is addressed. The design of training for effectiveness in value creation depends on everything that creates value.

3 DEPLOYMENT RESULTS

With DFSS being a well-accepted practice to improve ROI from engineering design, and axiomatic design also recognized as a core competency within DFSS, we now turn to a discussion of a deployment within an automotive supplier, Delphi Steering.

Good deployment of axiomatic design starts with pre-training project selection. While axiomatic design can be useful for projects focused on incremental improvement, it is most powerfully applied in new concept generation. So screening for these types of projects can be beneficial before beginning training.

Ideally, project selection begins with corporate goals such as revenue enhancement and cascades through a series of goal management processes. In practice, this can be quite messy, so some structure helps. One way to introduce structure in the process is to deploy a project charter. Charters can take many forms, but generally include a concise statement of the project goals, identification of stakeholders (sponsors, team, coach, etc.), documentation of the value of the project to the company, including its connectivity to corporate goals, a scope statement, and project deliverables and timing. See Figure 8 for an example format. By going through the process of constructing the charter, it can become quite clear when a project will be conducting concept generation, which will make it a prime candidate for the application of axiomatic design.

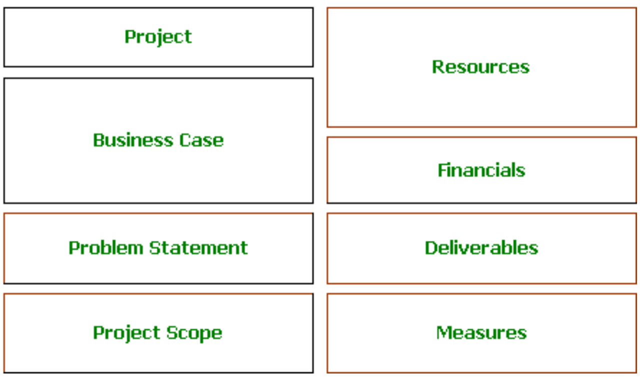

Figure 8. Example project charter.

An important final step in the pre-training preparation is lining up strong management support. This applies for both the project work as well as the support for the method of axiomatic design. If a management group is not convinced of the value of applying axiomatic design, it is unlikely to be effectively used. One way to do this is by training management before the engineers. Instruction should not be limited to the methodology itself, but include questions managers should be asking their teams to drive appropriate use of axiomatic design. Example questions include:

- Which design parameters impact which functional requirements?
- What is the plan to deal with an imperfect state of independence, i.e., coupling?

Effective instruction of axiomatic design, whether for management or for engineers, will include 1) a WIIFM ("What's In It For Me") for the participant, 2) plenty of examples of application (which is most effective when examples include products the same as or similar to those the company produces), and 3) simple exercises that quickly communicate the essential elements of axiomatic design and build skills for its application back on the job. It is well known that people learn best through application, and conducting exercises is a safe and fun way to first learn any skill [Pike, 1994].

Once instruction is delivered effectively, engineers must be supported through active coaching on their application. This follows the tried and true path of "teach-coach-do" that has made Six Sigma deployment so successful [Pande et al., 2000, Eckes, 2001]. What follows are some tips for coaching axiomatic design projects.

- A fairly common problem engineers face when initially documenting the decomposition of FRs is how detailed they should be. A helpful mnemonic for formulating FRs is "CEME min":
    - CE: Collectively Exhaustive. Care must be taken to avoid including constraints as FRs.
    - ME: Mutually Exclusive. This means FRs are independent and do not overlap.
    - Minimize the number. A rule of thumb is to not exceed 7 FRs.
    - An engineer may ask "When do you add more siblings vs. decomposing into children?" Answer: Whatever helps you do "CEME min" better.
- If a CN generates an FR you are going to take some action to satisfy the FR. If it's a constraint you won't take a specific action, but it must be checked for violation.
- All FRs, including lower-level FRs, should be stated in a solution neutral environment.
- Pick an appropriate "theme" to group FRs under. This helps drive "CEME min" and avoids non-productive iteration (see below). Some example themes are:
    - Time
    - Space
    - State
    - Condition
    - Boundary conditions

- Teams can get stuck in analysis paralysis when establishing FRs. To get "unstuck" pick a theme (perhaps from a prefabricated list), run it to ground and see if it works. If that theme does not work, change the themes and try again. A team may also find lower level themes work better and should be promoted to top level themes.
- Select children of FRs to help drive a minimum set of FRs. An example in an engineering structural analysis may be that moments are children of force FRs because forces are required to develop moments.
- Proper wording of FRs is crucial. For example, another way to look at the classic water faucet example is to state the FRs differently, as shown in Figure 9.

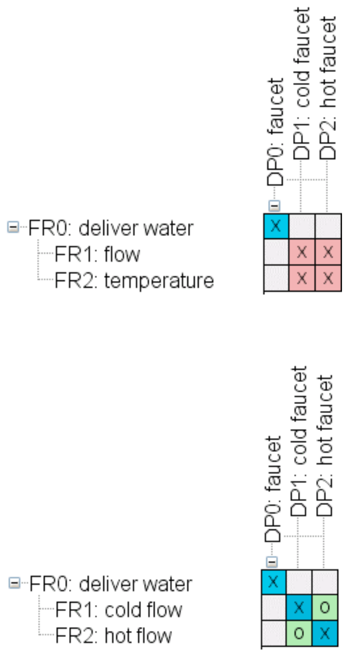

Figure 9. Care must be taken to use proper wording for FRs, as shown in example FRs for the water faucet.

- Use language in the FRs that clearly indicates ME (mutually exclusive). Example for an adjustable steering column:
  - OK: FR1 = provide good adjustment feel, FR2 = minimize deflection when locked
  - Better: FR1 = provide axial adjustment feel, FR2 = control radial stiffness
  - By using the underlined words, orthogonality is indicated, which will often directly lead to ME
- Ways to know whether an element in the design matrix is zero or non-zero are:
  - Science (physics, chemistry, etc.)
  - Simulation
  - Empirical experimentation
  - Experience
  - Vote
  - Tolerance argument – a change in the DP effects the FR but does not take it out of its tolerance
- Avoid non-productive iteration in group reviews:
  - In a design review a manager or a group examines decomposition, and possibly drawings, that an individual or smaller group has created. The objective of this kind of design review is to build consensus in the group for support of the design, which may require refinement of the design. Building consensus among the stake holders adds value to the design.
  - If consensus is not being reached quickly and if during the discussion the FRs, DPs or matrix elements have not changed, and if no notes have been added to the design, then the team should question if any value is being added to the design in this process. The facilitator or coach needs to assure that value is being added to the design, and that engineering time is not being wasted with non-productive iteration.
  - Refinement is a good form of iteration. When refinement is blocked by differing opinions, there may be a true lack of knowledge; break the roadblock by having one part of the team go with one approach and another part of the team take a different approach, then reconvene to debate the merits of each.
  - Repetition is not a good form of iteration. When repetition is occurring the coach needs to move the team along.
  - Discussion that relates to a different design problem, e.g., process as opposed to product, should be considered as a separate problem or a separate branch.

We've seen that driving axiomatic design in a corporation involves pre-training preparation in the form of good project selection and preparing management for their role in a successful application. We've also seen that effective training must be followed-up by coaching to drive further understanding. And we have made note of some useful tips for coaching axiomatic design. We now turn to the question of how to measure the use of axiomatic design in an organization. We know we must do this because "you get what you inspect, not what you expect".

At Delphi Steering axiomatic design use is currently measured through its application on DFSS projects. Every project in the company is tracked and final reports are required and posted as a shared resource for retaining lessons learned. This is a relatively easy way to track use of axiomatic design after training is deployed. However, this is a passive approach. To drive the use of structured innovation tools, like axiomatic design, more deeply, the use of the tool is being integrated into the product development process (PDP) itself.

PDP systems have critical steps that require management oversight, often called "gate reviews" [Perry and Bacon, 2007]. Examples include "Preliminary Design Review", "Critical Design Review", and "Final Design Review". Recent work in PDP has included studies of Toyota's Lean PDP, often cited as a benchmark process [Morgan and Liker, 2006; Ward, 2007]. An important concept from Toyota's Lean PDP, taken from Lean Manufacturing, is "Built-In Quality". The idea, transferred to the design world is to not pass on a quality problem to the next phase of the PDP. This can be done with the use of design review scorecards during staged gate reviews. These scorecards would measure activities that PDP requires. The scorecard would evaluate use of suggested tools that drive robust design, including axiomatic design. This is one approach to move from a passive to an active measure of axiomatic design's use in product development.

Another company that has successfully implemented many of the attributes of Lean Engineering PDP is Pratt & Whitney [Purrington and Bown, 2003]. P&W has developed what they refer to as Engineering Standard Work (ESW) for all aspects of its engineering work. ESW includes not only the activities that are required, but tools and methods that can or should be used to achieve a successful conclusion to those required activities. Similar to the discussion above, it is in the scoring of ESW within a PDP system that the use of axiomatic design can be embedded.

4 DISCUSSION

A theoretical solution and some details of an actual deployment have been have been presented. The alignment between the two is good. They are compared and contrasted below.

In the practical situation described above, the deployment of axiomatic design is in the context of existing design tools, in particular DFSS. Therefore, a subsection is dedicated to the discussion of DFSS.

4.1 VALUE MANAGEMENT SYSTEM

The care taken in training for the development of FRs in the decomposition is consistent with the theoretical importance placed on this development. The alignment with customer's needs is expected to be part of any design system. The only change that should be expected with axiomatic design is that this alignment is to be checked against the FRs each time a new level is reached in each branch.

The knowledge management system continues to be developed, and specific to the application of axiomatic design is at best part of the DFSS tracking system. The value in reuse of design knowledge is recognized as needed area of improvement.

4.2 COST MANAGEMENT SYSTEM

In practice the management of the direct costs of generating the designs appears reasonable for emphasizing the value adding activities. There is no mention of systematically identifying the cost drivers due to company confidentiality. It can be stated that value stream mapping of the design process and systematic identification of the cost drivers have revealed opportunities to better manage costs. Examples include streamlining change management and other approval processes.

4.3 INVESTMENT

The details of the training of engineers and building management support align well with the theory. The practice concentrates appropriately on the tracking of the utilization of axiomatic design. The emphasis on the development of FRs and selection of DPs addresses key elements in the value creation in axiomatic design.

The metric for design work that is often mentioned by practicing engineers is meeting the deadline. This may be because many companies lack effective means of measuring design quality or progress. Axiomatic design can supply these means. The effectiveness training (see tips discussion in section 3) is intended to address this engineering need. Coaching and training for the avoidance of non-productive iterations does help to address effectiveness. It may be worth the investment to make effectiveness training in itself a separate concern. This would fit well with the value stream mapping.

It is advisable to use consultants to help with the deployment of axiomatic design, especially early in the deployment and utilization process. It has been observed that teams attempting to utilize axiomatic design can have difficulties with completing decompositions. Generating the design decompositions and evaluating the design matrices can be challenging the first few times. Errors are often made and companies give up as the engineers are unable to create good decompositions. The expertise to correct these errors appropriately would not exist in the company early in the process. Once internal coaches have been developed the use of outside expertise can be reduced. At Delphi Steering coaches were given additional axiomatic design training beyond that for the general engineering population and this is the source of many of the coaching tips from section 3. Regardless of the source of expertise, it is recommended that companies apply the "teach-coach-do" method for developing competency.

4.4 DFSS

We have seen that investment will include costs of deploying training and the creation and ongoing deployment of a knowledge management system. We focus here on the investment in training, specifically in axiomatic design (and DFSS, more generally).

As Figure 10 shows, it is well understood that designs done poorly in the early phases will have escalating costs as launch of production nears. Application of DFSS brings these costs down. (It is again worth stating that many DFSS deployments today have axiomatic design as the core tool for concept generation.)

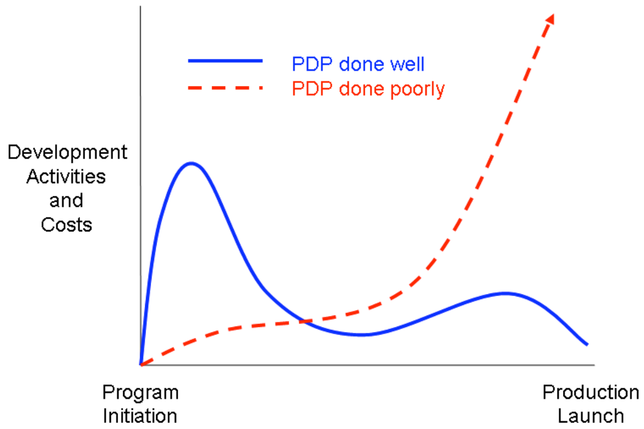

Figure 10. Costs can grow exponentially at launch if design is not done well.

To realize the savings potential of DFSS, a company must be willing to invest in the development of engineering competencies, such as use of axiomatic design.

5 CONCLUSION

A theory of design process has been proposed using axiomatic design. The theory has highlighted the need to drive value through embedding axiomatic design into the design process itself. Theory shows this should take place in three important areas: 1) evaluation of designs, 2) knowledge management of previous design activities and proper leverage of this knowledge in future design work, and 3) creation of designs. Each of these areas benefit from axiomatic design thinking, which can only be implemented after investing in developing competency in the application of axiomatic design.

The practical deployment appropriately emphasizes the essential value-adding steps in axiomatic design. The deployment described has benefited from a few years of DFSS and axiomatic design activities. These activities have resulted in tangible benefits for the company, demonstrating good return on the investment of developing axiomatic design as a competency. Areas for improvement include making more direct measurement of the use of axiomatic design (and DFSS more broadly) as part of the product development process, as well as improving reuse of design knowledge through the structure provided by axiomatic design's decomposition process.

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