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AXIOMATIC DESIGN FOR SIX SIGMA

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ABSTRACT

Six Sigma is one of the most innovative and successful methodologies to have been introduced in recent years at an industrial level. The goal of this approach is to increase the efficiency of the company system and to generally reduce the costs involved in the production process. The instruments used are mainly statistical: a representative CTQ characteristic is studied for each Six Sigma Project, and the causes of any non-conformities found, as well as their effects on the system, are analysed. This makes it possible to evaluate the best choice for optimising the system and to identify the risk associated with each choice; Six Sigma is, therefore, generally used for optimising processes. After an initial Define phase, Six Sigma can be subdivided into the following phases: Measure, Analyze, Improve & Control. Product optimisation can be developed in greater detail by using Design For Six Sigma (DFSS) techniques during the Improve phase. These techniques adopt a statistical approach in order to assess which design solutions are best and the system response associated with the solution chosen.

The aims of this paper are as follows. Firstly, to demonstrate that the DFSS techniques used for calculating a given process capability can interface with the Axiomatic Design (AD) schematisation of the product. In particular the meaning and use of the first and second axiom is focused on as a demonstration of how AD can be used within the framework of Six Sigma product optimisation. Secondly to demonstrate how the AD approach can be advantageous not only in the Improve phase, but also in the other phases of the Six Sigma Project. These integrative and innovative uses of AD have been named by the authors *Axiomatic Design For Six Sigma* (ADFSS).

1 INTRODUCTION TO SIX SIGMA

Six Sigma is a very effective tool for improving both operational quality and transactional processes in general. The Six Sigma methodology [6,7] uses technical statistics systematically and methodically, applying them to the entire organisation, thereby enabling the performance of all types of work activity to be evaluated. The innovative aspect of this methodology lies in its statistically oriented method, in the fundamental importance attached to the concept of measurement[1].

In this context, the definition of Quality changes with time, from being "appropriate to the use" to being "inversely proportional to the variability", i.e. Quality improves when the variability of the product and the productive process is reduced. For this reason, statistical tools play a vital role in the process of improving Quality [9,10,13]. The scientific nature of Six Sigma requires that statistics be used on the objective data in order to study the phenomenon being examined. The choice of the information sources for evaluating the variability of the data is shown to be strategic: the data has to be collected, differentiated and treated as *Long* and *Short Term*.

The Six Sigma approach is also characterised by the rigour with which Six Sigma Projects have to be developed. These Projects constitute the base

[1] The famous diktat of Mikel Harry, the father of this method, summarises this concept aptly: "We don't know what we don't know. If we can't express what we know in the form of numbers, we really don't know much about it. If we don't know much about it, we can't control it. If we can't control it, we are at the mercy of chance" [7]

upon which the entire methodology is developed and applied. In order to set up a Six Sigma Project it is essential that a CTQ[2] characteristic be chosen for analysis and optimisation. Once this choice has been made a working-team, whose members have all the necessary skills for dealing with the problem, has to be established. The development of the Six Sigma Project follows a well-defined sequence, the DMAIC phases (Define, Measure, Analyze, Improve and Control). These phases can be briefly summarised as follows:

Define the most important points
Measure the process capability
Analyze the causes of non conformity
Improve by eliminating these causes
Control the stability of performance

Figure 1 – A concise scheme of the DMAIC phases

In the Define phase the problem to be dealt with is characterised, a work team and a certain amount of resources are associated with the Project and an estimate is provided of the cost-savings that would ensue if the Project were developed. In the Measure phase the process is characterised statistically by quantifying the performance of the system being studied. The Analyze phase seeks the causes that result in performance specifications not being met. The aim of the Improve phase is to reduce, or at least eliminate, these causes so as to improve system performance, to this end *ad hoc* tools, known as DFSS (Design For Six Sigma), are used. A measurement network is organised to monitor the stability of the performance obtained in the Control phase.

2 AXIOMATIC DESIGN FOR SIX SIGMA

It is the enormous versatility of Axiomatic Design (AD) theory [12] which makes its integration with the Six Sigma method not only viable but useful: this integration greatly simplifies the development and management of both products and processes, business and organisations. Furthermore projects developed using AD have many points in common with those developed using Six Sigma. AD provides the designer with tools for readily identifying the critical aspects of his design thereby making the optimisation process simpler and more effective. The inventor of this theory, N.P. Suh, provides a brief summary [12] of the procedures to follow when applying AD:

1- Know Customer Needs
2- Define the problem that has to be solved in order to satisfy these needs
3- Conceptualise the solution though synthesis; this involves the task of satisfying several different functional requirements using a set of inputs such as product design parameters within given constraints
4- Perform analysis in order to optimise the proposed solution
5- Check the resulting design solution to see if it meets the original customer needs

These steps have something in common with the model first called the PDCA (Plan, Do, Check, Act) cycle, later revised by Deming to the PDSA (Plan, Do, Study, Act) cycle, an approach which is similar to Six Sigma. [11]. AD is also much simpler to integrate with other methodologies. It has already been integrated with the SPC [12], Robust Design and Functional Analysis [3] methodologies. In a similar fashion AD is used during the implementation of Six Sigma Projects as is explained in the following paragraphs.

2.1 PRODUCT AND PROCESS IMPROVEMENT

The most important benefits accruing to Six Sigma from the use of AD are obtained in the course of the Improve phase of the product, during which techniques known as DFSS are deployed. The aim of this phase is to improve product response so that it meets requested specifications, thereby reducing the costs associated with inefficiency and non-conformity. To this end tools such as DOE [9], ANOVA [10] and Robust Design are adopted. In this phase AD can be used

[2] CTQ-Critical To Quality, the critical characteristics of a product,which are either the cause of high extra-costs or strategically important for the firm.

to conclude optimisation more quickly and more accurately. One of AD's tasks is helping the designer choose which factors to use in the DOE tests. The Design Matrix (DM) [12] highlights which parameters are influencing each of the FRs; in order to optimise one of these characteristics a DOE, which treats all the DPs coupled with a certain FR as potentially influential factors, has to be carried out. In the case of there being a considerable number of these DPs, it is advisable to carry out a preliminary screening analysis using greatly reduced factorial plans, thereby eliminating all those factors whose influence on the response could be marginal. A complete factorial plan, which only considers the remaining factors, those significantly influencing performance, can then be carried out. A similar strategy can be adopted for choosing which factors should be used for ANOVA. Other important benefits are obtained when applying Robust Design. The three phases of Robust Design - Concept, Parameter and Tolerance Design – can be simplified by using AD schematisation. The Concept phase, which involves the structure of the product or process, can be associated with the first axiom. It has been proved that a system regarded as less coupled by the first axiom corresponds to what Robust Design considers a more robust system. In the Parameter and Tolerance Design phases the AD schematisation clearly highlights all the aspects influencing a given product or process characteristic, thereby making it possible to evaluate the robustness of the response by analysing the DPs and the functions present in the DM. An example of this approach is shown in

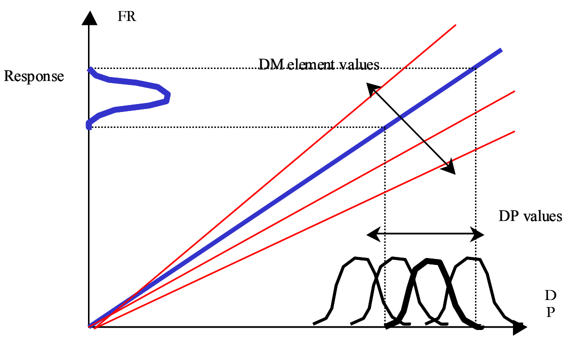

Figure 2 – Example showing the calculation of response robustness in an FR

Figure 2.

In particular AD distinguishes clearly between parameters that can be used in the Parameter Design phase and those that can be used in the Tolerance Design phase. In practice, all the DPs and the factors present in the DM's functions can be used in the Parameter Design phase and it would seem feasible to reduce DP dispersion by undertaking Tolerance Design although satisfactory results have not yet been forthcoming.

2.2 ANALYSIS OF THE CTQ CHARACTERISTIC

Fundamental to the choice of the Six Sigma Project to develop is the estimate of the CTQ improvement margins and the extent of the resultant cost saving. The resources required, both economic and human, for the realisation of the objectives chosen must also be taken into consideration. Each Six Sigma project delivers bottom line results in a relatively short time.
AD is capable of optimally managing all these characteristics. By calculating the Information Content of the principal FRs present in the system it is possible to ascertain from the AD schematisation which is the most critical characteristic of the process or product (CTQ). The Information Content measures the probability for every FR to be satisfied, so it can be used to evaluate to what extent the main FRs are able to meet the specifications. This characteristic can also be expressed in terms of the process sigma number, thereby making it possible to compare the two measurements. In this way the most critical FRs, which will become the CTQ characteristics of a Six Sigma Project, can be identified. In order to evaluate the cost saving associated with improving a given CTQ it is essential that the extent of the improvement margin during Project development of that CTQ, an FR of the AD schematisation, be known. In this case AD offers considerable advantages. Studying the degree of coupling of the DM relative to the FR chosen as CTQ it becomes apparent that optimising a coupled process, making it de-coupled, or at most uncoupled, results in greater improvement margins than when an already uncoupled process is optimised. The first case,

however, requires more resources for carrying out the optimisation because quite a considerable part of the system has to be redesigned. This study also indicates the direction in which the optimisation of the system has to proceed: if the design is coupled there is little use in trying to carry out an optimisation based on the choice of improved values for the DPs (Parameter or Tolerance Design). Instead it will be necessary to carry out more radical changes to the structure of the system. As Suh [12] states: *Althought many efforts are being made in industry to improve a bad design using optimization techniques, a design that violates the Independences Axiom cannot be improved unless it is first made to satisfy the Independence Axiom. Optimization of a bad design may lead to an optimized bad design or minor improvement. Optimization often implies a trade-off between competing FRs*. Designs that satisfy the design Axioms do not have to be optimized in the traditional sense. Another tool used to evaluate the cost saving related to the CTQ is the QFD. This tool use a matricial representation of the product in order to evaluate which FRs and DPs have the greater importance. Given this measure is possibile to decide which part of the design is the most imporant, so the spread of the response have to be more tight. The authors in a recent paper [3] have showed how the QFD, in particular the MacAbe method, is comparable to the AD representation of the product.

Six Sigma is applied to continuous improvement of existing processes as well as to the design of new processes. The scenario is a little different when a product/process is completely new, infact this has to be designed following DMADV (Define, Measure, Analyze, Design, Verify) methodology. This one, instead of the DMAIC methodology, should be used when:

- A product or process is not in existence at company and one needs to be developed
- The existing product or process exists and has been optimized (using either DMAIC or not) and still doesn't meet the level of customer specification or six sigma level

DMAIC and DMADV sound very similar, but on one hand I Measure the process to determine current performance and Analyze the root causes of the defects, on the other I Measure and determine Customer Needs and specifications and Analyze and Design (detailed) the process options to meet the CNs. Using DMADV methodology AD proves its usefulness by already indicating in the Design phase whether or not is a good design, thereby reducing the trial and error attempts and the Design/Verify phases. This is made possible by using the first axiom and by calculating the product coupling level.

Using these instruments it is, therefore, possible to carry out the Define phase of the Six Sigma Project very accurately: the CTQ to be studied by the Project is identified, the current situation is evaluated and the cost savings and the resources required for its development are estimated. AD can also be utilised in this phase to optimise the resources used. AD is a methodology well suited to representing and managing complex organisations [12], so this approach is, therefore, capable of optimally managing human resources the firm is prepared to invest in developing Six Sigma Projects.

2.3 REPRESENTATION AND ANALYSIS OF THE SYSTEM

AD can also be profitably adopted in other phases of the development of Six Sigma Projects. A clear functional representation of the product or process has to be constructed in the Analyze phase so that the causes leading to performance breakdown can be identified. Among the tools used there are three that are easily integrated with AD: Functional Analysis (FA), the Failure Mode and Effect Analysis (FMEA) and the Fishbone Diagram (also known as the Cause-Effect Diagram). In the first case the clear functional representation of AD can be used to create, with the assistance of a procedure elaborated by the authors [3], the Correlation Matrix used by FA. In this way the framework for the subsequent detailed analysis of the CTQ under investigation can be built very rapidly without the need for extra information, creating a common base for exchanging information among those working on the Project. In the second case, as another work proposed from the authors [2] has showed, the advantage to use the AD for the development of the FMEA are mainly correlated to the easiest way to carry out this analysis and to the greater precision in the research of the failure causes and effects. In conclusion the Fishbone Diagram contains all the possible causes that might influence the performance of the chosen CTQ characteristic. In order to identify these causes starting from the AD schematisation, all the DPs subordinate to the FR chosen as CTQ have to be analysed together with the related FRs. From this analysis is possible to find all the causes that influence the performance of the CTQ characteristic. A simple example, the cooling system of the diesel motor of a traction locomotive, is shown in Figure 3. The FR chosen as CTQ characteristic for this project is: "Guarantee motor cooling". This choice is explained by the fact that the original project had serious cooling problems, i.e. the amount of heat removed per unit of time did not meet the limits specified, thereby generating non-conformity.

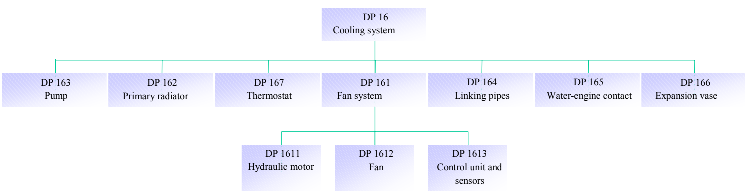

Figure 3 – AD Representation of the cooling system, DPs tree

In Figure 4 is proposed the Fishbone Diagram of the case study created using the method proposed. From the combined analysis of all the sub-level DPs and FRs of the CTQ characteristic it's possible to find all the possible causes that give a reduced heat exchange. These are mainly related to the poor functioning or the total failure of the components present in the system.

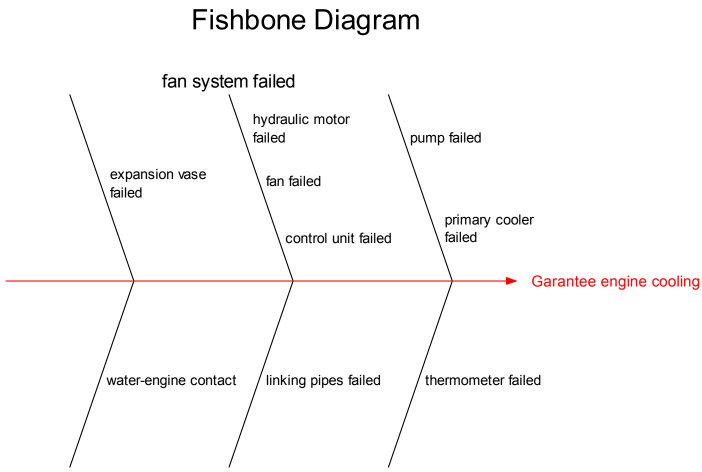

Figure 4 – Fishbone Diagram of the cooling system

The advantages of using AD to develop the Fishbone Diagram are the increased speed, accuracy and confidence in the results. These advantages are mainly obtained by the use of zigzagging: this method of breaking down the functional and the physical domain at the same time ensures that no aspect of the system, however marginal, is overlooked. In this way the risk of not considering characteristics that later could prove to be influential is avoided.

The AD representation has another advantage: highlighting the causes which most greatly influence performance deterioration. The functional relations between the FRs and the DPs are represented in the DM. This information can be used to assess the causes, and identify the DPs that exert the greatest influence on the FR representing the CTQ characteristic. In practice the greater the absolute value of the element which links that DP to the CTQ characteristic in the DM, the greater the influence of a DP on the response. This method has the advantage of reducing the number of DPs that have to be optimised in order to improve the response; it is possible to limit the inquiry to the DPs that this analysis indicates to be the most influential. This obviates the need for deploying complex tools for carrying out screening, thereby saving time and resources in the development of the Six Sigma Project.

2.4 CONCLUSIONS

This paper has discussed the important role of Axiomatic Design in Six Sigma, proving the base of the ADFSS approach, that is a link of some tools used in the DMAIC and DMADV phases. The advantages of applying ADFSS in the Improve phase of the product, where in practice it is integrated with some DFSS tools, have been described. The fact that ADFSS can also prove to be fundamentally important in the choice and Define phase of Six Sigma Projects has been noted. In this case it is possible to readily identify the characteristics of a product or process with the worst performance by assimilating them to CTQ characteristics of the Project to be developed. If the system being analysed is already operative it is possible to determine the extent of the cost savings that can be obtained from the Project. By analysing the coupling level of this CTQ it is possible to ascertain the complexity of the optimisation interventions, to decide whether parts of the system have to be redesigned (coupled situation) or whether a simpler optimisation is sufficient (uncoupled situation), and to assess the resources required by the team to develop the Project. There are further advantages in the Analyze phase of the system. Using ADFSS the construction of the FA's Correlation Matrix, the FMEA and the Fishbone Diagram, used for ascertaining the causes of performance deterioration, is simple. Finally, using ADFSS to integrate the Six Sigma techniques results in a considerable saving of resources during developing Six Sigma Projects.

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