INTEGRATING AXIOMATIC DESIGN INTO A DESIGN FOR SIX SIGMA DEPLOYMENT

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ABSTRACT

Design For Six Sigma (DFSS) is a systematic process for design conception intended to yield robust products that meet customer expectations. Robustness is defined here as product performance that is insensitive to variation, both in manufacturing and in the application environment.

It is widely accepted that no amount of robust optimization at the detailed design level can succeed if the design concept itself is flawed (does not satisfy all functional requirements). The author has specifically focused on DFSS deployment in his company in the area of concept generation. Integration of Axiomatic Design has been the most critical element of this improvement. This paper describes how Axiomatic Design has been integrated smoothly into a pre-existing DFSS deployment. It demonstrates how Axiomatic Design links with other well-accepted DFSS tools. The author emphasizes the importance of educating leadership and utilizing experienced trainers of axiomatic design to ensure deployment success.

Keywords: Axiomatic Design, DFSS (Design For Six Sigma), Robustness, Concept Generation, QFD, TRIZ, Pugh Analysis, Function Mapping, Organizational Deployment

1 INTRODUCTION

It is well documented how the continuous improvement process of Six Sigma has helped companies improve their product quality and thereby directly impact company profits [1, 2]. Companies that took the lead in Six Sigma subsequently launched more proactive approaches to product quality, commonly known as Design For Six Sigma (DFSS). DFSS was developed to aid engineers in their quest to design products right the first time and avoid quality problems at product launch [3, 4]. The key to getting the design right the first time is to ensure the product is intentionally designed to be robust. Robustness is defined here as product performance that remains consistent even in the presence of sources of uncontrollable variation, including 1) manufacturing process variation, 2) fluctuations in the operating environment, and 3) the wide spectrum of ways customers can use the product [3].

DFSS brings together various methods that have been individually developed by researchers and practitioners to aid engineers in product design. These methods include QFD [5], Axiomatic Design [6, 7], TRIZ [8], Pugh Analysis [9], FMEA [10], Robust Engineering [4, 11], and accelerated testing [12]. The DFSS thought process is shown in Figure 1, using an industry standard acronym – IDDOV; Identify, Define, Develop, Optimize, and Verify. The framework of IDDOV is intended to promote a repeatable design process that engineers can follow, independent of the product or process being designed. (Some practitioners use ICOV; Identify, Characterize, Optimize, and Validate [3]. The basic algorithmic thought process is the same as IDDOV.)

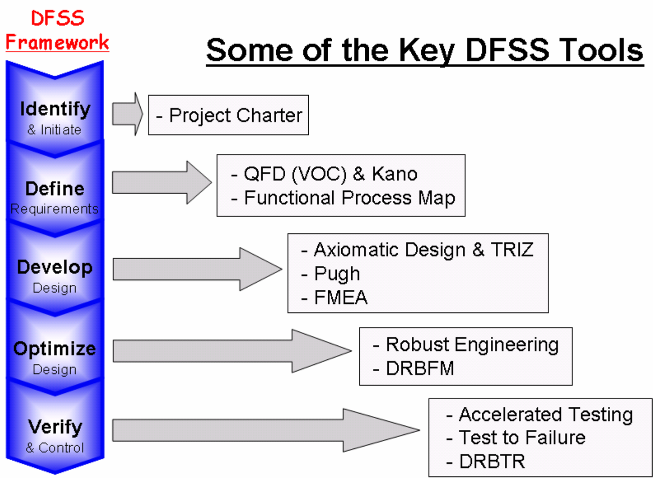


Figure 1 – DFSS Process: IDDOV

A simple way to communicate the steps in the DFSS process is shown in Figure 2. The first phases of DFSS ("IDD") are designed to help the engineer "Get the Right Product". These first steps are intended to facilitate the engineer to develop a robust concept prior to optimization. The centerpiece of "Get the Right Product" is Axiomatic Design and it is imperative that a DFSS deployment program adequately trains engineers in its principles.

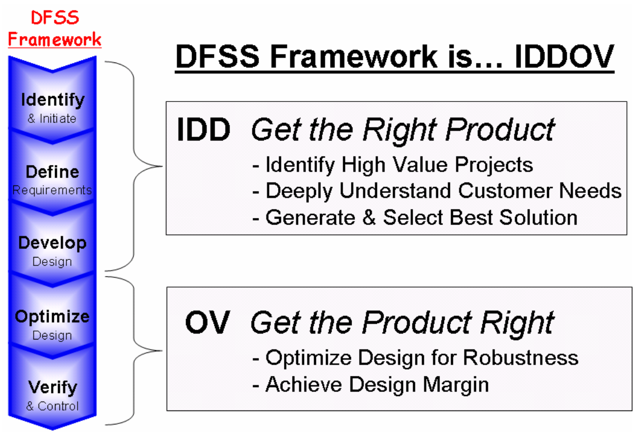


Figure 2 – DFSS Process: Concept Design and Design Optimization

The last phases of DFSS ("OV") facilitate the engineer to "Get the Product Right". The focus of these last steps is to optimize the product for robustness and then check for unanticipated failure modes. Taguchi's Robust Engineering is the core of the Optimize phase and much time is spent in training and coaching engineers in its philosophy and execution.

It has been the author's observation that many companies have spent much more time developing engineering competency in OV than in IDD. At times, this is a reflection of mature product lines. However, while it is widely accepted that innovation is the only way companies can be sure to outlast their competitors (especially in today's hyper-competitive global economy), this over-emphasis on OV is often because the need for rigor in concept generation is not understood. That is, innovation is often viewed as a creative process that defies a structured approach. DFSS stresses that robust design starts with a thorough understanding of the voice of the customer and then translating functional requirements into a robust concept. A quote from the late Stuart Pugh summarizes the importance of good concept design: "The wrong choice of concept in a given design situation can rarely, if ever, be recouped by brilliant detailed design." [9]

Much of the published work in Axiomatic Design has been associated with theory and application. Indeed, the author's company has successfully applied Axiomatic Design principles in product design. However, it is just as important to properly plan the deployment of Axiomatic Design training into an organization, and arguably this organizational point is even more important than the actual technical training and project execution. This should not be surprising given the evidence of the impact of proper deployment on the success or failure of continuous improvement initiatives such as Six Sigma [1, 2, 13]. This paper focuses on these more "soft-side" issues of Axiomatic Design deployment. Section 2 describes these organizational lessons learned. Section 3 shows the synergistic integration of Axiomatic Design with other DFSS tools. It is assumed the reader has knowledge of the basic principles of Axiomatic Design [6, 7].

2 DEPLOYMENT OF AXIOMATIC DESIGN

Many authors have focused on the technical aspects of deploying Axiomatic Design principles into a DFSS program. This is important, but the author has learned over years of deployment management experience, that a structured program deployment approach is just as important as the technical aspects.

Proper introduction of a methodology such as Axiomatic Design into an organization involves five steps:

1. Finding the right expertise
2. Gaining senior management support
3. Running a pilot
4. Integrating into an existing program
5. Establishing self-sufficiency

The remainder of this section will focus on these steps relative to Axiomatic Design deployment. The points that are made apply equally well to deployment of any business initiative within an organization.

2.1 DEPLOYMENT – FINDING THE RIGHT EXPERTISE

Introducing Axiomatic Design into an organization requires expertise. Of course, initially there has to be a recognized need. In the author's case, as a result of interacting with a valued customer [14], it was recognized that the company's DFSS program needed to improve on the first part of DFSS; IDD or "Get the Right Product". This initial voice of the customer led to much subsequent research and industry and academic contacts, eventually leading to the establishment of a formal contract to provide Axiomatic Design project selection coaching, training, and project coaching.

It can be argued that the most affordable method for introducing Axiomatic Design into an organization is to send a few talented individuals to the appropriate training, conduct a pilot usage of Axiomatic Design in a chosen product development program, assess the merits, and then have these individuals deploy training within the organization (if the organization is large enough for the need). In the author's experience, however, this approach, while certainly controlling spending, leads to a dissatisfactory and thus short-lived deployment.

Finding the right expertise to train engineers and coach them on actual application may require significant initial investment, but it ensures the following:

- A high level of enthusiasm. Engineers are trained to be cautious, so an expert resource with a vast supply of application experience helps drive credibility and excitement.

- A high probability of internal application success. Any successful change initiative requires early "wins" to keep the momentum going [15]. The expert resource can transition from training resources to helping them apply the method to an important application (we call this project coaching), thus ensuring application success.

2.2 Deployment – Gaining Senior Management Support

Acquiring leadership engagement is the most important ingredient for a successful deployment of Axiomatic Design. It is well documented that senior management support must be gained in order for any change initiative to last [1, 2, 13, 15]. For Axiomatic Design, this means senior engineering leadership must have a basic understanding of the method, its benefits, and the cost of implementation. (While Axiomatic Design can be applied in non-engineering areas, this has been the focus of the deployment in the author's company.) The best way to do this is to utilize the selected expert resource to introduce the method and provide tangible evidence of the benefits to key stakeholders in the DFSS program, which by definition includes senior engineering management. For example, the author brought a selected expert into the company for a one-day overview of Axiomatic Design with the engineering director and his staff of chief engineers.

This step is so crucial that if it is not followed eventual failure to permanently integrate Axiomatic Design into DFSS will result.

2.3 Deployment – Running a Pilot

Once senior leadership has decided to support deploying Axiomatic Design, it is necessary to run a pilot session of training. It is widely recognized that the best way to deliver training to engineers is to make the training project-based [1, 2]. This was done in the author's company by conducting project selection meetings with chief engineers, facilitated by the selected external expert. The expert serves the role of helping understand what types of product development projects are appropriate applications of Axiomatic Design. It's important that the initial projects be selected with an eye towards targeting early success. Projects that will likely have long timelines will result in lost momentum from the initial management buy-in phase (previous section).

The format for the pilot should be designed to provide instant feedback. The author's chosen expert delivered a 4-day workshop which blends lecture on theory and application with actual hands-on work on the selected projects. The goal was to come away from the workshop with tangible innovation – workshop-generated concepts that would excite the customer and lead to intellectual property that would drive competitive advantage.

A final note on the pilot is that it was recognized early on that the training would be much more successful if an IT tool was included. Iterations involved in mapping between domains and the construction of the design matrix can be quite frustrating if done manually. An example IT tool is described in ref [16]. Incorporating an IT tool in the launch of an Axiomatic Design deployment will pay significant dividends in the training, as it allows participants to concentrate on the method and not on bookkeeping and formatting.

2.4 Deployment – Integrating into an Existing Program

Companies have multiple initiatives that consume engineering time. Proliferation of methods and processes can frustrate an organization if they are not carefully and, preferably, seamlessly integrated into existing structures. In the author's company, an existing DFSS program was underway. While the addition of Axiomatic Design added training days to the existing DFSS curriculum, much effort was made to provide the proper context and fit of Axiomatic Design (see Figure 1). The synergy between Axiomatic Design and other DFSS tools is discussed in Section 3.

2.5 Deployment – Establishing Self-Sufficiency

If a company is a medium- to large-size company, it is likely that training of engineers in Axiomatic Design will continue over the course of years. In such a case, the author strongly believes the company needs to develop a core group of experts with sufficiently high competency such that this group can provide internal training of Axiomatic Design. This not only saves the expense of hiring outside expertise to continue training, it allows the company to hone its own internal expertise in Axiomatic Design. This is true because one can never quite become a true expert in a method until one has to teach it. Thus, the author's company has selected a group of core experts, called DFSS Master Black Belts, that are in the process of developing the skills to eventually take over training Axiomatic Design, with the intent of maintaining the established relationship with the chosen external expert for the purpose of communicating awareness of developments in Axiomatic Design theory and practice and to monitor the quality of the internally-driven training program. (The extent to which this self-sufficiency can be developed is a function of the company's available resources, both from a monetary and people perspective. A cost/benefit analysis of delivering training with internal vs. external expertise must be made to determine which works best for a company.)

Thus, the author recommends thinking this issue through with the selected outside expertise at the very beginning of an Axiomatic Design deployment. Self-sufficiency issues include:

- Who are the right people to develop as the internal experts?
- Will training material be available for internal use?
- What train-the-trainer requirements shall be established? For example, will internal experts practice teach first with the outside expert, followed by in-class observation and assessment?

Eventually it is hoped that Axiomatic Design will gain a greater foothold in academic training of our engineers. But until then, we need to rely on external expertise to train engineers and develop internal experts to take over this training.

3 INTEGRATING AXIOMATIC DESIGN INTO DFSS

In Section 2.4 it was emphasized that introduction of any new initiative should be carefully integrated into existing processes/structures. In the author's company, Axiomatic Design was not treated as a separate new initiative. It was integrated into the existing DFSS program. This section investigates the synergies gained between Axiomatic Design and other DFSS tools.

3.1 AXIOMATIC DESIGN AND QFD

One of the fundamental concepts of Axiomatic Design is the fact that design is the interplay between what a design must achieve and how it will be achieved. This must be accomplished through mapping between domains; customer, functional, physical, and process domains. Many DFSS processes capture the voice of the customer (VOC) through the use of Quality Function Deployment (QFD) [5].

Figure 3 shows a typical "house of quality" (HOQ). The HOQ facilitates and communicates the key information coming from the customer domain; translate the VOC to engineering performance metrics; understand interactions (both positive and negative) between various performance metrics; establish performance targets; document competitive benchmarking. The primary goal of QFD is to convert the VOC to the voice of the engineer (VOE).

Thus, QFD is the primary technique for mapping between the customer and functional domain. And this is where the synergy with Axiomatic Design comes in. One of the most difficult steps for engineers when they are developing their design's functional requirements (FRs) is keeping the language in a solution-neutral environment. QFD facilitates this process.

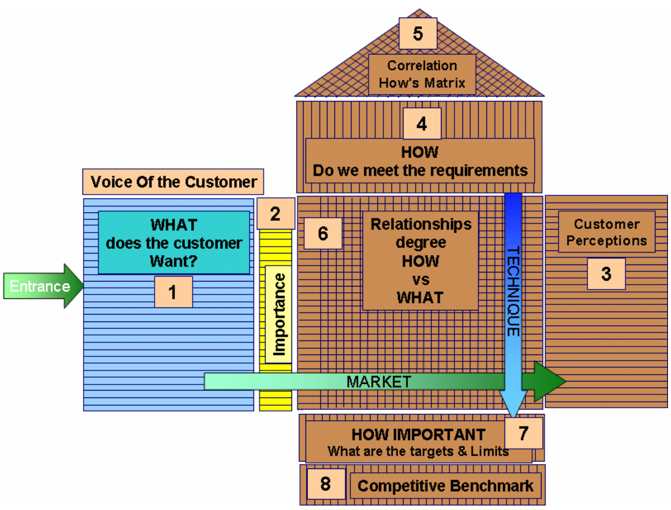


Figure 3 – Elements of QFD's House of Quality

3.2 AXIOMATIC DESIGN AND TRIZ

Once the mapping between the functional and physical domains is completed, engineers will be able to determine if their concept is flawed, i.e. coupled. The design matrix allows the engineer to see where innovation needs to occur. However, engineers must still come up with the design concept(s) that eliminates the coupling. Often, completing the design matrix and simply understanding the coupling sparks many ideas and innovation can proceed. However, occasionally, conceptualizing a solution is not readily possible, either due to lack of knowledge or simply due to constraints imposed by the physics and/or geometry of the particular design situation. In many of these cases, the problem cannot be solved because an engineer is stuck in a particular design paradigm. The engineer needs a stimulus to break mental inertia. A useful tool in this regard is TRIZ (theory of inventive problem solving [8]).

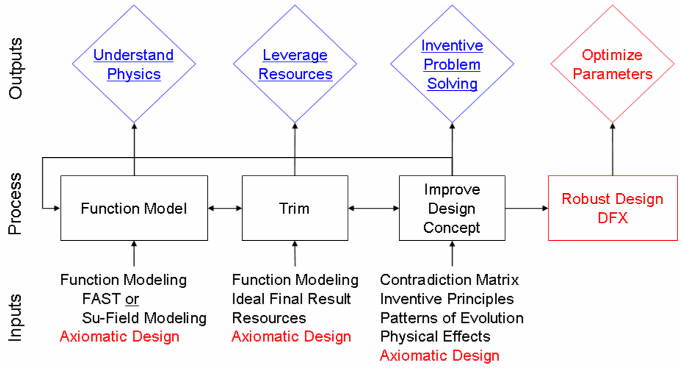


Figure 4 – Basic Elements of TRIZ

TRIZ is a large subject area, but the simplified view shown in Figure 4 shows that the three main elements are: 1) functional modeling, 2) trimming, and 3) improving the design concept. Each of these three elements is synergistic with Axiomatic Design.

Function modeling, for example, involves subject-action-object analysis, which can complement the mapping between the functional and physical domain – it helps enhance the engineer's understanding of the basic function and underlying physics. It also helps distinguish between useful and harmful effects (see example in Figure 5).

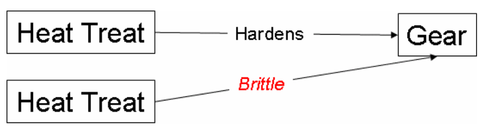


Figure 5 – Heat Treat Example of Function Modeling (Useful Function – Harden, Harmful Function – Brittle)

Trimming helps satisfy the Axiom 2 (minimize information content). The goal of trimming is to simplify the design by getting useful functions from previously untapped and available resources. But the engineer must iterate between trimming and checking for satisfaction of the Axiom 1 (maintain the independence of functional requirements).

Points of coupling in a design matrix can often be translated into a contradiction which can be analyzed using the TRIZ Contradiction Matrix and Inventive Principles. This last point is perhaps the most useful for innovation – Inventive Principles were derived by successful inventions that addressed a conceptually similar contradiction problem.

The author has found that many of the TRIZ Inventive Principles tend to supplement the principles in Suh's Complexity Theory [17]. One example that is always exciting for participants in our Axiomatic Design workshop is the use of functional periodicity to overcome combinatorial complexity. An example of combinatorial complexity is the build-up of wear particles between two sliding surfaces. The concept of functional periodicity would suggest the use of an undulating surface to trap wear particles. A very similar TRIZ Inventive Principle is the use of "Local Quality", or making a surface non-uniform in order to overcome the contradiction of the need for "Reliability" and the contradicting need of "Dynamic" parts moving relative to each other. When engineers begin to grasp the synergy between the TRIZ concepts and Complexity Theory, the real power of DFSS can come to life.

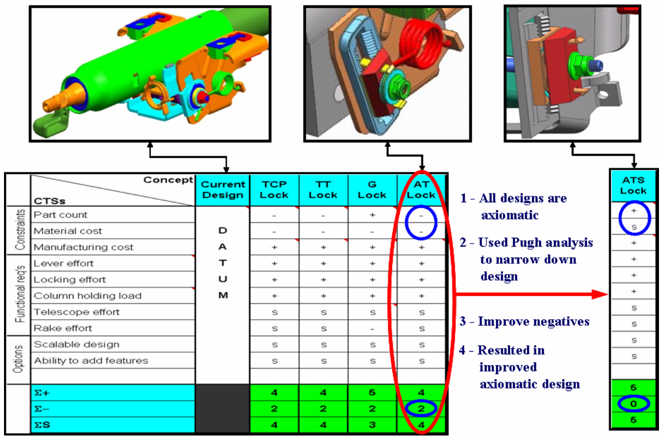
Finding a conceptual solution to fix a coupled design will not be "solved" using Axiomatic Design or TRIZ, but the two methods can be used synergistically to facilitate the engineer in finding a solution by pointing specifically to where innovation needs to occur and stimulating ideas to fix coupling.

3.3 AXIOMATIC DESIGN AND PUGH ANALYSIS

There are many possible combinations of design parameters (DPs) that can satisfy a set of functional requirements (FRs). Axiomatic Design teaches us to choose the design with the least information (Axiom 2). This is done formally through understanding the probability of a designed system's capability can satisfy the design specification. But, in preliminary stages, this is not often known.

The technique that can be used to ensure satisfaction of Axiom 2 in the early concept generation phase is Pugh Analysis [9]. The Pugh Analysis approach is to perform design synthesis via a controlled convergence (selection of best concepts) and divergence (synthesis of new concepts by combining positive attributes of multiple concepts).

An example is shown in Figure 6. The Pugh Matrix shows various concepts for a steering column position adjustment mechanism. Each concept is compared to a datum (typically the current design at the start of an analysis) for each of the criteria (typically a combination of FRs and design constraints). Some concepts are better than the datum for a given criteria and are marked with a "+". Others are worse ("-") and still others are the same ("S") as the datum.



	CTSs / Concept	Current Design	TCP Lock	TT Lock	G Lock	AT Lock	ATS Lock
Constraints	Part count		-	-	+	-	+
	Material cost	D	-	-	-	-	S
	Manufacturing cost	A	+	+	+	+	+
Functional req's	Lever effort	T	+	+	+	+	+
	Locking effort	U	+	+	+	+	+
	Column holding load	M	+	+	+	+	+
	Telescope effort		S	S	S	S	S
	Rake effort		S	S	-	S	S
Options	Scalable design		S	S	S	S	S
	Ability to add features		S	S	S	S	S
	Σ+		4	4	5	4	5
	Σ–		2	2	2	2	0
	ΣS		4	4	3	4	5

Figure 6 – Example Pugh Analysis. (Note that each synthesized concept is checked for satisfying Axiom 1.)

The key when combining Pugh Analysis with Axiomatic Design is as follows:

- Each initial concept should not be coupled (satisfies Axiom 1).
- As synthesis proceeds, check newly generated concepts are also not coupled.
- Newly synthesized concepts must also satisfy the design constraints.

If the above guidelines are followed, Pugh Analysis is a good way to apply Axiom 2 in the initial stages of design development.

3.4 AXIOMATIC DESIGN AND ROBUST ENGINEERING

One of the benefits of applying Axiomatic Design in the concept generation phase is that detailed functional relationships do not have to be known. What suffices in these early stages is knowledge that a functional relationship exists between a given DP and FR pair.

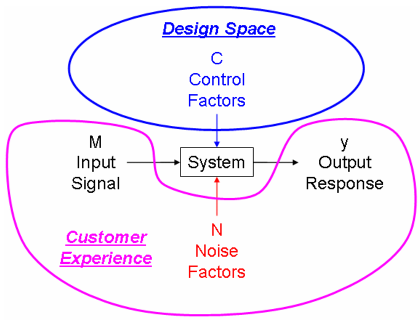


Figure 7 – Parameter Diagram

Once detailed design begins, the engineer is essentially determining the coefficients in the design matrix. Often, these are ideal functional relationships that apply in the absence of uncontrolled variation in manufacturing, operating environment, and customer usage. Thus, the detailed design phase will require engineers to understand the sources of variation and conduct numerical and physical experiments to ensure the product performance is insensitive to the variation (see a conceptual parameter-diagram in Figure 7 [4]).

The design matrix documents the relationships between FRs and DPs – the design equation. This knowledge can be used to quickly formulate the P-diagram as an initial step in robust optimization (see Figure 6 and ref. [4]). Since constructing the P-diagram, and thus documenting the engineer's knowledge of the underlying physics, is arguably the most critical step in robust optimization, preceding it with the construction of the design matrix will ensure this step is properly executed.

It will be much easier to establish design robustness if the concept is not coupled. In fact, for an uncoupled design, it may be as simple as conducting a robustness assessment, whereby the design is tested in the presence of noise factors and its signal-to-noise ratio compared with current or competitive designs.

4 CONCLUSIONS

This paper has demonstrated how Axiomatic Design can be integrated into a DFSS program. It has been argued that organizational deployment is just as important as technical execution. Some suggestions have been provided to ensure a lasting integration of Axiomatic Design into a company's product development process, and specifically integration within DFSS. It has also been shown that Axiomatic Design synergizes very well with other DFSS tools, such as QFD, TRIZ, Pugh Analysis, and robust optimization.

The author would like to extend his sincere appreciation to Prof. Nam P. Suh for all his teaching, mentoring, and guidance. The successful deployment of Axiomatic Design in the author's company is in large part due to Prof. Suh's unwavering support.

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