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THOUGHTS ON THE USE OF AXIOMATIC DESIGNS WITHIN THE PRODUCT DEVELOPMENT PROCESS

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ABSTRACT

Increased competitive pressures forced producers of goods to accelerate their product development time, minimize costs, improve organizational efficiencies, reduce product complexity, systematically design goods that are key for customer satisfaction and delights, innovative reuse of current technologies, and improve product quality. In this manuscript, we discuss the potential utilization of Axiomatic Design methods to enhance the development of Failure Modes and Effects Analysis, Parameter diagrams for robustness studies, and improve quality through robustness, testing and enhancing functional requirements specifications. A Line Pressure Regulating System example using this integrated framework will be provided.

Keywords: design, axioms, robustness, P-diagrams, FMEA

1. INTRODUCTION

In the era of product development complexity, needs for higher customer satisfaction, reduction of development time and cost, the utilization of system and customer focused engineering tools are very attractive to practitioners. Professor Nam Suh from Massachusetts Institute of Technology pioneered Axiomatic Design (AD) in the last decade. The method provides a general systematic procedure for system and sub-system designs and shed the lights on improving other engineering related practices as well.

The AD approach has been implemented in various levels of product development process to enhance design practices with a unique way of good design evaluation criteria. For instance, many papers have been published in the areas of software engineering, organizational structuring and product and manufacturing designs [Suh 1999]. In concept design, a design complexity measure has been developed by [El-Haik 1999]. Trewn and Yang studied the correlation between design complexity and vulnerability [Trewn and Yang 1999]. Axiomatic design approach was introduced as framework of enhanced concurrent engineering [Jung 1993, Albano 1994]. In this paper, we discuss the potential utilization of Axiomatic Design to improve existing products quality practices in terms of Failure Mode and Effects Analysis, robustness, system specifications, and testing.

2. AXIOMATIC DESIGN

According to AD, a system is supposed to satisfy perceived needs through mapping between the functional requirements domain (derived from the customer needs) and design parameters (derived from physical domain). A design process is defined as systematic procedure using the independence and minimum information contents axioms [Suh 1990]. The two axioms, and their consequences, of design are the main contribution of axiomatic design to product development. These two axioms call for the independence of functional requirements (by definition), and the minimization of information content in a design (simplify while improving performance). The intent is to reduce complexity while improving functionality.

The product realization process starts with the customer world as represented by the Customer Attributes (CAs), and then triggers the engineering world activities by translating the CAs to Functional Requirements (FRs). The design process is performed systematically through mapping between the (FRs) in the functional space and the Design Parameters (DPs) in the physical space. The physical Domain is also mapped to the Process Domain with Process Variables (PVs) defined. Importantly, the process parameters within this framework are defined based on the customer attributes.

Satisfying the two AD axioms may be impossible in practice due to cost, complexity, and/or available technology. Partial fulfillment of the axioms may be a feasible design solution. In this case, different degrees of vulnerability exist in the design depending on the violations of the axioms [Trewn and Yang 1999]. The mapping between the functional (FRs) and physical domains (DPs) is executed in a zigzagging hierarchy (Why-How-Why-How…) as shown in Figure 1. This mapping may be explained mathematically. When FRs and DPs are seen as vectors with m and n elements respectively, the relationship between FRs and DPs is expressed with the following equation:

[FR]=[A].[DP], where

$$\begin{vmatrix} FR_1 \\ FR_2 \\ \vdots \\ FR_m \end{vmatrix} = \begin{vmatrix} A_{11} & A_{12} & \dots & A_{1n} \\ A_{21} & A_{22} & \dots & A_{2n} \\ \vdots & \vdots & \vdots & \vdots \\ A_{m1} & A_{m2} & \dots & A_{mn} \end{vmatrix} \begin{vmatrix} DP_1 \\ DP_2 \\ \vdots \\ DP_n \end{vmatrix}$$

The matrix that defines the interrelationship between the FRs and DPs, A, is called the design matrix with *m* rows and *n* columns.

The independence axiom is satisfied completely when only the diagonal elements of matrix A are not zero and all off-diagonal elements are zero. This is a depiction of what is called uncoupled design. Otherwise the design is either coupled or decoupled. If one side of the diagonal matrix can be made zero, this case is called decoupled design. Information content increases as design becomes decoupled and coupled. A coupled design has more information content than a decoupled design. Among advantages of this mapping, we can realize that:

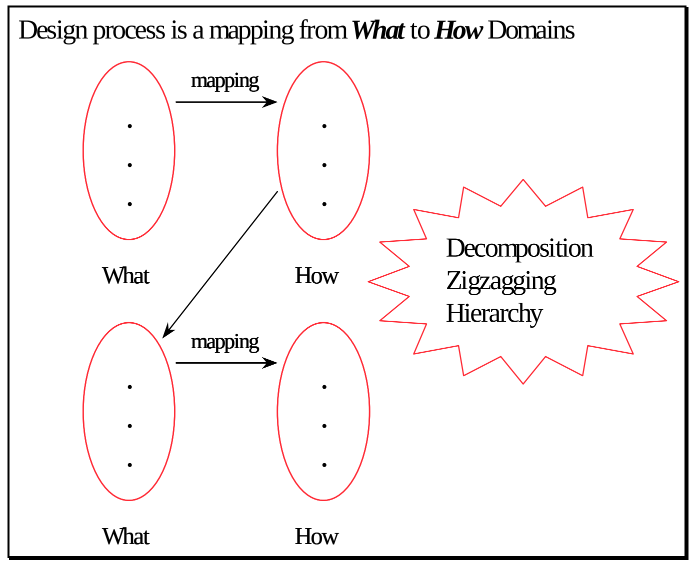

Figure 1. FRs and DPs mapping process

1. Customer driven design, and process parameters can be defined in a meaningful manner that leads to the development of the critical quality characteristics for the design or the process.
2. The emphasis is on innovation in design and manufacturing, or full understanding of the current design or process.
3. It is possible to have a simplified guidance to know-how engineering practices.
4. We provide a creative way to interact with other quality practices.
5. We made readily available information about critical parameters for robust designs optimization, and we have a solid ground to prioritize the optimization process.

Here we will focus on the hierarchical design structure created by AD and its implications on some of the current quality practices. That is, AD decomposition can be used to define an integrated framework to improve quality practices. Namely, the exercises of Failure Mode and Effect Analysis (FMEA), Parameter Diagrams (P-Diagram), Testing strategies, and Functional Requirements Specifications (FRS) can be made easy.

3. INTEGRATED FRAMEWORK

According to AD, independent functional requirements for a system are first defined at systems' level. Then, design parameters that are required to deliver those functions are defined. This process continues with zigzagging operations to a level where design decisions can be made.

At each level, design matrices describe the relationship between design parameters and functional requirements. Uncoupled design matrices are ideally desired since the functions can be optimized by adjusting the appropriate design parameters without harming other function. Coupled design matrices indicate inherent weaknesses in the system, and there is a level of vulnerability in performing the functional requirements. Optimization can still be done on a decoupled design using a sequential order using the relationship matrix A. The output of the axiomatic design from functional decomposition provides inputs to FMEA, FRS, P-Diagrams, and testing strategy (Figure 2). In the following sections, we discuss how axiomatic design approach can enhance the FMEA, FRS, P-diagram and testing strategy within the product development process.

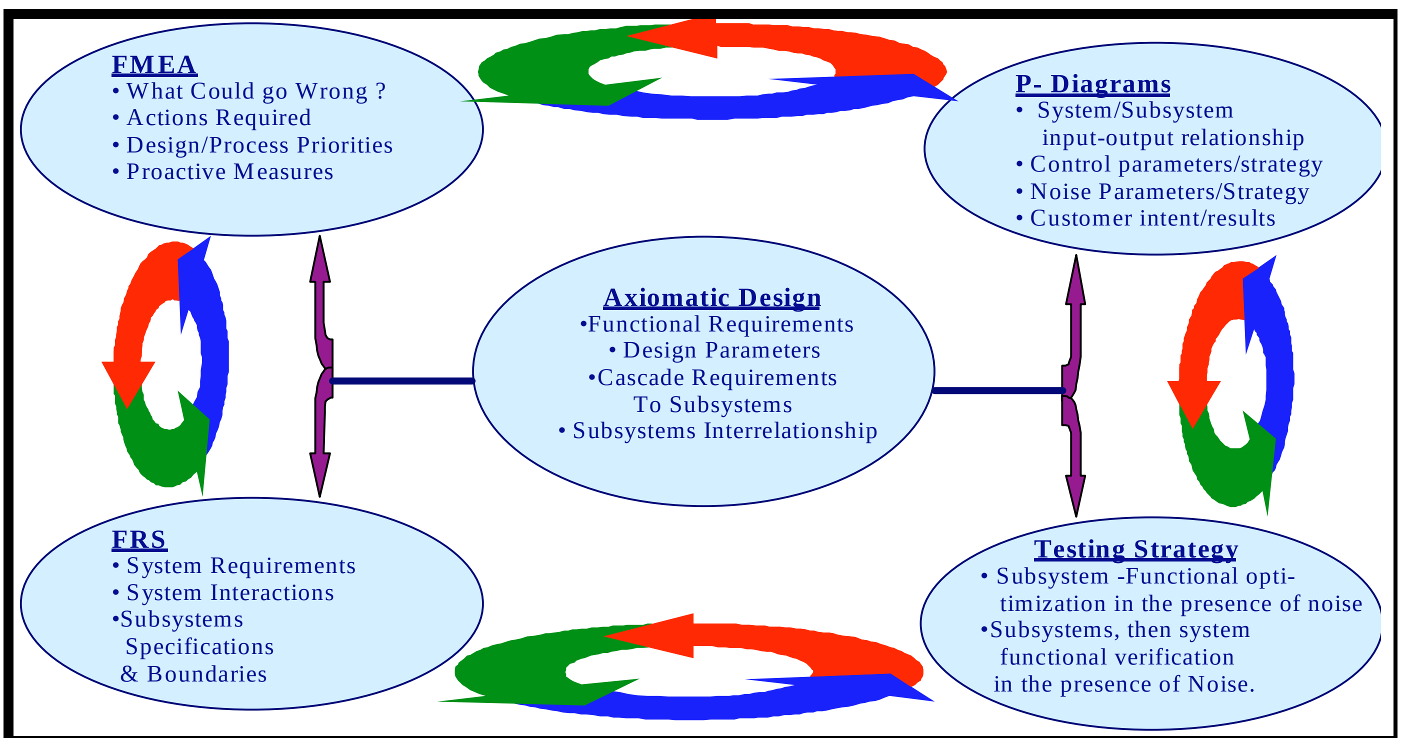

Figure 2: Integration of Axiomatic Design with Other Quality Tools

3.1 FAILURE MODE AND EFFECT ANALYSIS: FMEA

FMEA is a series of techniques for identifying potential failure modes, their effects on a product performance, and their significance. It is best utilized at the product/process design phase in order to minimize the risks associated with the concept and beyond, as well as for the process development

[Palady, 1995]. FMEAs may be listed as Concept (system) FMEA, Design FMEA and Process FMEA.

A conventional FMEA does not describe the functional requirements and design parameter systematically in a hierarchical way as it can be done through Axiomatic Design. Robustness opportunities may be missed due to this incapability. Axiomatic design provides relationships between functional requirements and design parameters in a hierarchy that can be used to improve the design/process robustness and minimize the risks associated with a given design.

In FMEAs, functions are first to be driven from customer requirement, company and government requirements and regulations for Concept and Design FMEA's. However, functions are driven based on the design requirements in case of Process FMEA. This being the case, one can use the functional domain from AD to define the functional requirements for the FMEA, since they are based on the customer domain. For the process FMEA, the mapping between the physical domain and the process domain can be used to define the functional requirements of the Process FMEA (PFMEA). In the AD approach, functional requirements are already defined in a structured way from high level to low level with the required design parameters. Thus, using axiomatic design, FMEA development becomes more systematic, since the functions are driven from design matrices that are cascaded from higher to a lower level of DPs.

In an FMEA, an engineer would have to determine potential failure modes for each of the listed functions. A potential failure mode describes how the design could fail to perform its required functions. The effects of these failure modes are described in terms of what a customer would feel. Potential causes of failures are the possible root causes that contribute to the failure. Axiomatic Design can be effectively used to determine the potential causes of failures for a particular failure mode for a given functional requirements. For, the DPs provide the physical means that affect the functional performance. Since a failure for a particular function will be explained in terms of the DPs, the AD decomposition will lead to an in-depth analysis for the potential causes of failures. More importantly, the possibilities of failures due to system interactions (coupling) will be clearer through the AD matrices. Consequently, AD approach can be used to have better FMEA.

The main difference between two approaches is on the understanding of functional requirements and on how these functions are delivered. Conventional FMEA is established based on high-level functions on the system/subsystem without further functional decomposition. Potential failure modes and their effects are investigated based on these high level functions. Using axiomatic design, functions will be clearly defined with the corresponding design parameters at various level of the system design. Further explanation of FMEA will be made available in the example section.

3.2 FUNCTIONAL REQUIREMENT SPECIFICATIONS- FRS

Functional Requirement Specifications (FRS) is a document that provides the specifications for the functional requirements of a system / subsystem. A system has to achieve a target level of performance, which can be specified in the FRS. The system target requirements need to be cascaded to the functional requirements at subsystem levels.

Functional requirements and required design parameters are determined with more systematic way in the AD approach. A complete decomposition, which is established through the independence axiom, provides a complete list of functional requirements. An FRS document would take the functional requirements information and define a complete performance targets for each of the requirements. Integrating functional decomposition of axiomatic design and FRS enhances the FRS document and gives the engineers more precise information for the design. It fits perfectly with the V concept of the system engineering [Ford Motor Company, 1997] approach where requirements are cascaded from higher system to a lower subsystem level.

3.3 PARAMETER DESIGN- PARAMETER DIAGRAM (P-DIAGRAM)

A robust system is expected to perform its intended function under all operating conditions (different causes of variations) throughout its intended life without necessarily eliminating noise factors (noise factors are defined as disturbance factors that cause system functional variability).

Robustness methods attempt to optimize the product function at the lowest cost. That is, the system's performance will be made on target and with low variability amid the presence of disturbance factors without necessarily eliminating the disturbance factors. A P-diagram format is presented in Figure 3. The P-Diagram [Phadke, 1989] integrates several ideas of the robustness process in a graphical mean. That is, a P-Diagram is a millstone in the development of a robustness study. Parameters of the engineered system include input and output of the system, controllable factors and uncontrollable (noise) factors.

The relationship between the input and the output of the system is called the ideal function. The ideal function is a mathematical description of the energy transformation within the system and it signifies what to measure to design quality into the product. The purpose of studying ideal function in the presence of noise is that it enables to select the control factor levels, which yields a response closest to the ideal in spite of the noise factors.

Axiomatic design can be used to formulate the P-Diagram of a system. Each defined function in an AD exercise need to be measured from energy transfer perspective. If done so, we can define the ideal function required for the P-Diagram. All the DPs in the AD decomposition define the control parameters.

One of the noise factors- the internal environment or neighboring system (coupling) noise-can also be defined using the Zigzagging process. In fact, a thorough decomposition exercise will yield a P-Diagram for each subsystem understudy, since inputs, outputs, what to measure, control parameters and at least one noise factor will be readily available through the functional decomposition. However, caution must be paid to develop a noise strategy with the remaining four sources of noise; external environment, piece-to-piece variation, effect of time, and customer usage.

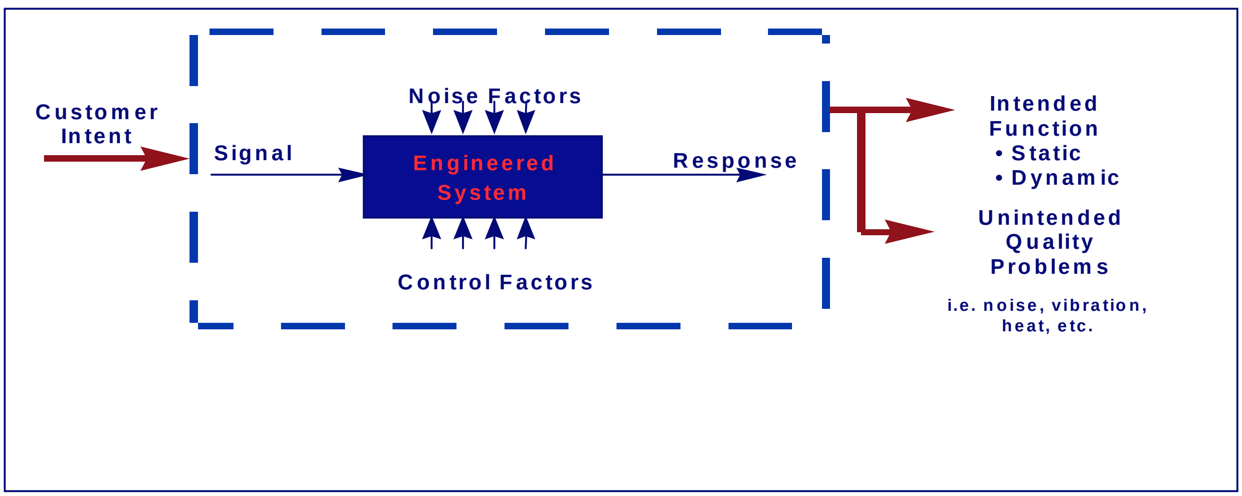

Figure 3: P-Diagram

3.4 TESTING STRATEGY

Testing or verification is used in design optimization and verification during or at the end of a product development process. The purpose of the design verification process is to ensure failure free operation in the hands of the customer. In all cases, it is crucial to include all the noise factors that may be affecting the system in real usage.

Both control factors and noise factors affecting the functions of the system are included in testing for optimization. P-diagram that is driven from a complete functional decomposition provides the information about control factors and the internal system noise factors. In addition, the functions that need to be verified are defined in the AD exercise, and they reflect the customer requirements. Verification testing can be done at system or subsystem level. The AD decomposition helps building up a test plan from subsystem to system level verifications.

When testing for verification, control factors are fixed at optimum levels. The aim is to check whether the system performs all its functions as required. However, noise factors are incorporated to simulate the real world. This may include manufacturing variation, aging, customer usage, environmental conditions and system interfaces.

4. AXIOMATIC DESIGN AS AN INPUT TO QUALITY TOOLS: LINE PRESSURE REGULATING SYSTEM EXAMPLE

A generic line pressure (LP) regulating system was considered to illustrate the proposed model. LP regulating system is one of the automatic transmission subsystems. At the higher-level decomposition, LP regulating system is a DP to satisfy a control line pressure requirement for Pressure Regulating System. The LP regulating system has three FRs and eight DPs. Table 1 illustrates the design matrix for LP regulating system. Since there are more DPs than FRs, the LP regulating system is considered to be a redundant system. However, FRs can be satisfied independently by a subset of DPs so the design can be considered as uncoupled.

As soon as functions are defined, the specifications of those functions must be determined. The determination of specifications is based on what is required from the system to deliver based on customer requirements. The determination of FRs specifications is a prerequisite to determine the optimum settings of DPs, and will serve also in testing and verification purposes. In our example, FRS of LP regulating system must be determined at the current decomposition level in Table 1.

Table 2 shows some partial information from FMEA of LP regulating system. FR3, actual LP to follow desired LP is considered for illustration purpose. A possible potential failure mode would be less actual LP than desired LP. Potential effects of this failure mode could be degraded shift quality as well as some other effects. Potential causes of failures are determined by investigating specific DPs' effects on FR3. The risk priority number (RPN) is obtained by multiplying severity (S), occurrence (O) and detection (D).

Figure 4 illustrates the P-diagram and ideal function for LP regulating system. Desired LP is the signal to the system and actual LP is the output of the system. The ideal function indicates that the actual LP should match with the desired LP. Possible control parameters are driven from functional decomposition of LP regulating system as K spring, valve diameter, feedback damping orifice, TV damping orifice and valve/port geometry. Similarly, noise factors are determined with the help of AD decomposition.

If the P-diagram of the system is completely developed, optimization can be performed based on the P-diagram. Once optimal DP levels are determined, verification of the functional requirements is carried out in the presence of the noise factors. Note that the verification should include a measurement on actual LP versus desired LP.

Table 1: Functional Decomposition of LP Regulating System

LP Regulating Systems	DP1 Valve F.B. area	DP2 Area for TV system	DP3 F spring	DP4 K spring	DP5 Valve diameter	DP6 Feedback Damping orifice	DP7 TV control damping orifice	DP8 Valve / port geometry
FR1 Sense actual LP on valve	1	0	0	0	0	0	0	0
FR2 Sense desire LP signal	0	1	1	0	0	0	0	0
FR3 Actual LP to follow desire LP	0	0	0	1	1	1	1	1

Table 2: FMEA for LP Regulating System

Item/ Function	Potential Failure Mode	Potential Effect(s) of failure	S	Potential Causes of Failure	O	D	RPN	--	--
FR3 Actual LP to follow desired LP	-Less pressure than needed …	Premature transmission failure -intermittent shifts -degraded shift quality …	7	Regulating system -does not provide actual LP to follow desired LP (Body & Valve Surface Finish) Valve body -does not provide housing for spool valves (Body & Valve Surface Finish) -does not provide housing for pupped valves (Body & Valve Surface Finish) -does not provide housing for ball check valves (Body & Valve Surface Finish) -does not provide context valve parts (Body & Valve Surface Finish) -does not provide passage for inter level connection (Valve Land Edge Shape) …	10	3	210		

S: Severity, O: Occurrence, D: Detection, RPN: Risk Priority Number

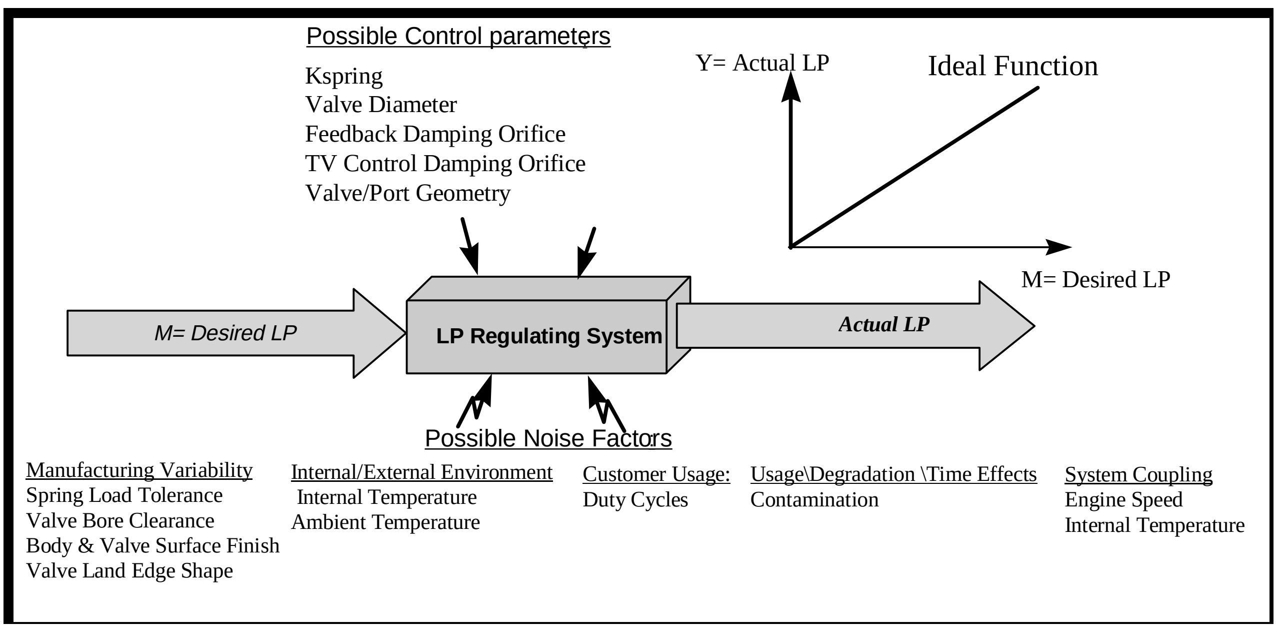

Figure 4: P-diagram for LP Regulating System

5. CONCLUSION

In this paper, we discussed the potential utilization of Axiomatic Design methods to enhance the product development process. Integration of AD with other quality tools such as FMEA, P-diagram, FRS and testing and verifications are proposed to achieve better quality products with minimum development time and minimum cost. The proposed integration was illustrated on LP regulating system of an automatic transmission system. An in depth exploration of each application linkage to AD is being explored by the authors for future publications.

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