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SIX SIGMA ROADMAPS AND THE DEGREES OF INNOVATION – AN EXPLANATION BASED ON THE AXIOMATIC DESIGN THEORY

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ABSTRACT

Six Sigma is a customer-focused, data-driven, and project-based approach that makes use of structured methodologies to drive business success through improving the functional performance of existing products, services and processes, or by creating new design solutions. All Six Sigma methodologies rely on a certain roadmap with well-defined stages, where for each one clear goals, deliverables, and outcomes are set. There are many Six Sigma roadmaps available. Knowing this, an important question arises: which Six Sigma roadmap to use in a certain continual improvement or design project? The answer depends on the project scope, namely in the degree of innovation inherent to such project. In this paper, we do show how Axiomatic Design Theory can provide a useful reasoning to help project team leaders to determine which Six Sigma roadmap should be employed in each situation, attending to the innovation degree inherent to the project.

Keywords: Design for Six Sigma (DFSS), innovation degree, Six Sigma.

1 INTRODUCTION

The majority of the implementations of Six Sigma employ the five-phase DMAIC (Define, Measure, Analyze, Improve, Control) roadmap for the execution and completion of continual improvement projects [Montgomery and Woodall, 2008]. However, DMAIC is not suitable for design or redesign projects; for such cases, the use of a Design for Six Sigma (DFSS) methodology is more appropriate.

Throughout the years, a wide variety of DFSS roadmaps have been proposed. The different roadmaps were identified, described and compiled in research work carried out by Shahin [2008] and Watson and DeYong [2010]. More recently, Marques [2013] studied the published literature on the subject, compared the different existing roadmaps, and, among other conclusions, demonstrated that the DMADV (Define, Measure, Analyze, Design, Validate) and the IDOV (Identify, Design, Optimize, Validate) roadmaps are the most often mentioned in scientific papers, as well as the most often used in practice.

On the other hand, the selection of the most suitable roadmap strongly depends on the degree [Shahabuddin, 2008] and type [Hambleton, 2008] of innovation involved in a Six Sigma project. Since the choice of the most appropriate Six Sigma roadmap must attend to the degree of conceptual changes to be introduced in the technical system, Marques *et al*. [2014] developed a Six Sigma Life Cycle model that distinguishes four degrees of innovation and relates these with the main Six Sigma roadmaps. In this paper, the reasoning behind this model is explained by making use of the Axiomatic Design concepts. The role of Axiomatic Design within these roadmaps is also discussed.

The paper is organized in four sections. Section 2 provides a literature review on how Axiomatic Design Theory has been used a Six Sigma context or applied during the development of a Six Sigma project. In section 3, the four different degrees of innovation that may be present in a Six Sigma project and their corresponding roadmap are explained from the viewpoint of Axiomatic Design. Finally, the main conclusions that can be drawn from this research are described in section 4.

2 LITERATURE REVIEW

The advantages of applying Axiomatic Design during a Design for Six Sigma (DFSS) project have been pointed out by many authors. Arcidiacono [2002] discussed the benefits in using Axiomatic Design principles during the stages that compound the DMADV roadmap; the authors called their approach as Axiomatic Design for Six Sigma (ADFSS). In their well-known book, Yang and El-Haik [2003] were probably the first to describe in great detail the benefits of making use of Axiomatic Design theory a DFSS project and how it can contribute to enhance the conceptual robustness of a design solution being developed; the authors adopt a version of the four-phase IDOV roadmap for the DFSS methodology. Jugulum and Samuel [2008] also suggest an extensive use of the Axiomatic Design Theory during a DFSS project, but they prefer to follow the DMADV roadmap. Dickinson [2006], by applying Axiomatic Design in the context of other roadmap (IDDOV – Identify, Define, Develop, Optimize, Verify) showed that the integration of Axiomatic Design in a DFSS context can actually be used accomplished in any roadmap.

Regardless the chosen roadmap, the usefulness of applying Axiomatic Design in a DFSS projects is justified by the following:

- To ensure that the flow-down of the critical to quality characteristics (CTQCs) of a given technical system is properly and coherently done [He *et al*., 2009].
- To create an architecture that completely captures the construction of a technical system functions [Jugulum and Samuel, 2008].
- To minimize the chance of conceiving and developing a product, service or process with design vulnerabilities, which might undermine its operational performance [Khalaf and Yang, 2006].
- To facilitate the functional optimization stage of the design process [Yang and El-Haik, 2003].

The employment of Axiomatic Design in a DFSS project is mainly done at the following three phases of the design process [El-Haik, 2005]:

1) Concept development, where alternative conceptual solutions for the high-level design are generated and evaluated, thus arising a winning design concept.
2) Preliminary design, where design decomposition tasks are carried out, thus detailing the functional and physical structures until the technical system can be implemented.
3) Optimization, where Axiomatic Design, by capturing the cause-and-effect relationships among FRs and DPs, can be helpful to develop transfer functions so operational optimization strategies, such as parameter and tolerance design, can then be put in place. In addition, the independence and information axioms can be used to maximize the conceptual robustness of the design before the operational optimization.

The "concept development" and "preliminary design" phases occur during the Design stage of both IDOV and DMADV, which are the most often adopted DFSS roadmaps. The "optimization" phase take place at the Optimize stage of IDOV and the Design stage of DMADV. Hu and Pieprzak [2005] demonstrated that the attainable level of operational robustness is much reliant on the chosen conceptual solution for the technical system, proving Axiomatic Design a rational structure basis for evaluation of proposed design alternatives and the subsequent selection of the best alternative. In a DFSS project, the high-level design often needs to be further detailed by decomposing the initial set of functional requirements (FRs) and design parameters (DPs); this can be effectively accomplished by employing the principles of Axiomatic Design [Mader, 2005].

Many of the DFSS approaches, especially for product design contexts, suggest the adoption of the Taguchi Robust Design strategy, which comprises three steps: 1) conceptual design; 2) parameter design; 3) tolerance design. As underlined by Yang and Pieprzak [2005], conceptual optimization must precede operational optimization, so Axiomatic Design should be employed before parameter design, since conceptual vulnerabilities usually cause operational robustness problems by introducing complexity/information into the design solution (axiom 2) that increase noise factors and increase variation in the functional response of the product or process. The relationships among Axiomatic Design and Taguchi Robust Design are explored by Kar [2000] and El-Haik [2005].

Axiomatic Design is rarely employed during the DMAIC roadmap since the design concept is not altered, but it is very useful for creating new design solutions, as well as for diagnosing and improving existing designs [Truscott, 2003]. Generally, DMADV is more suitable for redesign projects, while IDOV is more appropriate when a new design needs to be created [Shahabudin, 2008]. Jugulum and Samuel [2008] explicitly refer that the conduction of a Six Sigma project should attend to the type and degree of innovation inherent to such project.

The design hierarchy, which results from the top-down process of decomposition where design decisions are defined in an increasing level of detail, can be related to the degree of innovation associated to a Six Sigma project. When just small or incremental conceptual modifications are introduced in a technical system, only design changes the lower levels of the decomposition tree are likely to be affected. On the contrary, as Crawley *et al*. [2004] state, when a major/disruptive break occurs, it is necessary to undo choices at increasingly higher levels of the decomposition tree, so as technologies mature, the active design choices are pushed lower and lower, ultimately to the component level.

El-Haik [2005] distinguishes incremental design from creative design, as the former can be further divided into soft changes and hard changes. The author explains that, in the context of Axiomatic Design, a creative design case implies the definition of a completely new set of FRs and DPs to be further decomposed; in an incremental design case with the introduction of hard changes, the initial set of FRs are not changed but alterations in the DPs array are required; for incremental design soft changes, neither the FRs nor the DPs arrays are changed, but usually involve adjustments in the specification(s) in one or more FRs and/or in the values of some of the DPs within the permitted tolerances.

3 DFSS ROADMAPS AND THE DEGREES OF INNOVATION – AN EXPLANATION BASED ON AXIOMATIC DESIGN

Marques *et al*. [2014] recognized that the methodological approach (i.e. the roadmap) to be followed by a Six Sigma project, strongly depends on the conceptual maturity of the technical system targeted by the project, that is to say, on the degree/level of innovation inherent to the Six Sigma project. They developed a Six Sigma Life Cycle framework, comprising a Technical System Life Cycle model that suggests four levels or degrees of innovation and their corresponding Six Sigma project roadmap. This reasoning is exhibited in figure 1.

In this section, the relationship among the different Six Sigma methodological approaches and their corresponding degree of innovation will be explained from an Axiomatic Design theory perspective.

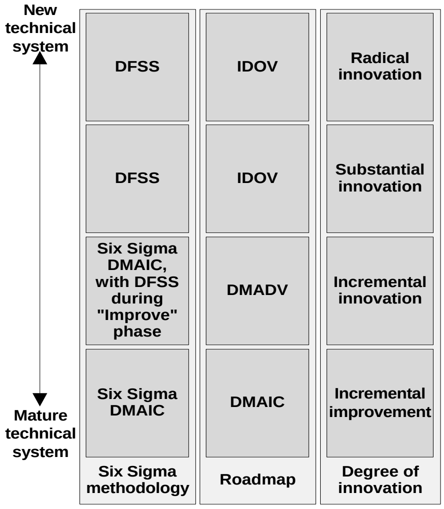

Figure 1. Relationship among the Six Sigma roadmaps and the degrees of innovation (adapted from Marques *et al.*, 2014).

In Six Sigma, a critical to quality characteristic (CTQC) represents the translation of a relevant customer requirement into a metric that is accompanied by an operational definition, which represents a clear, unambiguous, and observable standard of acceptance. When a CTQC is formulated in a functional mode, it corresponds to an FR. For this reason, CTQCs considered in a Six Sigma project can be regarded as being part of the functional domain [Yang and El-Haik].

In the following four subsections, the influence that each degree of innovation mentioned in figure 1 has in a Six Sigma project is explained using the Axiomatic Design theory.

3.1 INCREMENTAL IMPROVEMENT – DMAIC ROADMAP

Continual improvement projects are performed according to the DMAIC roadmap. This kind of projects usually consists in the optimization of one or few CTQCs, which is achieved by adjusting some of the key process input variables (KPIVs) in the process domain. Since redesign is not an option in DMAIC Six Sigma projects, the physical domain containing the DPs is generally ignored. This reasoning is illustrated in figure 2. Note that the decomposition tree is not shown because most of the time it is not necessary to develop this kind of detail in the process domain [Brown, 2006].

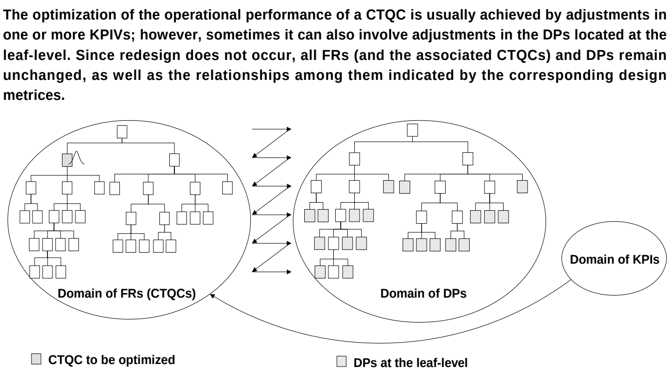

Figure 2. Scope of a Six Sigma DMAIC type of project explained by making use of the Axiomatic Design theory.

Sometimes the physical domain is considered; when this is the case, only adjustments in the values of the DPs, located at the leaf-level, within the permitted tolerances

3.2 INCREMENTAL INNOVATION – DMADV ROADMAP

Figure 3 depicts the reasoning behind redesign projects using the DMADV roadmap often utilized in DFSS. Similarly to DMAIC projects, it is intended to optimize the operational performance of a product, service or process regarding one or few of its CTQCs. However, in the DMADV case, the domain containing the DPs is always considered.

Because the degree of innovation is only incremental, no substantial or dramatic changes are introduced in the design concept. In the functional domain, the specifications associated to the FRs can be adjusted to reflect the intended enhancement in the operational performance of the system. The KPIVs in the process domain can also be adjusted, like in the incremental improvement case, but in the DMADV roadmap case, where redesign activities takes place, there are DPs located at the leaf-level within the decomposition tree that can be changed.

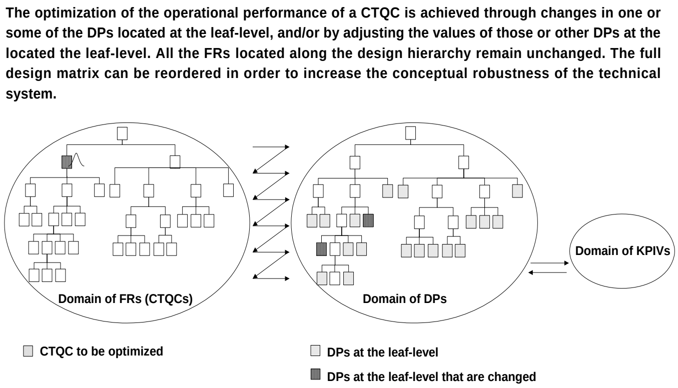

Figure 3. Scope of a Six Sigma DMADV type of project explained by making use of the Axiomatic Design theory.

3.3 SUBSTANTIAL INNOVATION – IDOV ROADMAP

The IDOV roadmap can be adopted in a DFSS project for either substantial or radical innovation. Substantial innovation involves redesign efforts and is characterized by the fact that the basic functions performed by the technical system remain unchanged. In this class of DFSS projects, at least one design concept that can effectively satisfy the set of top-level FRs is available to serve as reference.

This type of DFSS projects is often launched when substantial enhancements in the operational performance of the technical system, regarding some of its CTQCs, are required. This usually implies greater redesign efforts than simply introducing soft changes as described for the incremental innovation case. Substantial innovation is achieved by altering, adding and/or removing DPs somewhere in the design hierarchy, not limited to the leaf-level. Such changes in a given DP has consequences on the levels immediately below [Lindholm *et al.*, 1999], belonging to the same branch of the decomposition tree; actually, it implies the need of redefining the sets of sub-FRs, of their corresponding sub-DPs, and of the design matrices relating them.

The reasoning behind this type of DFSS projects, from an Axiomatic Design perspective, is illustrated in figure 4.

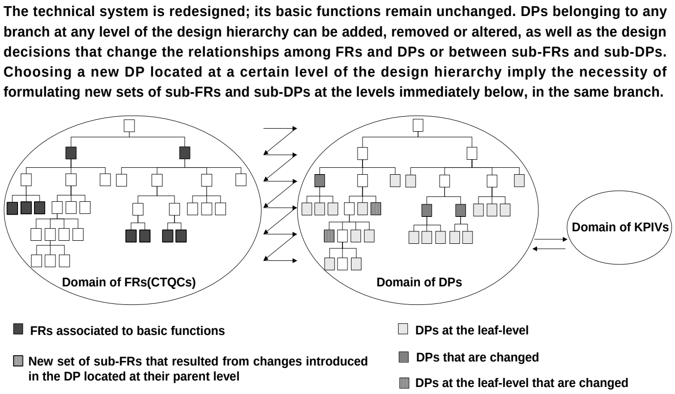

Figure 4. Scope of a DFSS project using the IDOV roadmap when substantial innovation is involved, explained by making use of the Axiomatic Design theory.

3.4 RADICAL INNOVATION – IDOV ROADMAP

This situation means that a complete new design is to be conceived and developed during the IDOV roadmap. In this type of DFSS projects, no design concept effectively meeting the FRs associated to the basic functions of the technical system is known. It means that a new set of top-level DPs needs to be defined, as well as the relationships among FRs and DPs at the highest level of the design hierarchy, provided by the design matrix. The whole decomposition, in a radical innovation situation, needs to be performed until the design can be implemented. This reasoning is exhibited in figure 5.

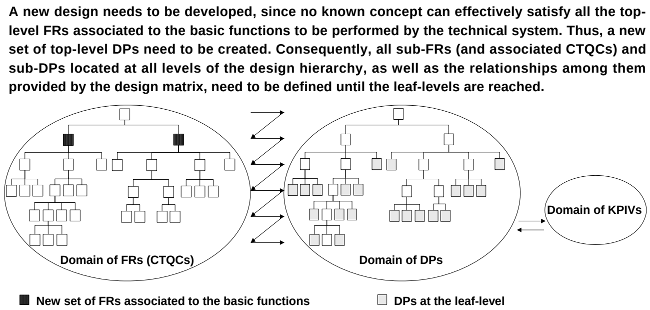

Figure 5. Scope of a DFSS project using the IDOV roadmap when substantial innovation is involved, explained by making use of the Axiomatic Design theory.

4 EXAMPLES

Table 1 depicts examples of real Six Sigma projects that were developed, the roadmap that was used and the degree of innovation inherent to them. These examples illustrate the reasoning behind the theoretical formulation described in section 3.

5 CONCLUSIONS

This paper discussed the role and applicability of Axiomatic Design in the context of different degrees of innovations inherent to a Six Sigma project. It was concluded that in traditional Six Sigma DMAIC projects, adopted for continuous improvement contexts, no DPs are changed, introduced or removed. For DFSS redesign projects carried out through DMADV, it was showed that in incremental innovation contexts changes in the DPs only occur at the leaf-level, while in substantial innovation situations, when the IDOV roadmap is used, changes in the DPs arrays can occur at any level of the design hierarchy, but usually not at the top-level. Finally, for radical innovation, which also adopts the IDOV roadmap, it was demonstrated that in the absent of a design concept that can effectively satisfy all the top-level FRs linked to a basic function, a new set o top-level DPs needs to be developed, which means the whole decomposition process needs to be carried out.

Table 1. Examples of Six Sigma projects, corresponding roadmaps used and the degree of inherent to each of them.

Six Sigma project scope	Roadmap	Degree of innovation
Quality improvement of a die casted product through the reduction of the likelihood of pores to occur. This was done by varying different levels of the controllable key process input variables in order to determine the optimal combination of these variables that minimizes the chances of pores to occur. The design decisions for the product were not altered.	DMAIC	Incremental improvement
A project was initiated with the objective of improving a casement window product model in terms of minimization of the heat transfer across its profiles. The minimization of the heat transfer is a requirement that is associated to a basic function of this product. To achieve that goal, small conceptual changes in the product's configuration and in some of its components needed to be introduced.	DMADV	Incremental innovation
A new transportation service targeting a new and specific market was designed. The highest-level basic functions of this service are identical to other transportation services, so this is not a radical innovation case. Only the design solutions/parameters needed to be tailored to the mentioned market, giving origin to specific sub-FRs formulated during the decomposition process.	IDOV	Substantial innovation

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