THE UNIVERSITY OF
WARWICK

SIX SIGMA vs. DESIGN FOR SIX SIGMA: SELECTION OF THE REQUISITE SIX SIGMA APPROACH USING MULTI-CRITERIA DECISION ANALYSIS

Innovation Report

Submitted in partial fulfilment of the requirements for the Degree of Doctor of Engineering

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June, 2005

Abstract

The literature suggests that organisations which have adopted Six Sigma have realised that upon achieving a Five Sigma level the only way to surpass this is to redesign the process(es) by means of Design for Six Sigma (DFSS). For others, the selection of Six Sigma over the DFSS approach is not a definitive question and just a guideline can be provided. A major objective of this research was to extend the selection of the requisite Six Sigma approach beyond the sigma level case and the general guidelines, towards a multi-criteria decision using established techniques. Thus, two research questions were defined: what influences the selection of the requisite Six Sigma approach, i.e. Six Sigma versus DFSS? and, how effective is the use of Multi-Criteria Decision Analysis (MCDA) techniques in the selection of the requisite Six Sigma approach?

An action research methodology was applied where one Six Sigma project, one DFSS project and one Six Sigma project applied in a non-manufacturing process were implemented and analysed in collaboration with 3M Corporation, General Domestic Appliances (GDA) and Land Rover. From the action research spiral it was concluded that the sigma level has a positive association with the selection of redesign or improvement efforts within Six Sigma, however the Five Sigma level cannot necessarily dictate the use of one approach over the other. Besides the sigma level the selection of the requisite Six Sigma approach is influenced by multiple and conflicting criteria. In addition, the selection can occur at different stages of the methodologies. To assist decision-makers in organising, synthesising and optimising the criteria affecting this decision, the Stochastic Analytic Hierarchy Process (SAHP) was developed and applied to the problem at hand. The SAHP was developed on the basis of Analytic Hierarchy Process (AHP) and disparate sources of relevant literature. SAHP provides a mechanism for achieving a more effective selection of the requisite Six Sigma approach in the form of considering multiple and conflicting criteria using quantitative and qualitative information under uncertainty. In contrast to the traditional AHP, SAHP incorporates probabilistic distributions to incorporate uncertainty that people have in converging into a Likert scale their judgments of preferences. The vector of priorities is calculated using Monte Carlo simulation and the final rankings analysed for rank reversal using statistical analysis with managerial aspects introduced systematically.

The concept and implementation of SAHP is new to the selection of the requisite Six Sigma approach and as such it constitutes the main innovation to result from this research. It extends the selection of the requisite Six Sigma approach towards a systematic multi-criteria decision considering multiple and conflicting criteria under uncertainty. Furthermore, while SAHP was originally conceived as a specific aid to the improve or redesign issue within Six Sigma, this research indicates that it is potentially much more widely applicable. This research also provides evidence of how different factors affecting the selection of requisite Six Sigma approach were considered. Further areas of research include the use of a positivist method in order to increase the sample size of the research and identify different factors affecting the decision improve or redesign. The development of SAHP software and extending the SAHP practice to different multi-criteria decisions are also potential areas for further research.

Acknowledgements

There are a number of people who I would like to thank for their support during the course of this research. However, before I acknowledge them I would like to express my profound gratitude to my wife Clara Amador, who literally embarked with me on my journey of reading for an Engineering Doctorate. Her support, encouragement, help and love during the course of the past four years made it possible for this work to materialise. I would also like to offer thanks to the other members of my family, my mom - for her precious example of work and dedication-, and my sisters and brother.

Special thanks to Dr. Ian Tuersley and Dr. Charles Tennant for their valuable supervision, their comments and corrections. To Dr. Jiju Antony for starting this project with me and for the long and enjoyable talks about Six Sigma. Thanks also to Martin Brace, Noel Byrne, Karen Vyrse, Phil Rowe, Nick Shubotham, Alwyn Hines, John Powell, Rod Dewey, Andy Foster, Tom Butler and Julie Richards from the collaborative companies. Thank are due to the referees from the TQM Magazine, The International Journal of Production Research, The International Conference of Quality, Reliability and Maintenance 2004 and The Journal of the Operational Research Society for their comments during the review process. I would like to thank my friends in the Warwick Manufacturing Group, Dr. Carlos Mena and Mark Johnson, the Director of the Engineering Doctorate programme, Dr. Kevin Neailey, and the course administrator, Emma Underwood. Special thanks to Liza Sandell for proof reading this document.

Declaration

I, Ricardo Bañuelas Coronado, hereby declare that all the work presented in this Innovation Report is my own unless otherwise stated in the text. To the best of my knowledge, none of the work has been submitted as part of any other award and all sources of quoted information have been acknowledged by means of reference.

Signature

Ricardo Bañuelas Coronado

Table of Contexts

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List of Acronyms

AHP:	Analytic Hierarchy Process
ANOVA:	Analysis Of Variance
BOM:	Bill Of Materials
BPR:	Business Process Reengineering
CTQ:	Critical-To-Quality
DCOV:	Define, Concept, Optimise, Verify
DFMEA:	Design, Failure, Mode and Effect Analysis
DFSS:	Design For Six Sigma
DMADV:	Define, Measure, Analyse, Design, Verify
DMAIC:	Define, Measure, Analyse, Improve, Control
DOE:	Design Of Experiments
DPMO:	Defects Per Million Opportunities
DTMFSS:	Design, Technology, Marketing For Six Sigma
GDA:	General Domestic Appliances
IJPR:	International Journal of Production Research
IT:	Information Technology
IDOV:	Identify, Design, Optimise, Verify
MCDA:	Multi-Criteria Decision Analysis
MCDM :	Multi-Criteria Decision Making
MSD:	Mean Square Deviation
NPI:	New Product Introduction
QREI:	Quality, Reliability Engineering International
R&D:	Research & Development
RSM:	Response Surface Methodology
SAHP:	Stochastic Analytic Hierarchy Process
SOP:	Standard Operation Procedure
TQM:	Total Quality Management
UK:	United Kingdom
US:	United States

Innovation Report

1 Introduction

Quality is seen as one of the key performance criteria of almost every organisation. It is difficult to identify any major organisation in which quality is not seen as key to success. It has generated a tremendous amount of interest in many sectors of the economy and in many countries around the word. It can be argued that the quality paradigm has seen little evolution since the 1980s and now it is seen as an order qualifier and not as an order winner. Nevertheless, Six Sigma has made a significant impact since the late 1990s, and nowadays is seen for some as the new "breakthrough" quality philosophy "revolutionising" many organisations (Harry and Schroeder, 2000; Pande, Neuman and Cavanaugh, 2000; Chowdhury, 2001:2002; Eckes, 2001; Tennant 2001:2002). However, the contribution of Six Sigma has not been in the tools it uses or revolutionary thinking, but rather in its marketing of the central ideas of radical and continuous improvement and its integration of these ideas with business incentives and objectives (Maguire 1999; Caulcutt, 2001; Rowlands, 2003). According to the author, it should not be assumed that Six Sigma has proceeded in a direct line from the past towards the present forming a "revolutionary" or a "breakthrough" business strategy as Six Sigma consultants claim (Harry and Schroeder, 2000; Pande *et al.,* 2000;

Chowdhury, 2001:2002; Eckes, 2001; Tennant 2001:2002). Six Sigma is quite literally what the past, as received and interpreted by the present, has made it (Fuller, 2000). It is not a simple outdated approach, but has been transformed and recombined to produce what it is now called Six Sigma. A review of the roots of quality and management in the literature suggests that Six Sigma development is benchmarked by historic-graphical landmarks that give structure and coherence to it. The need to improve organisational effectiveness and efficiency emerged from a long time ago, much earlier than Total Quality Management (TQM) times and from a broad range of civilisations.

Nowadays, the implications of Six Sigma and Design for Six Sigma (DFSS) in industry are considered profound. Six Sigma is a philosophy that employs a structured improvement methodology to reduce process variability and to drive out waste within business processes with the use of statistical tools and techniques (Bañuelas and Antony, 2003). The reason for the name "Six Sigma" was that "sigma" is a statistical measure which denotes the standard deviation of a set of data. It provides a measurement of variability which indicates how all data points in the normal distribution vary from the mean or average value (Behara, Fontenot and Gresham, 1994; Klefsjo, Wiklund and Edgeman, 2001). The technical concept of Six Sigma is to measure the current performance and to determine the number of K sigmas existing in a process that can be measured from the current average until customer dissatisfaction (usually expressed in terms of specifications limits) occurs (Henderson and Evans, 2000; Eckes, 2001). Thus Six Sigma performance implies, with the normal distribution assumption, a defective rate of less than two defects per billion opportunities (0.002 Defects Per Million Opportunities [DPMO]). However, the value or number of defects of a process is also a function of the off-centring value of the process which translates into 3.4 DPMO assuming a 1.5 sigma shift of the mean.

The Six Sigma term has also evolved in the past few years as a more complex approach rather than simply a way to enumerate defects (Breyfogle, 1999; Antony and Bañuelas, 2001; Bañuelas and Antony, 2002). Therefore it can now be defined as:

"an organised and systematic method for strategic process improvement and new product and service development that relies on statistical methods and the scientific method to make dramatic reductions in customer defined defect rates."

(Linderman, Schroeder, Zaheer and Choon, 2003).

Six Sigma is usually applied through the work of cross functional project teams. Project members, often called Black Belts and Green Belts, are trained in statistical tools and techniques, problem solving and leadership. Generally, Black Belts work full-time in the implementation of Six Sigma, whereas Green Belts only work part-time (Henderson and Evans, 2000; Barney, 2002). The practice of Six Sigma generally takes the form of projects involving the implementation of the different phases (Define, Measure, Analyse, Improve and Control) usually recognised as the DMAIC methodology (George, 2002; Stamatis, 2003). Projects seek to enhance existing processes by continuous incremental improvements (Halliday, 2001; Berryman, 2002; Huber, 2002; Johnson, 2002; Brue and Launsby, 2003). This approach is well accepted in industry since existing defects can be rapidly quantified in monetary terms, and Six Sigma projects can show significant financial benefits due to the cost of poor quality (Huber, 2002; Brue and Launsby, 2003). Therefore it is characterised as a continuous improvement approach (also known in the quality field with its Japanese name *kaizen*[1]), which facilitates change on a steady and progressive basis (Tennant, Warwood and Chiang, 2002). This same constant and incremental method is used in Total Quality Management.

The aim of Six Sigma DMAIC projects is to do what the company already does but more efficiently by eliminating variation from processes (Berryman, 2002). The projects are developed from today's perspective and are often constrained by assumptions made during the development and design stages (Huber, 2002). Generally DMAIC improvement projects assume that the design of product or service is essentially correct and the most economical; customer needs are satisfied with that design, and the current product configuration satisfies the functional requirements of the market and customer. Since variability is seen as one main cause of waste and customer dissatisfaction, its primary enabler is generally statistical techniques such as Design of Experiments (DOE) (Huber, 2002; Nave, 2002). Furthermore, DMAIC could be fundamentally characterised as a reactive quality strategy based on statistical methods for defect removal and optimisation (Finster, 2001; Berryman, 2002).

Most Six Sigma efforts are focused upon taking variability out of the existing processes by employing the DMAIC methodology. However, at the same time, variability is also introduced in new products. In order to avoid this, Design for Six Sigma efforts have focused upon predicting and improving quality before products and processes are

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[1] *Kaizen* according to Imai (1986) means, *"improvement". Moreover it means continuing improvement in personal life, home life, and working life. Kaizen means improvement involving everyone- managers and workers alike."*

launched. It can also be employed to redesign current processes and products. This approach can be seen as an effective proactive way to obtain Six Sigma quality levels and avoid future problems at the manufacturing and service stages (Bañuelas and Antony, 2003).

Contrary to the incremental improvement DMAIC Six Sigma methodology, DFSS has the ability to discard existing processes and substitute them with radical new processes. Therefore it is considered that DFSS can improve not only process efficiency[2] but also process effectiveness[3] (Finster, 2001; Berryman, 2002; Bañuelas and Antony, 2003). DFSS intends to create designs that are resource efficient, capable of reaching very high yields regardless of complexity and volume, "robust" to process variability, and highly linked to customer demands (Harry and Schroeder, 2000). The process of DFSS is a four-step approach. It recognises the customer and progressively builds on the system concept of robustness in product or service development and finally testing and verifying the results against the designs (Stamatis, 2002). To this end, DFSS uses an equivalent DMAIC methodology, the IDOV (Identify, Design, Optimise and Verify) methodology. Although DFSS has several methodologies used across industry, the core of the DFSS approach applies in general, despite the specific DFSS methodology selected by one organisation.

Sometimes DFSS is seen as a logical extension of Six Sigma at the Research & Development (R&D) and design stages of the New Product Introduction (NPI) Process.

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[2] Efficiency is defined as the technical ability of the organisation to minimise the cost of transforming specified inputs into acceptable outputs (Roberts and Hunt, 1991).
[3] Effectiveness is defined as the organisation's ability to maximise its returns by whatever means, including not only efficiency but also management of its input and output environments (Roberts and Hunt, 1991).

Although generally DFSS takes place in the those areas (Johnson, 2002; Joglekar, 2003), it can also be employed to redesign current processes and products. This approach can be seen as a much more effective way to obtain Six Sigma quality levels and avoid future problems at manufacturing and service stages. Consequently, these two approaches differ in several ways and can be contrasted in terms of their philosophical assumptions, the methodologies they employ and the tools and techniques they use.

For current processes the point when the DFSS approach becomes a priority over a continuous improvement methodology is not well-documented in the literature and is also a controversial issue (Bañuelas and Antony, 2004a). As both activities compete for scarce resources, organisations must formulate explicit decision-making policies for allocating resources. In practice, Six Sigma teams decide early on in the project if they need to redesign an inadequate process or improve it, however this decision is a subject of discussion. Scholars and consultants have tried to set criteria to select the requisite Six Sigma approach producing two fundamentally different perspectives about this issue, i.e. the mono-criterion and the multi-criteria cases.

The mono-criterion case states that once processes have achieved Five Sigma quality levels (i.e. 233 DPMO) using DMAIC, the only way to surpass this level is to redesign their products, processes and services by means of DFSS (Harry and Schroeder, 2000; Chowdhury, 2001:2002; Tennant, 2001:2002). Conversely, the multi-criteria approach states that many variables need to be taken into account to select the requisite Six Sigma approach, consequently just a general guideline can be provided (Pande *et al.*, 2000; Eckes, 2001; Truscott, 2003). Such a guideline guides this decision using criteria such as risk, process capability, technology availability and change in the company's strategy. This lack of unanimity formed the foundation of this research and raised the following research question: *What influences the selection of the requisite Six Sigma approach, i.e. Six Sigma versus DFSS?*

The problem of selecting an alternative under multiple and conflicting criteria is well documented in the operational research field. To help practitioners and decision-makers deal with complex problems, the field of operational research has developed a wide range of Multi-Criteria Decision Analysis (MCDA[4]) techniques. MCDA is defined as: *"an umbrella term to describe a collection of formal approaches which seek to take explicit account of multiple criteria in helping individuals or groups explore decisions that matter"* (Belton and Stewart, 2002).

However, the literature does not report the application of MCDA techniques to deal with the selection of the requisite Six Sigma approach. Consequently, this research also intends to answer the question: *How effective is the use of Multi-Criteria Decision Analysis (MCDA) techniques in the selection of the requisite Six Sigma approach?*

The research and project work implementation described in this Innovation Report provides an answer to the research questions. It is presented as evidence of an innovative application of knowledge regarding the selection of the requisite Six Sigma approach (i.e. Six Sigma vs. Design for Six Sigma), using the Stochastic Analytic Hierarchy Process (SAHP) within three major organisations with operations in the United Kingdom. This work led to the creation and implementation of the SAHP, a Multi-Criteria Decision Analysis (MCDA) technique that helps people set priorities and

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[4] Also called Multiple Criteria Decision-Making (MCDM), or Multiple Criteria Decision Aid (MCDA).

make better decisions when taking into account qualitative and quantitative information under uncertainty (Bañuelas and Antony, 2004a).

1.1 Objectives of the research

The identification of criteria affecting the selection of the appropriate Six Sigma approach could lead organisations to focus their Six Sigma efforts upon applying the appropriate approach. A major objective of this research was to extend the selection of the requisite Six Sigma approach beyond a mono-criterion case towards a multi-criteria decision using MCDA techniques. Therefore, the principal objective of this research is: *"To select the appropriate Six Sigma approach by the understanding of the factors and their interactions affecting this decision using Multi-Criteria Decision Analysis techniques."*

This main objective can be divided into three sub-objectives:

1) To determine the main criteria in the collaborative companies which decide when a given project should employ the Six Sigma or Design for Six Sigma approach.

2) To identify, select and apply multi-criteria decision techniques to select the requisite Six Sigma approach at the collaborative companies.

3) To extrapolate the findings in the companies researched to a wider context, by developing a consistent methodology and techniques which represent and analyse the decision system for Six Sigma approach selection.

It is important to mention that the selection is within a spectrum, since projects seldom fully manifest as "pure" DFSS or Six Sigma projects. Consequently a degree of convergence exists between these two approaches. This concept is further developed in section 5.4.

Using action research as a method of investigation, one Six Sigma project, one Design for Six Sigma project and one Six Sigma project in a non-manufacturing process were carried out in collaboration with 3M, General Domestic Appliances (GDA) and Land Rover respectively. The in-depth participation and application that action research provided (Susman and Evered 1978; Westbrook, 1995; Coughlan and Coghlan, 2002), gave the researcher the opportunity to identify multi-criteria affecting the decision of choosing DFSS or Six Sigma. It also allowed the researcher to legitimately intervene in the Six Sigma practice at the collaborative companies to test the applicability of specific MCDA techniques such as Analytic Hierarchy Process and Stochastic Analytic Hierarchy Process in order to deal with this problem.

1.2 Structure of the portfolio

The purpose of this section is to provide a brief overview of the individual Submissions including their main themes, the outcomes and achievements generated. A route map of the portfolio structure provides a guide to the reader. This section is designed to help the reader allocate items of specific interest and to underline the innovative application of knowledge in this research.

1.2.1 Outline of the Submissions

A preliminary phase took place to establish the broad goal of the research and to develop the research strategy. This phase started with the identification of the research area, which was narrowed through a literature review. Submission 1 and 2 present this preliminary phase. Submissions 3, 4 and 5 formed the second phase of the research. During this phase the action research took place at the different collaborative companies. Each of these Submissions represents a cycle in the action research spiral. The aim was to demonstrate an innovative application of knowledge by an understanding of the factors involved in the improve or redesign issue using AHP and SAHP. The third phase, Submission 6, Personal Profile and Innovation Report, complete this portfolio.

Submission 1: *"Research Strategy"*. During this Submission the overall configuration of the research strategy was established. This includes the explanation and the explicit relationship of the problem formulation; the research questions generated and the type of evidence to be researched and its source. As a result, the researcher identified action research as a suitable research method to answer the research questions. A paper "Going from Six sigma to Design for Six Sigma: An Exploratory Study Using AHP" which appeared in The TQM Magazine (Bañuelas and Antony, 2003) was published as a result of the work undertaken in this Submission. This paper is shown in Appendix I in Submission 6.

Submission 2: *"Literature Review"*. The objectives of this Submission were to understand the development of Six Sigma by identifying key studies; to explain Six Sigma's major issues and practical problems which lead to identification of the matters this research intends to look at, and to consider matters other researchers have considered important in order to answer the research questions. As an outcome of this Submission the researcher narrowed the research idea into specific research questions, hypotheses and objectives. In addition, the key studies which addressed the research questions and hypotheses were critically reviewed.

Submission 3: *"Selection of the Requisite Six Sigma Approach; Using the Analytic Hierarchy Process in a DMAIC Six Sigma Project".* The main objective of this Submission was to identify criteria used to select Six Sigma over Design for Six Sigma within 3M Company and to test the applicability of the AHP technique for this selection. As a result, financial benefit, cash avoidance, risk reduction and capability enhancement were identified as the main criteria affecting this decision. To resolve this multi-criteria decision, the Analytic Hierarchy Process (AHP) was employed and a redesign of the process was suggested. The savings generated from this project were in the order of £100,000 annually. This core action research project provided evidence of how different criteria were considered in this selection and how AHP was implemented. In addition, the Six Sigma project carried out during this Submission was the first implemented at 3M Atherstone. This project is published in Quality Reliability Engineering International (QREI) (Bañuelas, Antony and Brace, 2005) and the book World Class Six Sigma in a paper and a book chapter entitled "An Application of Six Sigma to Reduced Waste". This paper is included in Appendix V of Submission 6.

Submission 4: *"Selection of the Requisite Six Sigma Approach; Using the Stochastic Analytic Hierarchy Process in a Design for Six Sigma Project".* Submission 3 presented the selection of the requisite Six Sigma approach during a DMAIC Six Sigma project, however, it just represents one part of the spectrum. Therefore, Submission 4 focuses on the study of a DFSS project to identify criteria considered to select the requisite Six Sigma approach within General Domestic Appliances (GDA) and to test the applicability of AHP technique for this selection. The Analytic Hierarchy Process was applied in order to select between improving the current product or redesigning it. The reflection of the applicability of AHP in this project dictated the need to incorporate uncertainty, managerial aspects and statistical significance of the results into the AHP. A Stochastic Analytic Hierarchy Process (SAHP) was developed and applied to the original selection bearing in mind the above issues learned from the first application of the AHP. Based on the SAHP and considering criteria such as cost, risk, safety, reliability, performance, ease of assembly and recycling, the product was redesigned. As a result, the company was able to achieve the strategic targets set at the start of the project. The theory underpinning the SAHP was published in the International Journal of Production Research (IJPR) in a paper entitled "Modified Analytic Hierarchy Process[5] to incorporate uncertainty and managerial aspects" (Bañuelas and Antony, 2004a) which is included in Appendix III in Submission 6. The application of the SAHP in the white goods industry is under review in the Journal of the Operational Research Society in a paper entitled "An application of the Stochastic Analytic Hierarch Process within a domestic appliance manufacture" (Bañuelas and Antony, *under review*), shown in Appendix VI in Submission 6.

The results of the first two action research cycles, Submissions 3 and 4, were also published in The TQM Magazine in a paper entitled "Six Sigma or Design for Six Sigma?" (Bañuelas and Antony, 2004b) which is shown in Appendix II in Submission 6. They were also presented at the 2004 Conference on Quality, Reliability, and

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[5] At the beginning of the research SAHP was called by the researcher the Modified Analytic Hierarchy Process (MAHP), however the name of the technique was changed to avoid confusion with the Multiplicative Analytic Hierarchy Process (MAHP) and to reflect the nature of the process.

Maintainability, at St. Edmund Hall College, University of Oxford (Bañuelas, Tennant and Tuersley, 2004), as shown in Appendix IV in Submission 6.

Submission 5: *"Selection of the Requisite Six Sigma Approach; Using the Stochastic Analytic Hierarchy Process in a non-manufacturing DMAIC Six Sigma Project".* The main objectives of this Submission were to identify criteria used to select Six Sigma over DFSS during a non-manufacturing process within Land Rover, and to test the applicability of SAHP for the selection of the requisite Six Sigma approach in a different environment. During the improvement phase of the DMAIC methodology, the Six Sigma team generated two possible routes of action for the project: redesign the process or continuously improve it. This decision involved multi-criteria such as quality, risk, performance and project investment. Using the Stochastic Analytic Hierarchy Process the redesigning of the process was selected.

Submission 6: *"Published papers".* In this research; innovation, relevance, reliability and validity are, in great part, demonstrated by placing the research findings in the public domain. This Submission shows how the research findings were made public, debated and defended. It presents a collection of papers referenced below, including five blind peer-reviewed papers (one of them also published as a book chapter) one conference paper and two papers in which the researcher was the second and third author respectively. It also includes the peer-review comments from the journal's referees and how the research incorporated such comments. The papers published as outputs of the research were as follows:

ANTONY, J. and BAÑUELAS, R (2002): Design for Six Sigma: A Breakthrough Improvement Business Strategy for Achieving Competitive Advantage. *Manufacturing Engineering;* Vol. 8. No. 1. Pp. 24-26. **IEE best paper award 2002.** Also in *The SAIEE Electronics, Computing, Information & Communication Journal.* Vol. 19. No.10. Pp. 17-20.

ANTONY, J., BAÑUELAS, R. and KUMAR, A. (*in press*): *World-class applications of Six Sigma in the manufacturing and service industries.* Elsevier

ANTONY, J., FOUTRIS, F., BAÑUELAS, R. and THOMAS, A. (2004): Using Six Sigma. *Manufacturing Engineering.* Vol. 83. No. 1. Pp. 10-12.

BAÑUELAS, R. and ANTONY, J. (2003): Going from Six Sigma to Design for Sigma: An exploratory study using AHP. *The TQM Magazine;* Vol. 15. No. 5. Pp. 334-344.

BAÑUELAS, R. and ANTONY, J. (2004a): Six Sigma or DFSS? *The TQM Magazine.* Vol. 16. No. 4. Pp. 250-263.

BAÑUELAS, R. and ANTONY, J. (2004b): Modified Analytic Hierarchy Process to incorporate managerial aspects and uncertainty. *International Journal of Production Research*. Vol. 42. No. 8. Pp. 3851-3872.

BAÑUELAS, R., TENNANT, C., and TUERSLEY, I. (2004): From Six Sigma to design for Six Sigma. In McNulty (2004): Proceedings of the 5th International Conference on Quality, Reliability and Maintenance QRM 2004. Held at St. Edmund Hall, University of Oxford. 1st-2nd April 2004. Pp.131-134.

BAÑUELAS, R. and ANTONY, J. (*under review*): Application of Stochastic Analytic Hierarchy Process within a domestic appliance manufacturer. *Journal of the Operational Research Society.*

BAÑUELAS, R., ANTONY, J. and BRACE, M. (2005): An application of Six Sigma to reduce waste. *Quality and Reliability Engineering International.* In press.

Personal Profile. This provides an overview of the author's academic and industrial background prior to his enrolment on the Engineering Doctorate programme. It demonstrates the development of competences as a result of the taught modules attended and the project work implementation in addition to the dissemination of the work via publications.

1.2.2 Order of reading of the Submissions

The outline presented in Figure 1 indicates a path through the portfolio, as a guide for the reader. The portfolio Submissions are presented in chronological order, from Submission 1: "The research Strategy" to Submission 6: "Papers Published". The additional Submissions are the "Innovation Report" and the "Personal Profile". The suggested order of reading is to review the published papers to obtain an overview of the scope of the Engineering Doctorate and to determine the level of internalisation of the research. Then the six remaining Submissions may be read in chronological order.

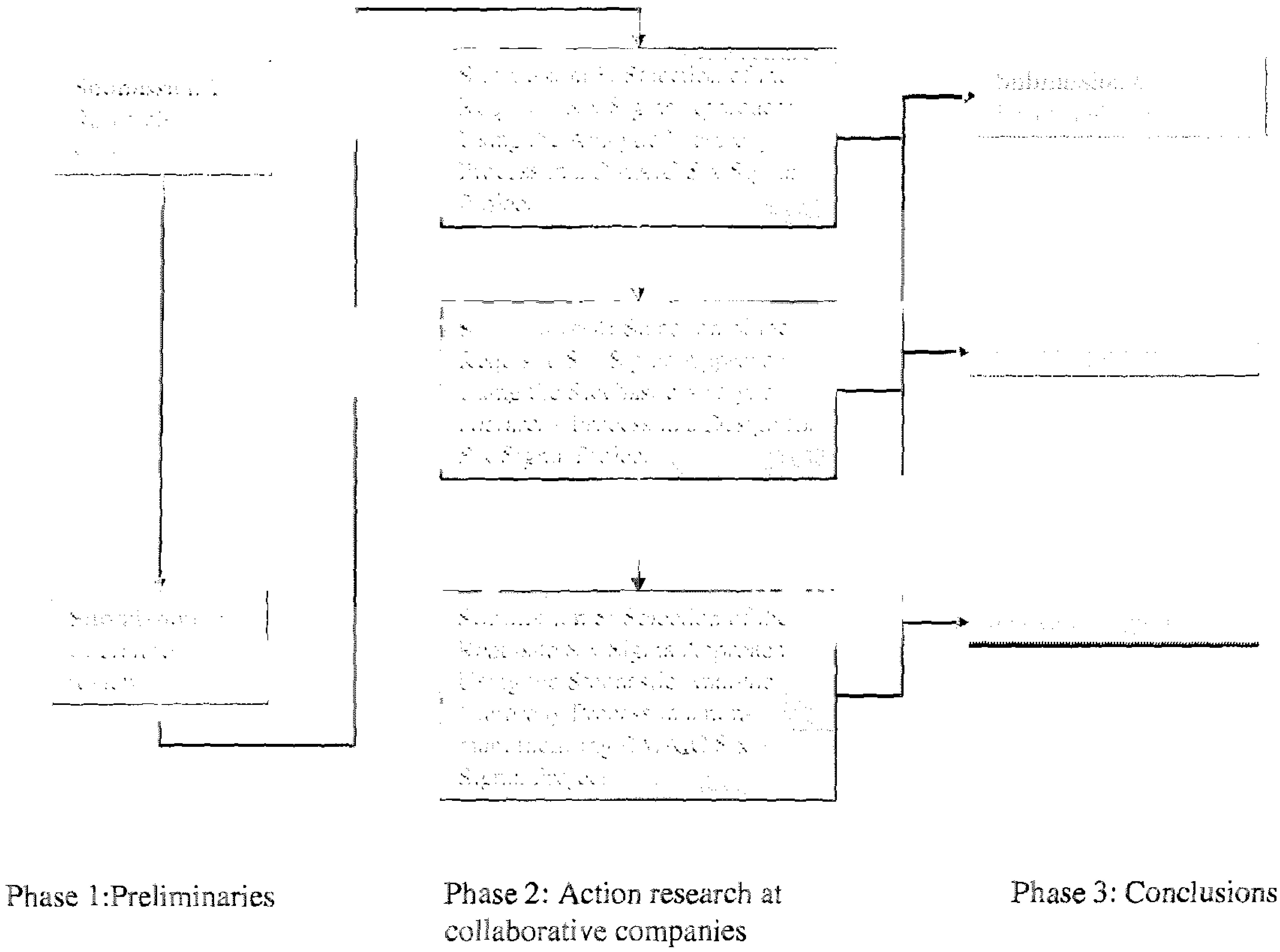

Figure 1: Order of reading the Submissions

1.3 Structure of the remainder of the Innovation report

This Innovation Report continues with a literature review which summarises the current body of knowledge in the field of the selection of the requisite Six Sigma approach. Chapter 3 describes the research methods employed during the research, which were discussed in more detail in Submission 1. In chapter 4 the action research spiral is presented which is formed by three action research cycles each represented by a Six Sigma project. The information presented in chapter 4 is a summary of Submissions 3, 4 and 5. After that, chapter 5 presents the findings generated from the research. Chapters 6 and 7 state the innovation and discuss the validity of the research respectively. Finally, chapter 8 concludes the research and offers directions for further research.

2 Literature Review

The main objective of the literature review was to understand the major issues and practical problems of Six Sigma which led to identification of the questions this research investigated and to consider matters other researchers have considered important in order to answer the research questions (Hart, 2001). Therefore, the literature review was carried out in four main domains: firstly, the evolution of the quality movement and the origins of Six Sigma; secondly, Six Sigma and DFSS philosophies, methodologies, tools and techniques; thirdly, redesign as opposed to continuous improvement in parallel areas of research; and finally a review of MCDA techniques was undertaken. The literature review was also extended to the research philosophies and methods in order to define a suitable research strategy for this work. In addition, a literature review of each industry where the three action research cycles were performed was also carried out.

As discussed in the introduction, scholars and consultants have tried to set criteria to select the requisite Six Sigma approach producing two fundamentally different perspectives which can be categorised as mono-criterion and multi-criteria approaches. These two approaches are discussed in this chapter. In addition, in an effort to identify potential mechanisms to test the research hypotheses and answer the research questions, the author reviewed how researchers have tried to solve the improve or redesign issue in parallel areas of investigation, presented in section 2.3. Due to the eminent multi dimensionality of the improve or redesign issue, the researcher selected a suitable

MCDA technique for the problem at hand, which is presented in the final section of the literature review.

2.1 Selection of the requisite Six Sigma approach; the mono-criterion case

The mono-criterion approach for the selection of the requisite approach between Six Sigma and DFSS is dominated by the sigma level as the only criterion affecting this selection. According to Harry and Schroeder (2000), Chowdhury (2001:2002) and Tennant (2001:2002), the only way to surpass the Five Sigma quality level is to redesign products, processes and services by means of DFSS. Harry and Schroeder (2000) stated that the average company performance is at a level of Three Sigma, as Table 1 shows.

Table 1: Sigma levels after Six Sigma implementation

Sigma level	Years implementing Six Sigma	Six Sigma approach
3 sigma (66,807 DPMO)	Average US and European companies before Six Sigma.	None
4 sigma (6,210 DPMO)	After first year of Six Sigma DMAIC implementation (Based on US and European companies). Average Japanese company.	DMAIC
4.7 sigma (687 DPMO)	Second year of Six Sigma DMAIC implementation for US and European companies. First year for Japanese companies.	DMAIC
5 sigma (233 DPMO)	Third year of Six Sigma DMAIC implementation (US and European, second for Japanese companies)	DMAIC and DFSS
6 sigma (3.4 DPMO)	A 0.1 sigma improvement per year it is expected after the "Five Sigma wall".	DFSS

Source: (Harry, 1994; Harry and Schroeder, 2000)

By adopting the Six Sigma philosophy, processes or products could be improved in one year to the Four Sigma level. During the second year it is expected to improve to 4.7

sigma. As it becomes closer to the Six Sigma level, it becomes more difficult to improve the sigma capability level. However, the first capability improvements, up to 4.7 sigma, can be performed relatively easily and without large investments (refer to Table 1). When the company has reached Five Sigma, the strategy is no longer defect removal, instead the Six Sigma strategy will require a radical approach, by employing Design for Six Sigma (DFSS) (Harry and Schroeder, 2000). Various authors have tended to support this contention (Chowdhury, 2001:2002; Tennant, 2001:2002; Harris, 2002). However, the author is of the opinion that it is highly arguable, because of a lack of data to support the claim and the absence of assumptions used to formulate it. Moreover, the sigma calculation can produce different results for the same process depending on the assumptions used to calculate it (i.e. rational sub-grouping or the 1.5 inflationary factor). It is not clear if Harry's and Schroeder's criterion is just applicable to the Motorola Company, where much of their work was carried out, or whether it can be applied to any industry. In addition, the role of variables such as risk, complexity, new technology, time, cost and customer demands, which may determine the redesign efforts, are not specified. Consequently, this research tested the hypothesis:

"*The sigma capability of products/processes has a positive association with the selection of redesign or improvement efforts within Six Sigma, however the Five Sigma level does not necessarily dictate the use of one approach over the other.*"

2.2 Selection of the requisite Six Sigma approach; the multi-criteria case

Several authors consider that many variables need to be taken into account for the selection of the requisite Six Sigma approach, consequently a general guideline can be provided (Pande *et al.,* 2000; Eckes, 2001; Truscott, 2003). Accordingly, a second hypothesis this research tested is that:

"Numerous process/product criteria are associated with the decision as to when to embark on redesign efforts"

According to Pande *et al.* (2000), there is no definite answer as to when redesign efforts should be used over Six Sigma continuous improvement and they propose to base this decision on two main criteria: (1) *if a major need, threat, or opportunity exists*: for instance, shifts in customers needs and requirements, demand for greater flexibility, new technologies, new or changed rules and regulations, competitors are changing, old assumptions are invalid, or the current process is in chaos; (2) *if risk is acceptable*: for example; longer lead-time for change is acceptable, resources and talent are available, leaders and the organisation as a whole will support the effort and/or the risk profile is acceptable. For Truscott (2003), the emphasis on, and the importance of, continuous improvement as opposed to redesign Six Sigma projects may change according to circumstances such as maturity of the sector, industry, organisation, technology product or service, with which one is concerned.

Like Pande *et al.* (2000) and Truscott (2003); Eckes (2001) proposes that process redesign is suitable when a new process will assist an organisation in achieving a strategic objective; when a current process is irreparably broken or when a process has already reached its full potential outcome. However, from the criteria proposed by Pande *et al.* (2000), Eckes (2001) and Truscott (2003), it is difficult to asses the importance of each individual criterion in the decision. In addition, their work does not specify how these criteria interact with each other in order to make a selection which will satisfy the overall business performance. Moreover, Pande *et al.* (2000), Eckes (2001) and Truscott (2003) do not introduce tools and techniques that could assist in this decision.

2.3 Selection of the requisite approach in parallel areas of research

Six Sigma is not the first quality philosophy that emphasises business improvement using continuous improvement and redesign efforts. The subject of the coexistence and selection of continuous improvement (Six Sigma) as an incremental improvement method, and redesign (DFSS) as a radical strategy is not a new subject of discussion (Weston, 2001) and has parallels in other fields. In the quality arena examples are Business Process Re-engineering (BPR) in opposition to *kaizen* and TQM (Imai, 1986; Hammer and Champy, 2001); continuous improvement and continuous innovation (Cole, 2001) or exploitation and exploration (March, 1995). These families of philosophies can be grouped in two main categories called redesign and improve. Accordingly, Six Sigma, TQM, *kaizen* and exploitation can be considered improvement philosophies, whereas redesign philosophies can include DFSS, BPR, exploration and continuous innovation. It must be recognised that the classifications proposed are not claimed to be "correct", and that inevitably some latitude will be required in extrapolating the lessons learned in these areas to that of Six Sigma and DFSS. Previous research in these parallel fields has attempted to determine (1) the level of commensurability[6] between them and (2) when an organisation should employ one or

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[6] The incommensurability thesis asserts that because paradigms differ in terms of the fundamental assumptions that they bring to organisation inquiry, practitioners must chose (1) whether more than one approach is used or not, (2) whether or nor they can be used in the same intervention and (3) whether or nor whole approaches are used or parts are taken out and combined (Mingers, 1997:2001; Mingers and Brocklesby, 1997; Mingers and Gill, 1997).

the other. Several authors affirm the two approaches can be linked through a pattern of incremental improvement interrupted by phases of dramatic innovation (Porter, 1985; Deming, 1986; Imai, 1986; Rohleder and Silver, 1997; Gonzalez, Martinez and Dale, 1999; Hill and Collins, 1999).

Imai (1986) states that whenever an innovation is achieved, it must be followed by a series of efforts to maintain and improve it. As new processes are defined, teams should employ continuous improvement models to maintain the gains which make incremental improvements and help reach the full potential of the redesigned process. Continuous improvement also provides problem solving and data collection to alert management as to when it is time to re-engineer and aids the realisation of full benefits by improving the infrastructure (Rohleder and Silver, 1997; Gonzalez *et al.,* 1999; Murray, Priesmeyer, Sharp, Jensen and Jensen, 2000).

In the exploration and exploitation field, March (1995) states that companies specialising in either exploration or exploitation will under-perform. Exploration and exploitation are linked in an enduring symbiosis, each requires the other in order to contribute effectively to an organisation's survival and prosperity. However organisations tend to persistently fail to maintain an effective balance between the two.

In the Six Sigma field, Design for Six Sigma is considered necessary to set new performance standards highly linked to customer needs in order to improve process effectiveness and efficiency. If just Six Sigma is introduced, systems are likely to deteriorate once they have been established (Bañuelas and Antony, 2004a). Using Six Sigma DMAIC continuous improvement the redesigned processes are maintained and high standards are set. Figure 2 provides a visual image of this phenomenon. DFSS provides an opportunity for an organisation to leap ahead (B) of its competitors by redesigning processes or services; Six Sigma, on the other hand, is characterised by incremental improvements (A) and typically uses DMAIC projects to accomplish local changes.

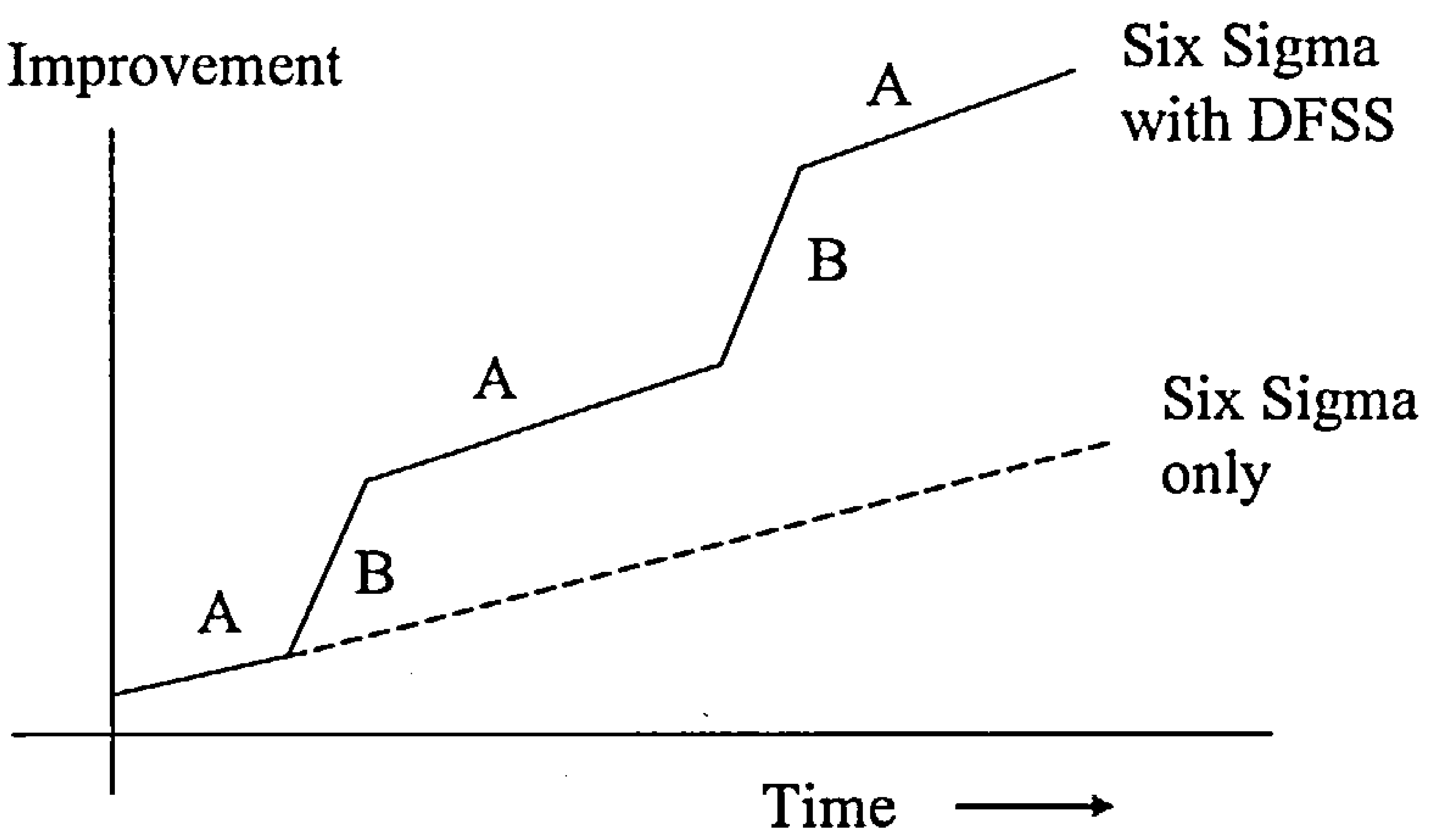

Figure 2: Leapfrogging

The literature does not report cases when for a single intervention (i.e. project), elements of both approaches are taken out and combined. According to Pande *et al.* (2000) DMAIC Six Sigma is modified to DMADC (Define, Measure, Analyse, Design, Control) for Design for Six Sigma efforts. For Pande *et al.* (2000), Six Sigma and DFSS methodologies (i.e. DMAIC and DMADC) are only differentiated during the fourth step. The improve phase of DMAIC methodology focuses on analysing, developing and implementing root cause-focused solutions; whereas the design phase of the DMADC design/redesign concentrates in the effective development of new work processes. However, factors influencing whether to select one approach over the other have not been well defined, either in the Six Sigma field or parallel areas of research (BPR, TQM, *kaizen*, exploitation, exploration, continuous innovation). In addition, the degree of commensurability between Six Sigma and DFSS regarding whether or not whole approaches are used or parts are taken out and combined in both approaches has not been fully researched. Thus, this raised the fourth hypothesis this research tested, "*Six Sigma improvement efforts have traces of redesign activities and vice versa*".

Researchers, such as Finster (2001), conclude that research should not only be focused on determining the degree of commensurability of both extremes of philosophies, but also on understanding the conditions where redesign efforts and/or continuous improvement are appropriate strategies and under what circumstances one strategy has priority over the other (Cole, 2001; Finster, 2001; Melton, 2001; Weston, 2001). Similarly, Al-Mashari, Irani and Zairi (2001) state that techniques and tools that help to link different scales of change into one integrated improvement strategy are needed. Therefore, more research is needed to determine when and how a specific approach can be implemented (Al-Mashari *et al.*, 2001).

As can be seen from Table 2, several authors have raised the issue of selecting the requisite approach and the issue is not limited to the Six Sigma, quality or business fields. Scholars and consultants have tried to find a solution considering different criteria. Lee, Lee and Lee (2003) and Garcia, Cantatone and Levine (2003), for example, studied the selection between exploration and exploitation using simulation and systems dynamic modelling respectively[7]. However the use of tools and techniques is still limited in parallel areas of research. In the Six Sigma field the literature does not report the usage of any specific tools. Nevertheless, it is well accepted today that the

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[7] The research of Lee *et al.* (2003) and Garcia *et al.* (2003) was published in the same year this author published "*Going from Six Sigma to Design for Sigma: An exploratory study using AHP*". However, their research focuses on the exploitation/exploration issue and using simulation; where this research focus is on the Six Sigma/redesign issue using MCDA techniques.

decision-making process extends beyond the optimisation of a single criterion to a set of feasible solutions with the aid of tools and techniques.

Table 2: Improve versus redesign

To select between...	***authors such as...***	***suggest to base this selection on criteria such as...***	***using as an aid the technique/method/ tool***
Six Sigma and DFSS	Harry and Schroeder, 2000; Chowdhury, 2001: 2002; Tennant, 2001:2002; Harris, 2002.	sigma level	sigma capability index
Six Sigma and DFSS	Stamatis, 2002.	variability and sensitivity	not specified
Six Sigma and DFSS	Pande *et al.*, 2000.	customers needs, flexibility, new technologies, changed rules and regulations, competitors are changing, old assumptions are invalid, current process is in chaos risk, lead time, resources availability	not specified
Six Sigma and DFSS	Eckes, 2001.	entitlement, strategic objective or process is irreparable/broken	not specified
Six Sigma and DFSS	Truscott, 2003.	maturity of the sector, industry, organisation, technology, product or service	not specified
kaizen and innovation	Imai, 1986.	not specified	not specified
exploitation and exploration	Lee *et al.*, 2003.	complexity, cost, demand, power users.	simulation
exploitation and exploration	Garcia *et al.*, 2003	availability of resources, exogenous competitive forces, aging of knowledge and adaptive capacity	systems dynamic modelling
continuous improvement and continuous innovation	Cole, 2001; Finster, 2001; Melton, 2001; Weston, 2001	not specified	not specified

2.4 Need for research

Six Sigma has made a significant impact on industry (Linderman *et al.,* 2003; Antony, 2004), as evidenced by the success of those companies that have embraced it and the many other organisations that are expressing interest. However the theory of Six Sigma is lacking in fundamental research other than "best practice" studies and scholars have tended to lag behind in their understanding. It is the role of the academic fraternity to provide well-grounded theories to explain Six Sigma and bridge the gap between the theory and practice (Antony, 2004; Mitra, 2004). This research investigated the selection of the Six Sigma approach in order to make it a more robust philosophy by rigorously intervening in it.

The author argues that it is pointless to try to improve a process by means of Six Sigma DMAIC or any other philosophy based on a continuous improvement approach where the fundamental design of the process is wrong. Therefore it is important to identify conditions where the effectiveness of processes can be improved by employing redesign efforts or where the efficiency of a process needs to be improved through Six Sigma. This will also facilitate companies in making the appropriate resource allocation and to maintain an effective balance between the two approaches. Consequently efforts concentrated on increasing customer satisfaction and business performance should be correctly addressed.

Reductionist recommendations based on mono-criterion could lead to the selection of improvement areas with the use of an erroneous approach. On the other hand, when very general variables are set (e.g. those of Pande *et al.,* 2000; Eckes 2001; and

Truscott, 2003), organisations could make decisions by satisfying one variable/factor at a time and focusing upon options that satisfy the most important criterion and eliminate the remaining options. Consequently, this may leave the whole organisation more disturbed than it was before (Saaty, 1988). Decisions need to be made in a holistic way, where the essential properties of the system taken as a whole derive from the interaction of their parts, not their actions taken separately, and in terms of their structure, functions and objectives (Ackoff, 1981; Saaty, 1988).

There are many potential criteria involved when considering redesign efforts instead of continuous improvement; from the scope and capability of the process, to the potential financial benefits, to the urgency of major performance gains (Pande *et al.,* 2000). These criteria can also vary depending on the prevailing conditions and the interactions between them. Consequently, which approach to undertake is not a mono-criteria decision but a multi-criteria one where most of the information relevant to the problem is complex and conflicting in nature (Guitouni and Martel, 1998). As a result, *"The provision of a consistent methodology and techniques, for representing and analysing the decision system for Six Sigma methodology selection has a positive association with an effective Six Sigma approach assortment"* represented a hypothesis to test during this research.

2.5 Selection of the requisite Six Sigma approach using MCDA

Multi-Criteria Decision Analysis (MCDA) techniques provide a focus to sharpen discussion and balance and challenge intuition, however, they do not replace judgment or experience (Lindley, 1971). In addition the process of MCDA helps to justify, explain, document and consider decisions (Lindley, 1971). MCDA techniques are formalised on the basis of a model of preferences, well shaped in the decision-maker's mind and rationally structured from a set of attributes. The MCDA approach implicitly introduces a set of preferences or criteria, each representing a particular dimension of the problem to be taken into account (Bana e Costa, Steward and Vansnick, 1997).

Most of the research in the MCDA field has been devoted to the development of different techniques for dealing with multiple conflicting criteria producing an enormous number of techniques. The variety and increasing number of MCDA techniques has produced the need to compare and integrate different methods (Denpotin, Mascarola and Spronk, 1983; Roy and Vanderpooten, 1997; Zanakis, Solomon, Whshart and Dublish, 1998; Oslo, Meichtov and Moskovich, 1999; Raju and Pillai, 1999; Mohmoud and Garcia, 2000; Bell, Hobbs, Elliott, Ellis and Robison, 2001; Zopoundis and Doumpos, 2002). Although the great number of these techniques can be considered a weakness (Al-Shemmeri, Al-Kloub and Pearman, 1997), it is important to recognise the great diversity of scientific origins of the researchers and practitioners who developed them for a great variety of problems, thus encouraging their growth (Bane e Costa *et al.*, 1997). For Zanakis *et al.* (1998) another major criticism of MCDA techniques is that they yield different results when different techniques are applied to the same problem, under the same assumptions and by a single decision-maker. The study of different MCDA techniques reveals that every model has its assumptions and axioms in which are the basis of its theoretical development. These assumptions and axioms are the frontiers beyond which technique cannot be used. As a result, individual methods and techniques have their strengths and weaknesses with regards to the complexity of the organisational context and the stage of the intervention (i.e. through analysis and assessment to implementation and action [Rosenhead and Mingers, (2001); Mingers, 1997:2001]).

For Guitouni and Martel (1998), in practice, many decision-makers and researchers are incapable of justifying clearly their choice of one MCDA technique rather than another one. In general, this choice is motivated by a sort of familiarity and affinity with a specific technique. However, not all techniques are applicable to a specific decision situation generating similar solutions. This includes the possibility of sub-optimal results, discarding of useful models due to improper application and it may discourage potential users from applying MCDA (Al-Shemmeri *et al.*, 1997). This justifies highlighting the issue of the selection of the MCDA technique. The researcher, by taking into consideration the problem content, the intervention system and intellectual resource systems as suggested by Mingers (2001) selected the Analytic Hierarchy Process (AHP) as a suitable MCDA for the selection of the requisite Six Sigma approach. For more information about why AHP was selected, refer to Submission 1.

AHP, first developed by Saaty in 1971, has been widely applied to decision problems in areas such as economics, operations and production, logistics, finance, accounting and forecasting. Its widespread use is evidence of its popularity among decision-makers (Goodwin and Wright, 1998). It involves structuring a problem from the main goal to the criteria, to the different alternatives, forming a hierarchical structure with several levels. AHP then develops priorities among each criterion within each level (Bodin and Gass, 2003). It is based on both predetermined measurements and the decision-maker's judgement throughout the system, which are calculated using pairwise comparisons. Thus, it can cope with criteria that have not been effectively quantified using exact measurements. Decision-makers evaluate each criterion against each other within each level of the hierarchy; each level is related to the levels above and below it, and the entire system is connected together mathematically including the options that can solve the problem. For an illustrative example of how AHP can be used for the selection of the requisite Six Sigma approach, please refer to Submission 6. AHP is also discussed in Submissions 2, 3 and 4.

AHP is not without its critics. Goodwin and Wright (1998) describe six criticisms of AHP including, (1) problems with conversion from verbal to numeric scales, (2) inconsistencies imposed by the 1 to 9 scale, (3) degree to which responses of questions are meaningful, (4) new alternatives can reverse the rank of existing alternatives, (5) the number of comparisons may be large and (6) the axioms of the method. All these issues have been extensively debated and researched by the operational research community for the last 20 years, proving its validity. For example, alternative methods and axioms have been integrated to avoid rank reversals using methods such as the multiplicative method (Stam and Duarte, 2003) and the logarithmic least square method (Fichtner, 1986; Kwiesielewicz, 1996). Further research on the numerical scale and the potential inconsistencies caused by the scale can be found in Saaty (1986a:1986b:1987:1988).

Before presenting the application of AHP for the selection of the requisite Six Sigma approach, the next chapter presents a suitable research methodology for the Engineering Doctorate portfolio.

3 Research Methodology

3.1 The research strategy rationale

Research is an intricate and rigorous process that should be carried out in a structured manner (Mentzer and Flit, 1997). It is a series of logically ordered choices which run from the formulation of the problem and the research strategy, to the analysis of results and their interpretation (Mentzer and Flit, 1997). The research strategy aims to establish the overall configuration of the research. This includes the type of evidence researched, its source and how it will be interpreted in order to test the hypotheses formulated according to the research questions (Easterby-Smith, Thorpe and Lowe, 1999). There are a variety of research strategies which are most valid within a certain domain of ideal use. The researcher constrained this domain based on the type of research questions and the researcher's intervention over the actual phenomena under study, as suggested in the literature (Yin 1994; Hussey and Hussey, 1997; Easterby-Smith *et al.*, 1999; Hart, 2001). Traditional positivist research methods assume that the researcher should be independent from the phenomena being studied if there is to be any validity in the results. However, this cannot be guaranteed during this research. Conversely, the phenomenological philosophy claims that researcher's independence is harder to sustain and the researcher's involvement needs to be considered when interpreting the research results. In addition this research is seeking to explain and enhance, rather than only describe. Most of the positivist methods only describe the situation as it is, without taking into account the social and personal factors that makes it so (McNiff, 1988).

Case study research, a phenomenological method, can be used to accomplish various aims such as to provide description, test theory or generate theory by taking into account the social factors that make up the reality (Eisenhardt, 1989). However, the case study's characteristic of non-intervention, in which the researcher seeks to study organisational phenomena but not change it (Yin, 1994), makes it incapable of dealing with the investigation of the applicability of MCDA techniques for the selection of the requisite Six Sigma approach. The researcher argues that it is difficult to study the impact of a MCDA technique for this selection, without intervening and modifying the current MCDA techniques in some way to adapt them to the Six Sigma field and specific company environment. On the other hand, action research is one of the research methods that can be reasonably employed to study the effect of specific modifications in decision systems, such as that concerning the research objectives (Baskerville and Wood-Harper, 1996; Avison, Baskerville and Myers, 2001). This guided the researcher to adopt action research as a method of inquiry.

Hult and Lennung (1980) define action research as:

"a research strategy which simultaneously assists in practical problem solving and expands scientific knowledge, as well as enhances the competences of the respective actors, being performed collaboratively in an immediate situation using data feedback in a cyclical process aiming at an increased understanding of a given social situation, primarily applicable for the understanding of change processes in social systems and undertaken within a mutually acceptable ethical framework"

From the above definition it can be noticed that action research is essentially practical and applied (Coghlan and Brannick, 2001). Action research also challenges the position of the researcher as a privileged observer, analyst and critic. Thus, to prevent the researcher from taking the role of disinterested observer, he took the role of Black Belt/researcher during each of the three cycles of the action research spiral obliging him to clarify and represent his own ethics, values and framework of ideas so that they can serve as guidelines against which to assess jointly planned actions (Susman and Evered, 1978).

The testing of the applicability of MCDA techniques implicitly involved their introduction and thus, it was necessarily interventionist. In addition without intervening in the collaborative companies' Six Sigma practice it was impossible to inject the new technique into specific environments. Action research is one of the few valid research approaches that can be legitimately employed to study the effects of specific alterations in systems development methodologies in organisations (Baskerville and Pries-Hege, 1999). It not only aims at the generation and application of knowledge, but also at the developing of the researcher's competencies (Susman and Evered, 1978; Baskerville, 1999).

Action research is an "organic" process, involving a self-reflective spiral or cycle of planning, acting, observing, reflecting and re-planning (McNiff, 1988). Later cycles, consist of iteratively refining methods, data and interpretation in the light of the understanding developed in the earlier cycles. It is thus an emergent process, which takes shape as understanding increases. This process represents the fundamental structure of this research, where each core action research cycle of planning, acting, observing, reflecting and re-planning, is linked to the other, forming a spiral.

Action research is a holistic research strategy, rather than a single method for collecting and analysing data. Thus, it allowed the incorporation of several different research tools, techniques and methods. The researcher made use of a range of tools including keeping a research journal, participant observation recordings, unstructured interviews and gathering documents that the companies routinely produce.

3.1.1 Problems with action research

Action research is not without its problems. Sometimes action research is perceived to be relevant but not rigorous. Rigour in action research refers to how data is generated, gathered, explored and evaluated, how events are questioned and interpreted through multiple action research cycles (Coghlan and Brannick, 2001). Lack of rigour is not a problem attached to action research strategy alone, but potentially may affect any research strategy and method. According to Avison *et al.* (2001) this problem is emphasised during action research because of its "double challenge" that is, of combining both action and research. To minimise the double-challenge issue, the researcher and the collaborative companies put in place some mechanisms for controlling the research project, as suggested by Avison *et al.* (2001). These mechanisms included the initialisation of research projects, the determination of authority and the degree of formalisation. Accordingly, during the three action research cycles the initiation of research projects was considered as research driven. That is; the researcher was in possession of a general theoretical approach to address problematic situations and explored settings characterised by such problems (Westbrook, 1995).

Thus, the collaborative companies and the projects carried out corresponded to the theoretical frames of this research.

The determination of authority for action research projects was shared between the researcher and the collaborative company. The incorporation of AHP and SAHP to select the requisite Six Sigma approach is an example of the researcher's influence on the three projects. This authority presented a relatively high degree of formalisation. The researcher's role and responsibilities were recognised in each project (i.e. researcher/Black Belt) and the company and the researcher's objectives were established prior to the start of each project.

These controls contributed to make action research more feasible and rigorous through the course of this research. Rigour was also incorporated by matching the research strategy to the problem in order to produce valid scientific explanations, and the use of multiple methods to produce valid research conclusions (Baskerville and Wood-Harper, 1996; Coughlan and Coghlan, 2002). The issue of validity in this research is discussed in chapter 7.

3.2 Selection of the collaborative companies

The concept of population is crucial, because the population defines the entities from which the research sample is to be drawn. In addition, company selection controls variation and provides the limits for generalising the research findings (Eisenhardt, 1989). In contrast with positivistic research in which the researcher can randomly select the sample from the population and statistically select the sample size needed to obtain statistical conclusions about the population, action research employs theoretical sampling. In theoretical sampling core action research projects may be chosen to replicate previous cases, extend theory, to fill theoretical categories and/or provide examples of polar cases (Eisenhardt, 1989; Zuber-Skerrit and Perry, 2002). Zuber-Skerrit and Perry (2002) suggest that a doctorate degree core action research project may probably need to progress through at least two or three major cycles to make a distinctive innovation in the application of knowledge. Given the time and resource constraints the researcher carried out three action research cycles. Each cycle represents a Six Sigma project in which the decision improve or redesign is analysed using Multi-Criteria Decision Analysis. These projects were chosen based on extreme situations in order to be more likely to replicate and extrapolate the emerging innovation. Accordingly, the three polar cases are: a DMAIC Six Sigma project; a DFSS project and; a DMAIC Six Sigma project in a non-manufacturing process. These projects were carried out in collaboration with 3M, GDA and Land Rover respectively, where the researcher obtained a position as privileged participant observer playing the role of Green Belt or Black Belt and researcher. The selection of the specific companies was also based on theoretical sampling procedure, based on extreme cases. Therefore, the three candidate collaborative companies are classified in three different industrial sectors (i.e. abrasives, white goods and automotive).This research is focused on large organisations with operations in the UK, thus the size and geographical constrains will limit the research and control these environmental variations.

3.3 Scope of the research

The area of application of this research is focused upon organisations which are currently implementing Six Sigma and Design for Six Sigma. It is also focused on the selection of the requisite Six Sigma approach (i.e. Six Sigma versus DFSS) at a project level and is limited to the study of three organisations with operation in the UK (i.e. 3M, GDA and Land Rover). Nevertheless, the author is of the opinion that the SAHP technique developed during this research is a generic technique which has the potential to be applied in a wide range of situations and problems.

4 The Action Research Spiral

Each of the following action research projects represents a cycle in the action research spiral. The aim of each cycle is to answer the research questions, to test the hypotheses, to generate reflection, action and ultimately demonstrate innovation in the application of knowledge. In each of the cycles, the researcher assumed the role of a Six Sigma practitioner and researcher on a full time basis within the collaborative companies for the duration of the projects.

The action research spiral was structured following the approach suggested in the action research literature (Coghlan and Brannink, 2001; Coughlan and Coghlan, 2002). Accordingly, the context of the research is first described at the beginning of each cycle, followed by the Six Sigma or DFSS projects. Each of the Six Sigma projects was carried out by the researcher and the collaborative companies. During the course of the projects, the researcher was able to observe and facilitate the companies' efforts in implementing Six Sigma. In addition, the researcher was able to identify the different criteria that either proved or disproved the research hypotheses. Reflection on the projects in the light of the experience, with the use of supporting evidence to reinforce or undermine the research hypotheses, complemented the action research structure.

4.1 Selection of the requisite Six Sigma approach; Using the Analytic Hierarchy Process in a Six Sigma project

4.1.1 Background to the case

The first action research project was carried out in collaboration with 3M Atherstone. 3M manufactures and markets about 60,000 different products, across 40 product divisions world-wide. At the time when this action research took place (2002) the company was going through a restructuring process. As part of this process, a Six Sigma initiative was launched to impact three key strategic areas: growth acceleration, cost reduction and cash improvement. In this context, typical Six Sigma growth projects were focused on product quality, response cycle times and/or commercialisation cycle times. Cost reduction projects were characterised by productivity improvements, cost of poor quality reductions and capacity and yield improvements (without investment). Projects with emphasis on better utilisation of cash flow were focus on attempting to reduce receivable turn/cycle and increase inventory turn/cycle payables.

In addition to the DMAIC methodology to improve current processes, 3M utilises Design, Technology and Marketing for Six Sigma (DTMFSS). While Six Sigma is seen as a philosophy that accelerates performance improvement through significant financial results in 4 to 8 months ensuring that the company meets its strategic goals, DTMFSS is seen as a program focused on growth and cultural change. DTMFSS projects are aimed at value creation but not always through cost savings, as is the case with projects following the DMAIC approach. DTMFSS is also seen as a way to build emerging businesses and create viable options.

The project presented here focuses on reducing the costs associated with manufacturing waste in one of the production lines. From the research point of view, the project served to study how DMAIC became a priority over DFSS and to test the applicability of Analytic Hierarchy Process (AHP). Data was collected primarily through actions taken during the course of the DMAIC project, observations, archival resources, training materials, meetings and informal interviews.

4.1.2 Story and outcomes

The Six Sigma DMAIC approach was used to reduce waste in one of the manufacturing lines. As with most of the Six Sigma DMAIC projects at the company, the re-winder project works within the framework of the business' existing processes. This project was developed from today's perspective and constrained by assumptions made during the development and design of the re-winder machine. Therefore it was initially assumed that this design was essentially correct and the most economical; delivery partner needs were satisfied with the design and it was configured to satisfy the functional requirements of the coating line. The manufacturing line under study is a continuous process with equipment designed to allow non-stop production during roll changes of web materials and the unloading of finished rolls of production (Shepherd, 1995). It is not fully automated and operators are necessary to unload finished rolls and load new rolls of web material coming from the previous production process. The re-winder machine at the end of the line allows the line to run continuously (refer to Figure 3). It winds up the "web" of film in controlled tension producing rolls of sandpaper. However it frequently fails to change from one roll to the other. A failed chop-over results in a loss of web tension and therefore a line stop.

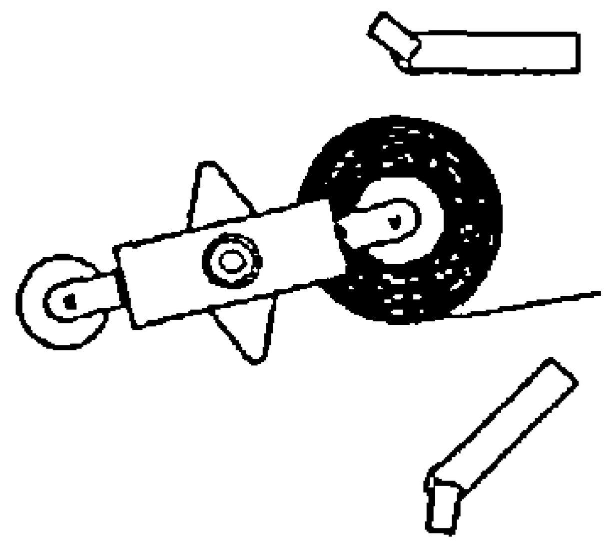
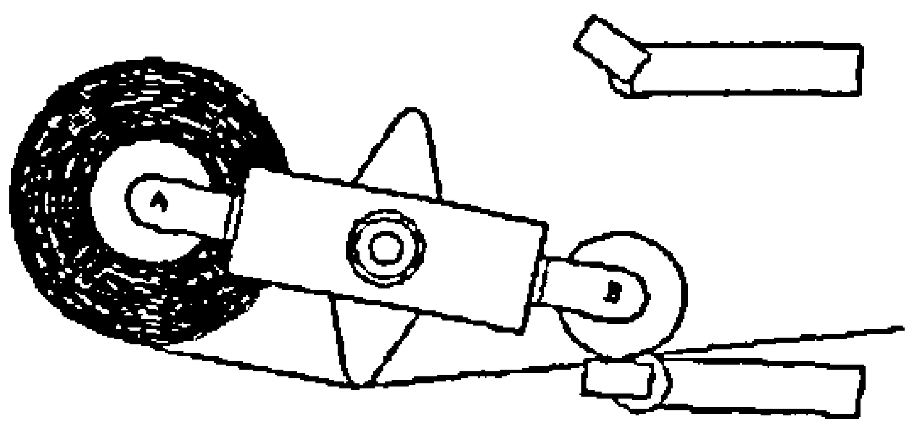
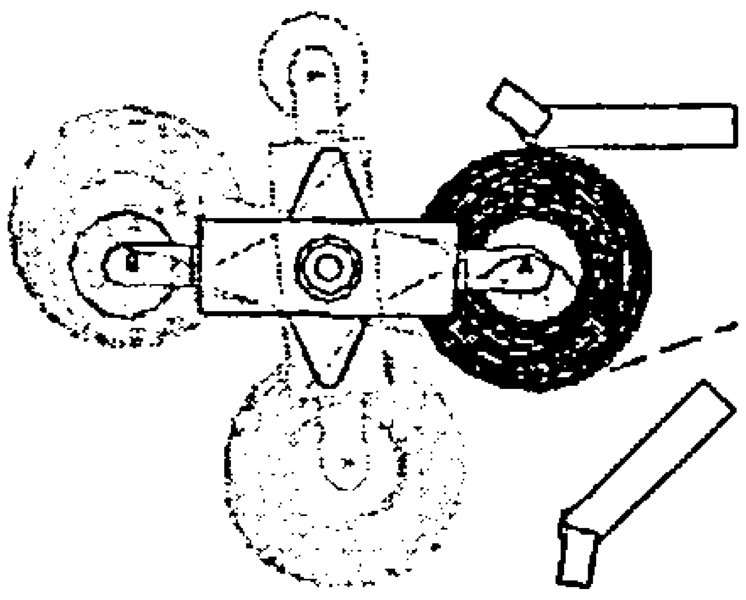
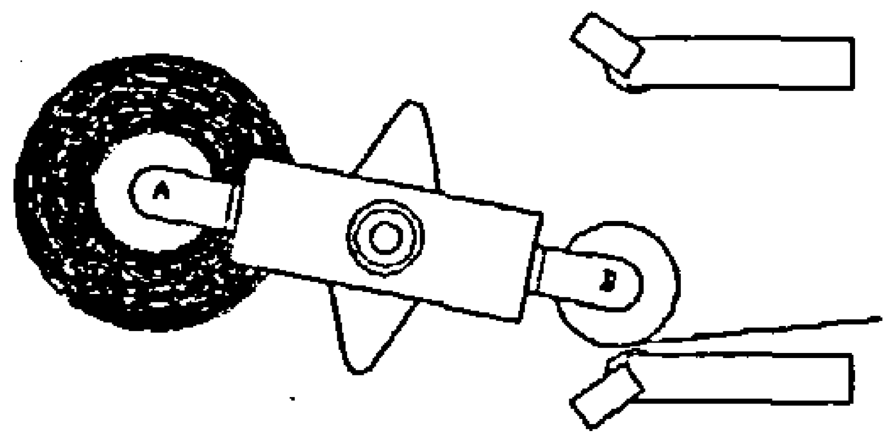
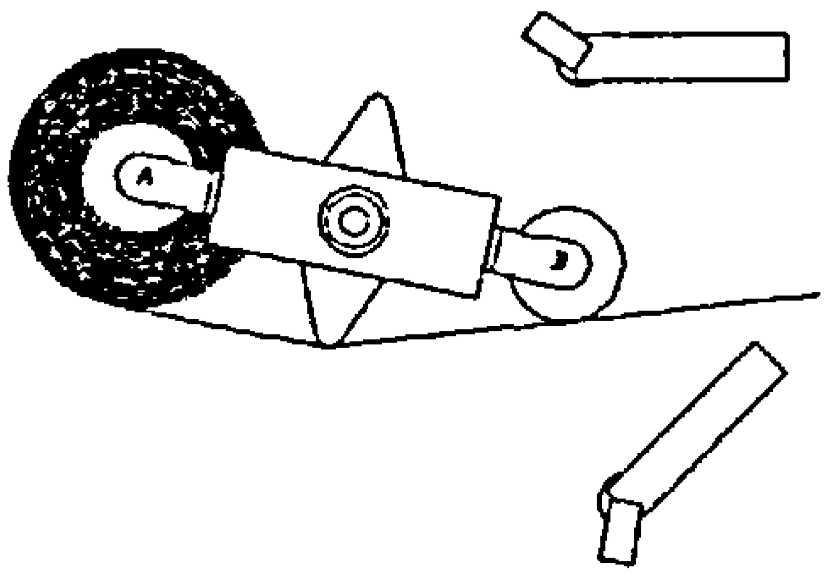
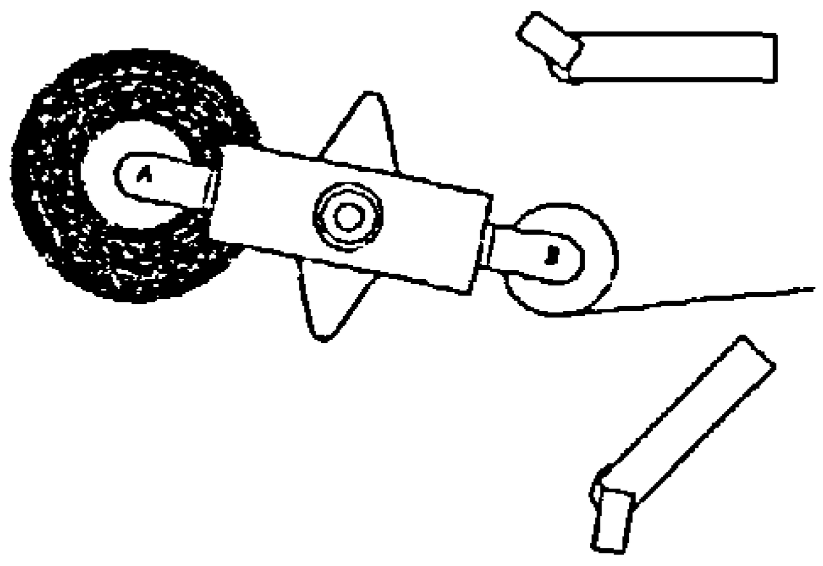
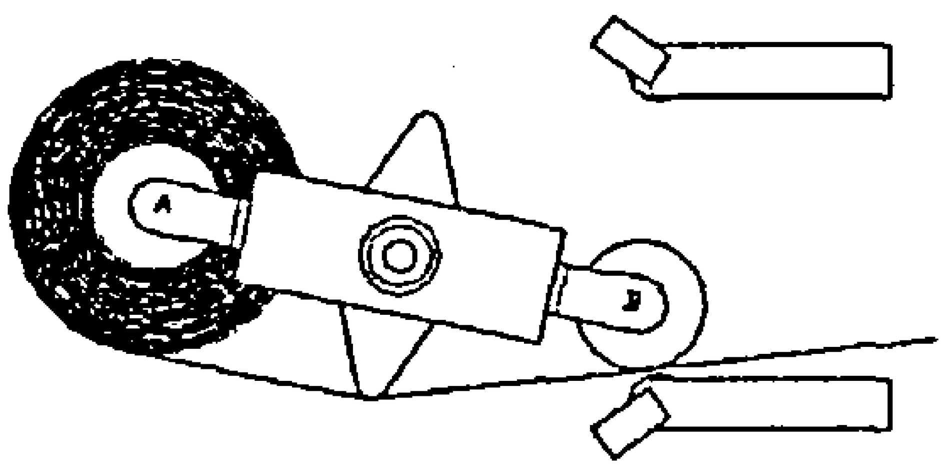
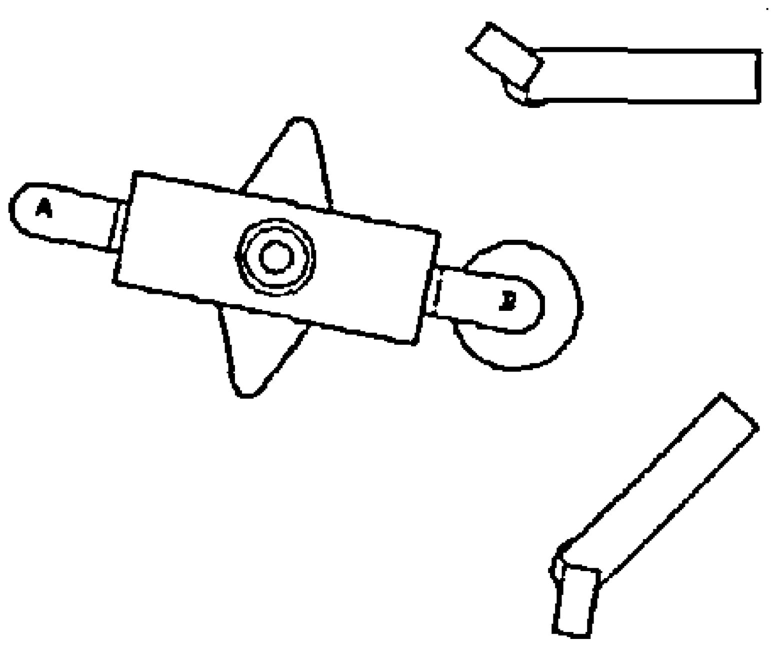
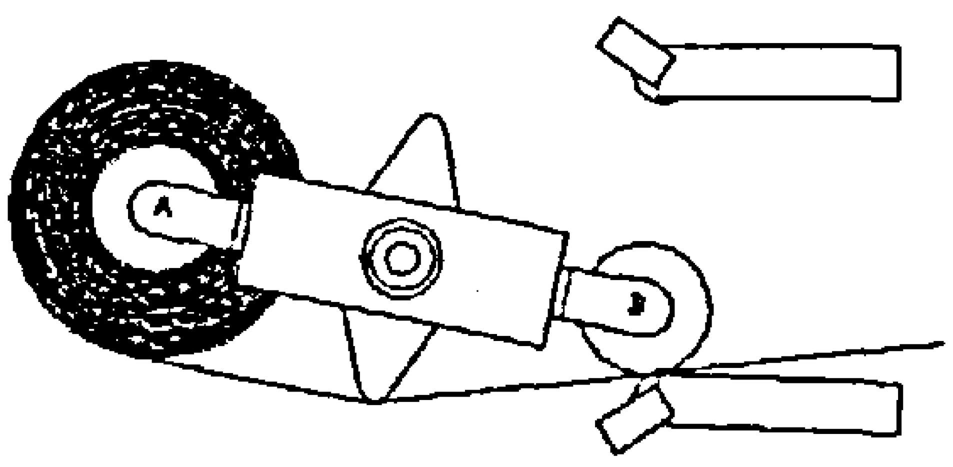
Issued by: R. Bañuelas	Process: Re-winder
 1) The sandpaper is continuously produced and wound into rolls, allowing the PDC line to run continuously.	 6) Cutting takes place bonding the cut sandpaper into a fresh roll.
 2) The re-winder machine rotates to change from one spindle to the other	 7) Pack arm remains in the above position to ensure that the sandpapers bounds to the core.
 3) The re-winder machine is stopped to the position in which the bumping and cutting will be performed	 8) Knife (pack arm) returns to no-cutting position
 4) Knife (pack arm) is moved to cutting position	 9) Roll and core are removed to be transported to the warehouse. A fresh core is placed on the re-winder and double sided adhesive tape is applied to it, to ensure that the sandpaper binds to the fresh core
 5) Bump occurs to pressure sandpaper and to facilitate cutting	

Figure 3: Re-winder

The purpose of this Six Sigma project was to identify, quantify and eliminate the source of variation that results in failure to change from one spindle or roll to another by the re-winder machine. The details of the project are shown "An application of Six Sigma to reduce waste" in Appendix V of Submission 6.

The first step of the DMAIC methodology involved identifying the project's Critical-To-Quality/cost characteristics, approving the project charter and estimating financial benefits. Thus, a project charter was carried out to state the opportunity that exists in financial terms. It summarised the define stage from the business critical "Y[8]" and its linkage to the project "Y". It also cascaded the project description, goals and potential financial benefits. Having defined the project, the team moved to the measure phase.

The measure phase had the purpose of defining the current process and establishing metrics that described the project "Y" performance in order to narrow the problem to its major factors or "vital few" root causes (Pande *et al.*, 2000). To this end, the process was represented graphically using standard operational procedures. Using rational sub-grouping the process baseline was calculated. The initial process capability was 1.29 sigma long-term (88.5% yield). A data collection plan was formulated in which potential "X's" were recorded during a relative long period of time. The data collected from the measure phase served as an input for the analysis phase.

The purpose of the analyse phase was to start learning about data in order to generate, segment, prioritise, and verify the possible root causes and their relationship to the

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[8] The basic equation of Six Sigma, $Y = f(x)$, defines the relationship between a dependent variable (Y) or outcomes of a process and independent variables (the x's) or possible causes of problems associated with the process (Brue and Launsby, 2003).

"Y's" or outputs (Waddick, 2001). Different tools and techniques were employed to relate the "Y" to the "X's" in order to reduce the number of factors and select the "vital few" for further analysis. Multi-vari studies helped associate the "Y" and the key "X's", identify noise variables and reduce the "X's" for the improvement phase. In addition, they helped to obtain an in-depth understanding of the process during its natural variation. In fact, during the multi-vari study some special causes[9] were eliminated and countermeasures were put in place as the process was understood.

The improvement phase had the objective of considering the causes found in the analysis phase, and also selecting and targeting solutions to eliminate such causes in order to achieve the improvement goals set during the define phase. Using a multi-vari study technique, the Six Sigma team identified the source of variation and its impact on the re-winder. The team developed an improved system to reduce the variability of the main critical-to-quality characteristic. This system allows operators to know the optimal value of the critical-to-quality characteristic and to set the re-winder to that optimal setting. This improved method enabled process improvement to the 2.06 sigma level. However, through the knowledge obtained from the Define, Measure, Analyse and Improve phases the team suggested a redesigned alternative, which would involve the redesign of the turret indexing system of the re-winder, to potentially greatly reduce the variability. In addition, the current technology of the re-winder was becoming obsolete, increasing costs of spare parts and the lead-time to supply them. The ageing of the components also meant the likelihood of a breakdown and its inaccuracy greatly increased. From the maintenance department's perspective, all this comes to a point

[9] Special causes are assignable to unusual or unexpected changes or events, which may cause defects to be produced (e.g. machinery poorly adjusted, untrained operators, etc.). In contrast the common causes are assignable to the system: poor design, inadequate materials, etc. (Escalante, 2004).

where redesigning the re-winder is a more feasible solution than trying to improve it. However, there are also other factors to take into account such as the risk of the project, the potential savings, the cost involved, the potential system capability, the potential to automate the operation and eliminate one operator and the cash avoidance.

The author, with the support of the Six Sigma team at the company, decided to employ Analytic Hierarchy Process (AHP) to determine the feasibility of the use of the redesign alternative over the improvement option. Figure 4 depicts the AHP process in flow chart format. For more information on the AHP the reader is referred to Saaty, 1988; Saaty 1996; Bañuelas and Antony, 2003; Submissions 1, 2 and 3.

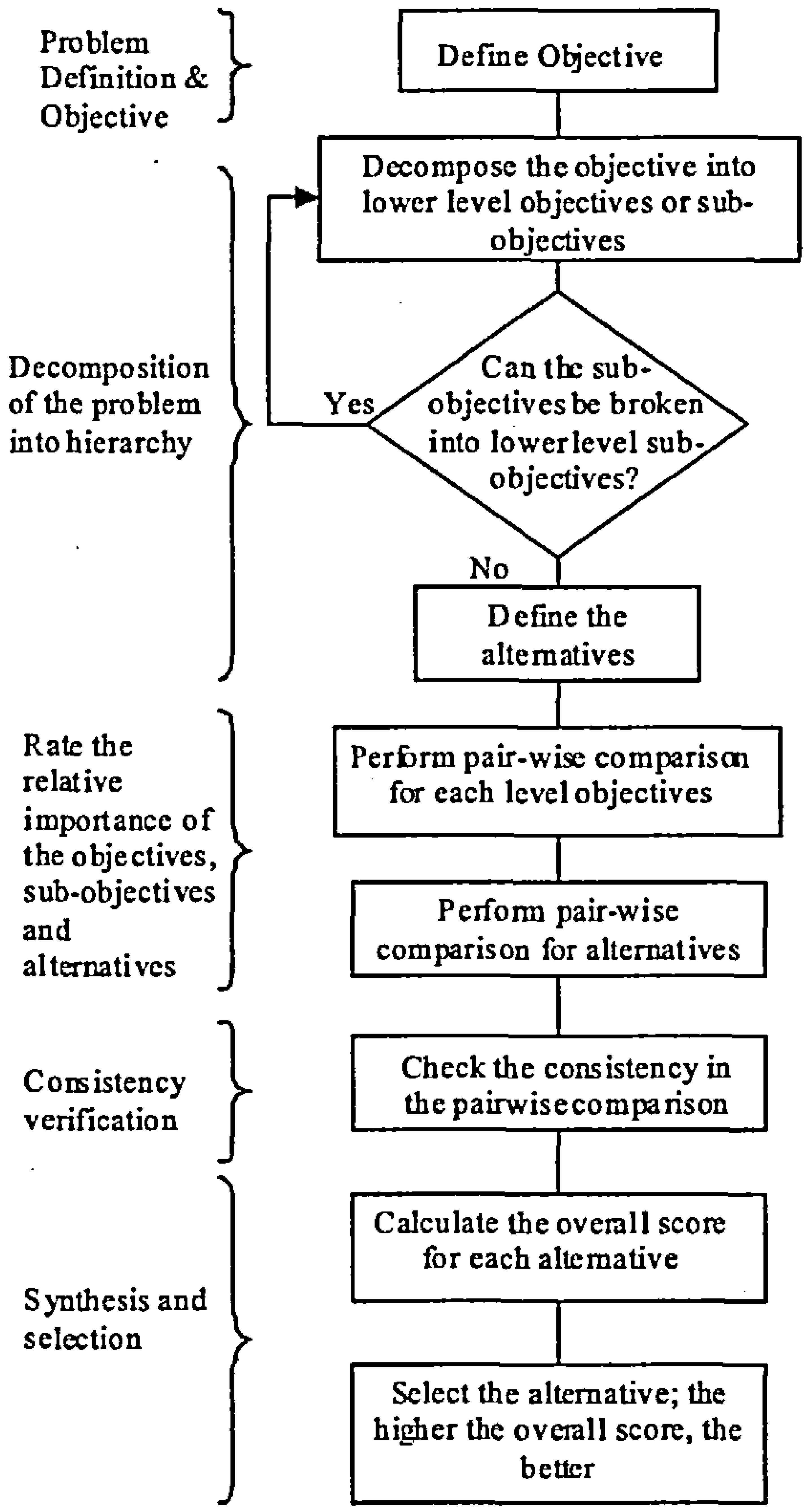


Figure 4: AHP flow chart

The decision to redesign the process or improve it was decomposed into the decision elements shown in Figure 5. That is, during a brainstorming session the Six Sigma team identified financial benefits, process capability, cash avoidance and risk as the main criteria affecting this selection. However, not all criteria are equally important in this decision. Therefore, pairwise comparisons were used to determine their relative importance. In this case, comparisons were performed during brainstorming sessions where the members of the Six Sigma team participated and evaluated each alternative on a criterion by criterion basis to produce an overall ranking using the standard AHP procedure, shown in Figure 4.

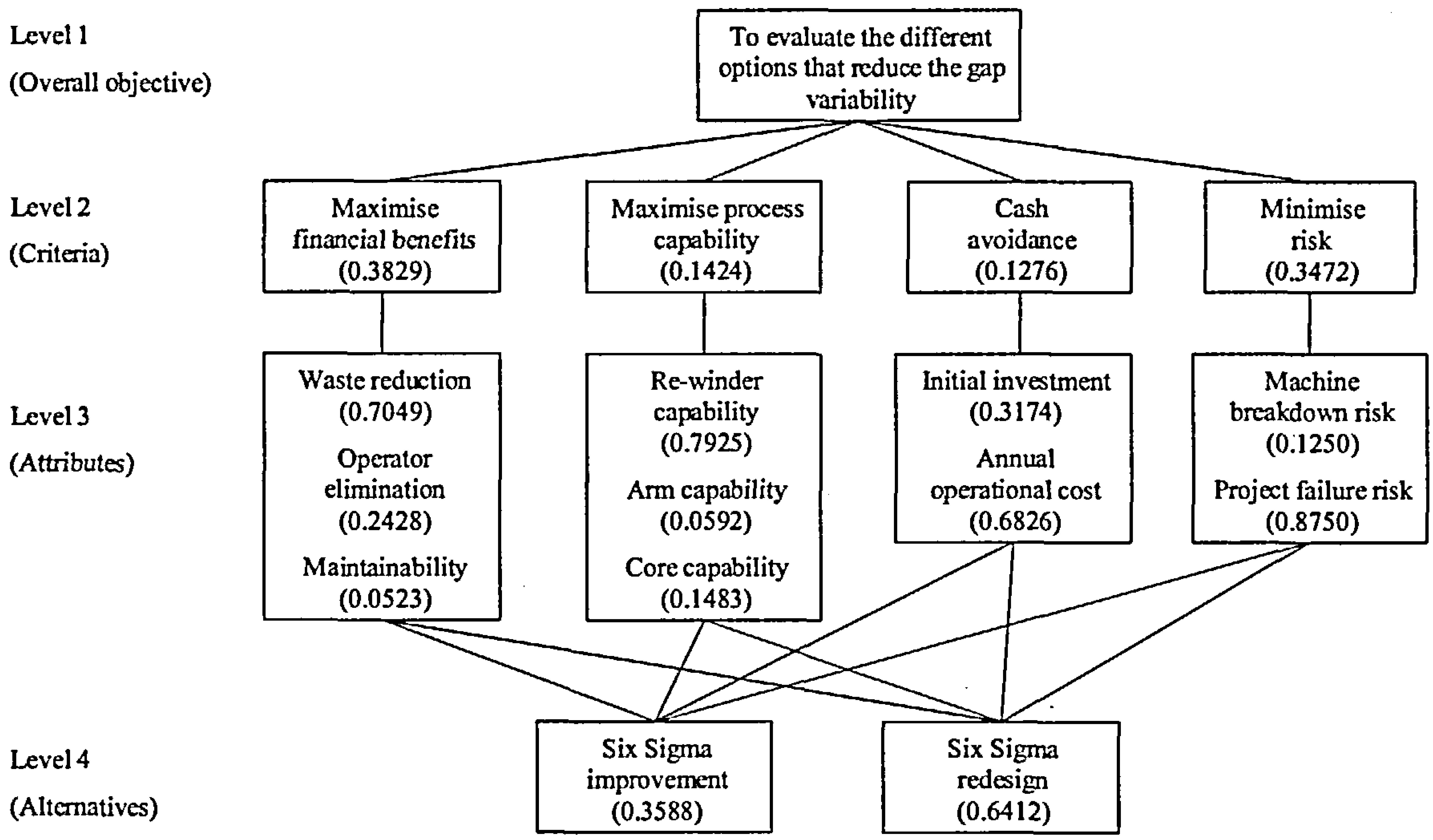
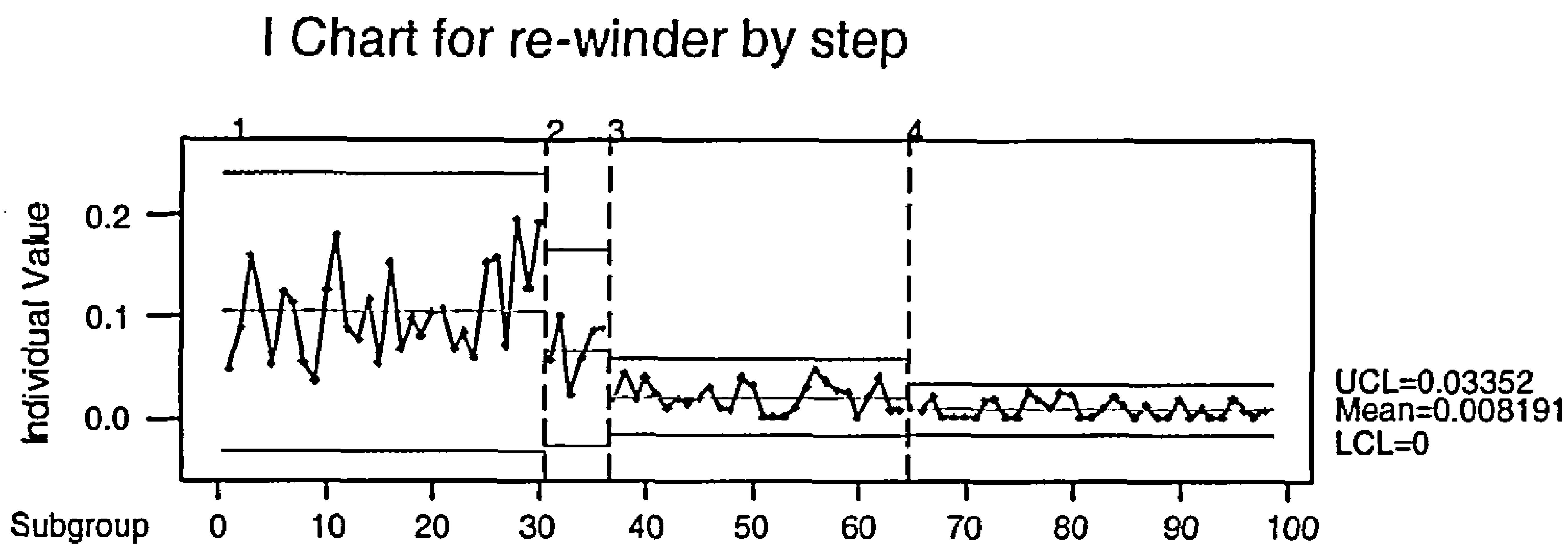


Figure 5: Hierarchy of the improve or redesign issue in a DMAIC project

As a result, it was determined that according to the AHP the redesign alternative may satisfy the considered criteria better than the improved version of the process (0.6412 versus 0.3588). For more information about how the rankings were calculated refer to Submission 3. Based on this result the Six Sigma team decided to redesign the process in order to reduce the variability of the Critical-To-Quality characteristic. The redesigned system is based on a new inverter to implement a controlled move to position, an absolute encoder to accurately measure this position and a disk brake to hold this location.

Having identified the root causes of the problem and the possible solution to reduce the variation of the process during the analysis and improve phases of the DMAIC methodology, the Six Sigma team moved to the control phase. This phase had the objective of implementing ongoing measures and actions to sustain the improvement by monitoring, standardising, documenting and integrating the new process into daily activities (Pande *et al.*, 2000). The control method consisted of a Standard Operation Procedure (SOP) describing how to perform the operation. In addition, it describes the reaction plan in case of failure.

Two years before the project started the process averaged 1.8 Sigma short term (1.29 Sigma long term), as shown in Figure 6. The problem was faced using Six Sigma in order to reach the 3 failures per week goal, which is around 3% defect ratio (97% yield). As the project moved forward special causes were identified and eliminated. For example, some parameters of the re-winder were readjusted, achieving with this a 6% defective rate. After that a temporary solution was installed to reach around 2.06 Sigma long term. This confirmed the strong relationship between the project "Y" and the CTQ characteristic. Once special causes were eliminated and only common causes were present in the process, a redesigned process was implemented. This changed the stats quo and improved the process capability even further to 2.7 Sigma (long term), as shown in the control chart in Figure 6. The savings of this project were estimated to be £100,000 annually.



Key: (1) Process before Six sigma; (2) Process after pneumatics were changed; (3) Process after temporary solution (Six Sigma DMAIC); (3) Process after sustained solution (Process redesigned)

Figure 6: Individual chart for re-winder by step

4.1.3 Reflection upon the Six Sigma project and outcomes

It can be said that the evidence in the form of data and background information of this project indicates that the capability of the process has a positive association with the selection of redesign or improvement efforts within Six Sigma. Analogous to the Six Sigma literature, which suggest that the use of the Six Sigma methodology will improve process capability as the cause of variation is reduced, through the course of the project different process capabilities were reached as the root causes were understood and eliminated using DMAIC. This trend can be seen in Figure 6. However, it contrasts with the literature, which suggests that DFSS should be employed to surpass the "Five Sigma wall" (3.5 Sigma short term) (Harry and Schroeder, 2000; Chowdhury, 2002), in this case the redesign option was employed to surpass 2.06 Sigma (long term). In addition, through the use of rational sub-grouping to estimate sigma capability level, it was possible to calculate the real process shift and discard the 1.5 Sigma shift. Nevertheless, the sigma level was not the only criterion that was taken into account to select redesign effort over the improvement alternative.

The Six Sigma team identified financial benefit, cash avoidance, risk and capability as the main criteria affecting this decision. These criteria were further sub-divided into attributes. The financial aspects were a main criterion affecting the selection of the requisite Six Sigma approach. The belief that redesign requires larger investment than continuous improvements coincides with this project. The redesign option investment is about 50 times more costly than that of the improvement costs needed to improve the process from 2.06 Sigma to 2.64 Sigma long term. However, the amount of waste and the possibility to automate the operation led to a return on investment in less than one year.

It is a general belief that redesign of a process may be a more risky approach than continuous improvement (Leach, 1996; Pande *et al.*, 2001). However, it was anticipated that this project would be high risk if the continuous improvement approach was chosen over the redesign alternative. This was attributed to the rapid change in the coating technology which makes the support of the current technology both risky and expensive. Also the spare parts for the re-winder were becoming obsolete, increasing their acquisition costs and the lead-time to supply the spares.

The cash avoidance criterion presented a trade-off between the two alternatives. The redesign alternative required a substantial initial investment, whereas the improvement alternative did not require any initial investment. Nevertheless, the redesign option was capable of reducing the annual costs by approximately £100,000, whereas the improvement alternative reduced them by approximately £50,000 annually.

The decision to redesign the re-winder instead of continuously improving it, involved the consideration of several criteria. These decisions during the Six Sigma projects at 3M Atherstone were based on the experience of people and decided without the application of tools and techniques. However, this Six Sigma project employed the AHP to deal with this multi-criteria decision. After applying AHP there was little doubt about its positive implementation. The realisation, understanding and awareness that involved the comparison of alternatives were in itself an advance. The awareness that is necessary to consider the different objectives that may affect the situation made the decision-makers contemplate the outcomes of the decision making much more carefully.

It is important to mention that the tools, techniques and methods employed on this DMAIC project did not differ significantly to those employed in DFSS. A review of the Black Belt training material at 3M showed significant similarities between DMAIC and DFSS regarding the tools taught. Most of the commonly used DMAIC tools and techniques were employed during this action research project. However, not all the tools employed in this project are part of the DMAIC toolkit. Statistical tolerancing, a DFSS technique, was employed during the improvement phase. In addition, during the course of this project the use of DMAIC was initially employed because the approach to tackle it was highly defensive and it was assumed that the design was essentially correct. However, it was not until the root cause of variability was understood that the Six Sigma team proposed a redesign alternative to reduce process variation. Moreover, the redesign alternative was not suggested by employing DFSS but by employing DMAIC and understanding the root causation and the possible way to eliminate it. Therefore, in some instances the selection of DFSS over DMAIC may take place during the course of either a continuous improvement DMAIC project or during a DFSS project.

Another issue that DFSS and DMAIC traditionally diverge on, is the scale of improvement associated with both approaches. Traditionally, DFSS as with any redesign effort is associated with larger and discontinuous improvement, whereas DMAIC is usually associated with steady continuous improvement. During this project, the improvement efforts can be categorised as continuous improvement and redesign can be classified as a radical improvement. However, the scale of improvement reached using DMAIC compared with that of redesigning, does not necessarily differ in scale. Therefore this distinction does not necessarily apply to this specific project.

4.2 Selection of the requisite Six Sigma approach; Using the Stochastic Analytic Hierarchy Process in a Design for Six Sigma Project

The project presented in section 4.1 demonstrates how the DMAIC approach opted for a redesign, however, it represents just one part of the spectrum. The researcher was primarily concerned with the study of a DFSS project in order to be more able to generalise conclusions.

4.2.1 Background to the case

The DFSS project carried out in the second action research cycle took place in the home laundry appliance division of General Domestic Appliances (GDA). This company develops, designs and manufactures domestic appliances for the European market. The company's products include washing machines, tumble dryers, dishwashers, fridges, freezers, electric and gas cookers, ovens, hobs, storage and panel heaters, gas fires and air management products. GDA employs the DMAIC methodology for the deployment of Six Sigma and the IDOV (Identify, Design, Optimise and Verify) methodology for the implementation of the DFSS.

DMAIC is used to identify inadequacies in the existing processes and to make lasting and controllable changes to products and processes that improve product quality, customer satisfaction, and company's profitability. DMAIC is commonly applied to manufacturing, design or commercial quality. On the other hand, the DFSS IDOV (Identify, Design, Optimise, Verify) methodology is implemented to ensure a product has robust component specifications that are integrated into the project from the embryonic stages of design and development. DFSS is seen as the means to make new products and process introductions more efficient and capable by providing a disciplined approach to predict and verify product quality. The company's champion Six Sigma training material states that without DFSS, traditional DMAIC Six Sigma projects cannot cope with improvements to poorly designed new products. Accordingly, DFSS and DMAIC Six Sigma methodology are seen as complementary approaches to business success. Six Sigma DMAIC is considered a way to eliminate variation in products, processes and services, as a driver of productivity and is used to improve current issues, whereas in Design for Six Sigma the vision is product and service excellence from the start by having customer-centric products and specifications.

The researcher, in collaboration with GDA, carried out a Design for Six Sigma (DFSS) project aimed at achieving "B" rated energy consumption (i.e. the second best energy rating for a domestic appliance) for the new platform of tumble dryers produced by GDA. From the research point of view, the researcher aimed at having in-depth participation and action in a DFSS project in order to identify the criteria used to select DFSS over Six Sigma and test the applicability of AHP for this selection. The aim was to identify the criteria that define when to embark on a redesign and to compare them with the first action research cycle.

4.2.2 Story and outcomes

At the beginning of the project it was believed that the inherited technology of the product could not cope with the increasing customer demands, consequently a redesign approach was selected following the IDOV methodology. The first step of the IDOV methodology involved the gathering of the voice of the customer and translating it to critical-to-quality (CTQ) characteristics. In this project the CTQ under study was energy performance which is dictated by several engineering sub-systems and elements. This project was mainly concerned with the selection, designing and optimising of the heat element of the appliance in order to facilitate the achievement of the "B" energy in the final product.

To achieve the primary goal it was necessary to select a design concept between a set of four heat element concepts, including the current concept, flat spiral, and three alternatives used in competitive products (wire, sheathed and sheathed with heater exchanger). Therefore, if the current heat element were to be selected over the rest, then the team of designers would proceed to improve its energy efficiency. However, if a different heat element concept was selected, the team would start a detailed redesign of heat element and the sub-systems affected by it. In addition, the selection of the most appropriate heat element not only depended on the ability of the heat element to achieve the "B" energy rating but also on improvement of the design for manufacturing score and the achievement of reliability targets at reduced costs. Moreover, governments have introduced tough regulations with regard to safety and environmental issues. The new platform has aggressive goals and the risk to not delivery them is significant.

There were special concerns about the likelihood of failing to deliver the desired level of performance, in meeting the legislation and in achieving reliability goals. It was believed that the technology inherent in some heat elements may facilitate or hinder the ability to achieve these multiple and conflicting criteria. The evaluation of four different design concepts against multiple and conflicting criteria without the aid of analytical techniques is a difficult task. Consequently, AHP was chosen and presented to the collaborative company by the researcher to assist with the selection of design concepts, and consequently as whether to improve or redesign the current design. Following the flow chart presented in Figure 4, subject matter experts performed the analytic hierarchy process forming the hierarchy shown in Figure 7. The group of subject matter experts included fifteen people from various areas of the company such as marketing, design, manufacturing, Six Sigma, engineering, development, value management and computer aided design.

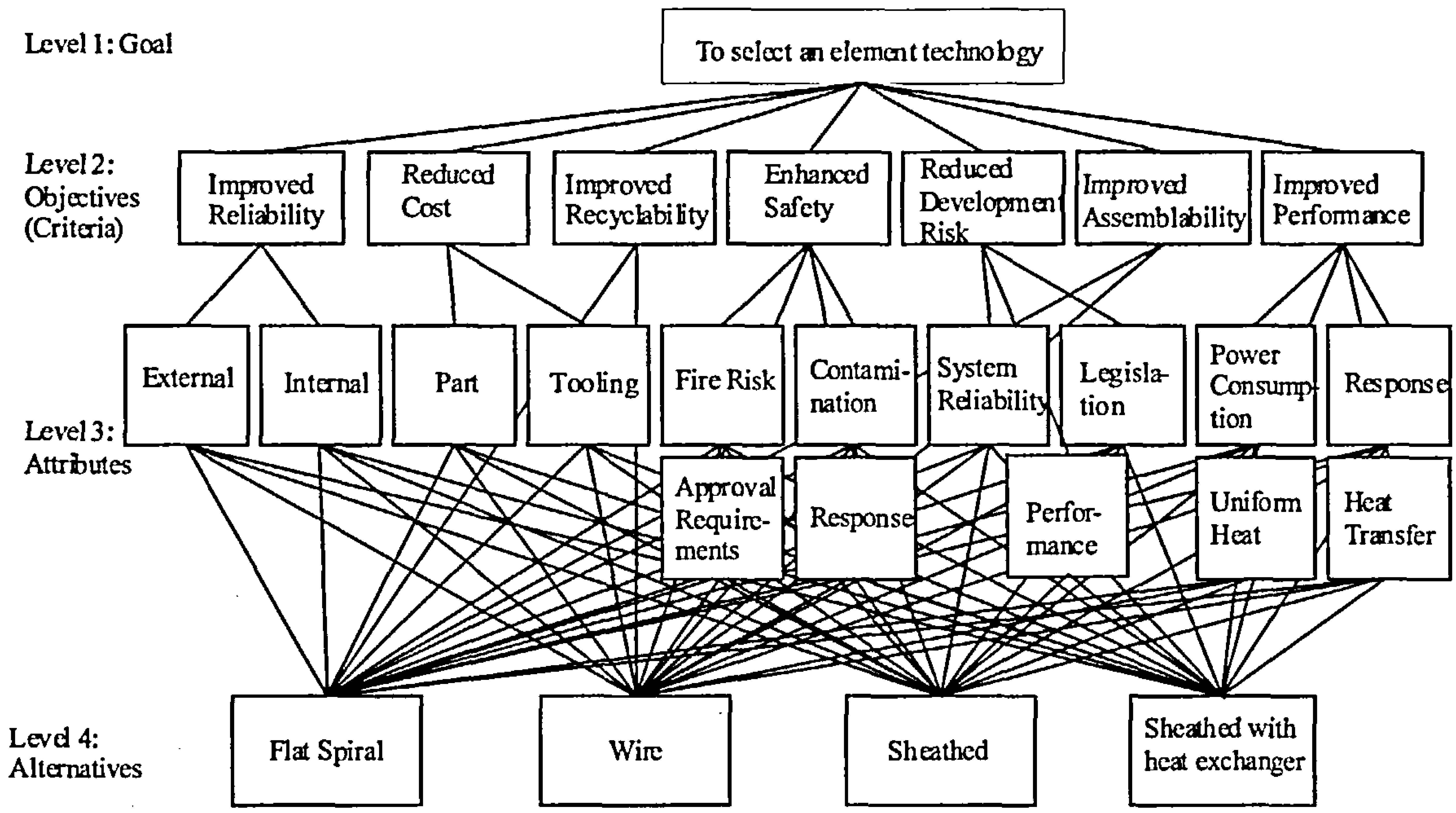


Figure 7: Hierarchy of the improve or redesign issue in a DFSS project

The group made the pairwise comparison required to calculate the ranking for the different alternatives producing a ranking for the four alternatives under study. Sometimes in AHP a clear apparent winner among alternatives will emerge. However, in this case the two top ranked alternatives, i.e. sheathed with heat exchanger and sheathed design concepts, were very close to each other (0.2954 vs. 0.2942). For Scott (2002) the final rankings provided by the AHP are used as a general guide in the selection of a particular alternative and a small difference in scores is not to be taken as definitive evidence that one alternative is preferable to another. Therefore, the team felt uncomfortable in selecting the concept with the higher score. People in GDA were suspicious about the validity of the AHP results. They highlighted the importance of incorporating the degree of uncertainty that a group of decision-makers have to converge ambiguous judgments to a Likert scale in order to describe a pairwise comparison of objectives and alternatives (Hauser and Tadikamalla, 1996). In addition, the group of designers and product scientists recognised the importance of testing the resultant rankings of alternatives for statistical significance. In summary, the following questions were raised:

1) Is there a practical and statistical difference between the rankings of the various alternatives?

2) Can the closeness of the results be attributed to uncertainly that people have to converge ambiguous judgments to single point?

3) How confident are we of selecting the right design concept?

4) What is the role of managerial aspects in the AHP?

Some research has been done to address some of the issues described above. Previous researchers have incorporated uncertainty in the AHP using probabilistic judgements (Hauser and Tadikamalla, 1996; Rosembloom, 1996; Levary and Wan, 1998) fuzzy sets (Ruoning and Xiaoyan, 1992; Chang, 1996) and intervals (Lee, Lau and Samson, 2001; Arbel and Vargas, 1993). However, traditional AHP does not allow decision-makers to draw any statistical conclusion about the difference between alternatives. Rosembloom (1996) states:

"the only interpretation of say $w_i > w_j$ *is that* w_i/w_j *is the ratio of preference of i over j. Thus, in AHP if two alternatives have scores that are quite close, it is unclear whether there is a statistical significant difference between the alternatives"*

In addition, few researchers have incorporated managerial aspects into the AHP and have given them the vital importance they have for the successful application of the AHP. The author developed the SAHP which addressed the above issues and was developed on the basis of AHP and disparate sources of relevant literature. SAHP uses probabilistic distributions to incorporate uncertainty that people have in converging their judgments of preferences into a Likert scale. The vector of priorities is calculated using Monte Carlo simulation, the final rankings are analysed for rank reversal using statistical analysis, and managerial aspects are introduced systematically. For more information about the theory underpinning the SAHP, please refer to Bañuelas and Antony, (2004b), Submissions 4 and 6.

4.2.3 The Stochastic Analytic Hierarchy Process

The Stochastic Analytic Hierarchy Process (SAHP) is a powerful Multi-Criteria Decision Analysis technique that helps people set priorities and make better decisions when taking into account qualitative and quantitative information under uncertainty (Bañuelas and Antony, 2004b). It differs from AHP in several dimensions which can be grouped into "soft" and "hard" characteristics. Traditional AHP as a "hard" operational research technique has a dominant tendency to look for technical solutions to well-structured problems in which desirable ends can be easily stated (Checkland, 1999). However, real world interventions such as the selection of the requisite Six Sigma approach involve the relationship between people, and their differential willingness and ability to adjust to the changed circumstances of the desired state of the problem. In addition, different people and departmental factions can have different conceptions of what the problem is. All these might affect reaching consensus and converging ambiguous judgments to a Likert scale in order to describe the pairwise comparisons of objectives and alternatives required in the AHP (Hauser and Tadikamalla, 1996). Therefore it is important to understand the problem and structure it before attempting to solve it by means of AHP. There are different "soft" methods used to deal with managerial aspects (i.e. problem identification, context of the problem). Different authors have also highlighted the importance of incorporating different methods to link "soft" or managerial issues and "hard" issues in a single real intervention (Jackson and Keys, 1984; Mingers and Gill, 1997; Checkland, 1999; Rosenhead and Mingers, 2001). For Mingers and Brocklesby (1997) combining soft methods, to deal with managerial aspects, with hard operational research methods is necessary to deal with different dimensions of the situation and because some methods are more suitable at different phases of the intervention. Therefore, the author decided to incorporate managerial or "soft" issues in the planning phase of the SAHP. From the first attempt of implementing AHP, it was believed that the accuracy of the comparisons of all pairs of criteria and decision alternatives may be affected depending on the information available to the decision-makers and their understanding of the problem under consideration as well as their previous perceptions (Levary and Wan, 1998). These "soft" or managerial aspects may be related to problems to input preferences in the AHP. Lack of information of objectives, vague description of objectives and alternatives, insufficient information regarding the stakeholder strategies and poor selection of subject matter experts are all issues that need to be addressed before performing any pairwise comparison. Consequently, the author implicitly introduced these issues in a step-by-step fashion into the planning phase of the SAHP, as shown in Figure 8.

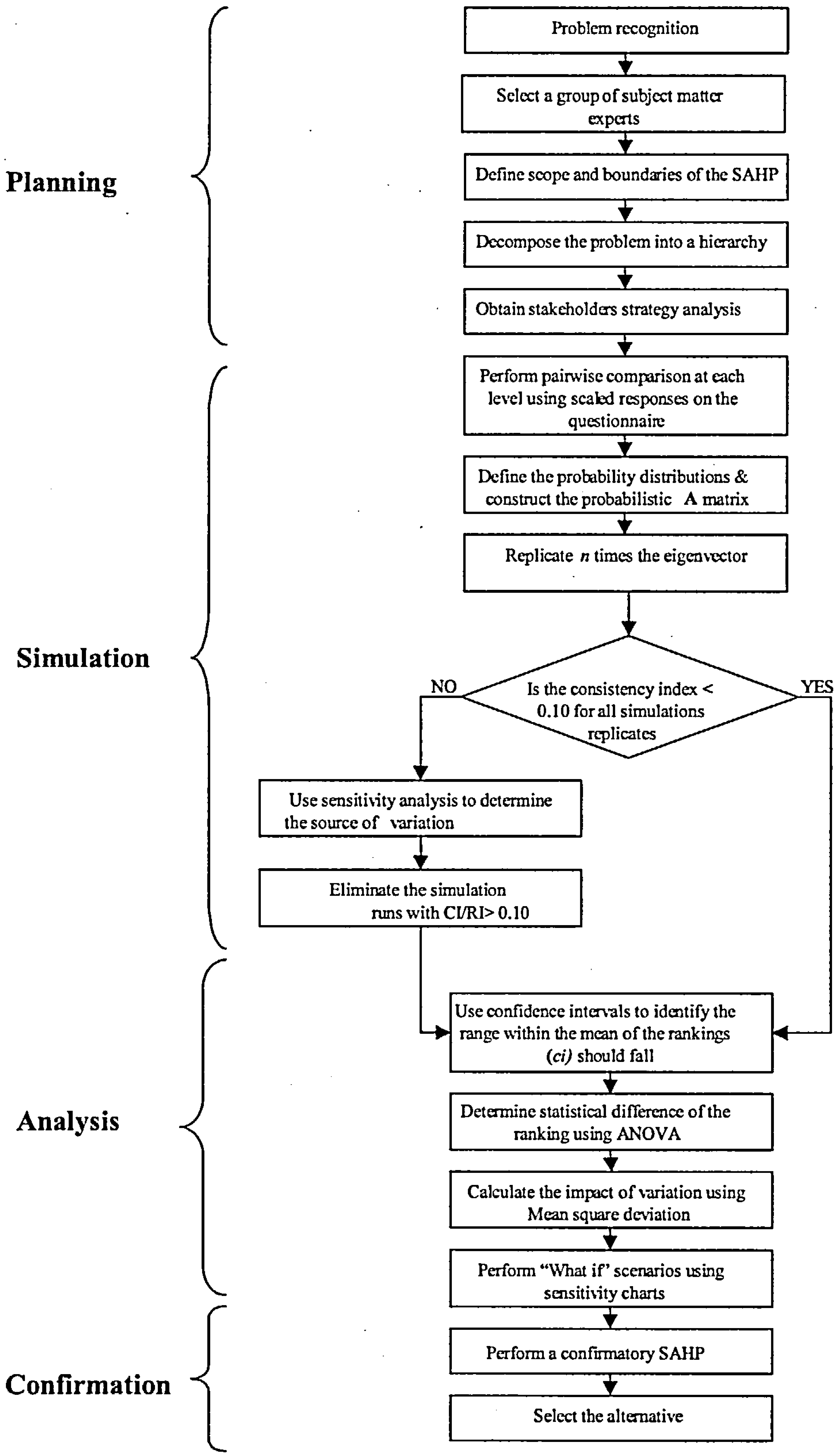


Figure 8: The methodology for SAHP

Regarding the technical or "hard" issues, one main concern in the traditional AHP is that the pairwise comparisons used to express preferences are assumed to be deterministic rather than probabilistic. Thus, a preference in the pairwise comparison remains fixed and it is assumed that all the decision-makers agree with that preference. However, the perception of people inevitably changes from one person to other. Since in many cases this problem is present, a degree of uncertainty will be associated with the pairwise comparisons (Paulson and Zahir, 1995, Levary and Wan, 1998). Saaty (1988) states that if several people are involved, they can assist each other in sharpening their judgements in order to attempt consensus and reduce uncertainty. In practice, this approach transforms the AHP preferences ranking into a bargaining process in which some people tend to dominate the session. Conversely, in the SAHP, consensus is derived along different lines. During the planning phase, the subject matter experts interacted and all the available information is presented. Such debate would assist in providing information and reaching consensus. Nevertheless, to deal with the remaining degree of uncertainty and inexactness, SAHP introduces probabilistic judgements instead of using a deterministic scale. For example, the i^{th} objective can be preferred over j^{th} with an average of "*x*" and standard deviation of "*z*". That is, the *A* matrix of the AHP contains probabilistic distributions (e.g. normal, triangular or uniform distributions). Monte Carlo simulation is then used to calculate the *Aw* and *c* vector of the AHP. Accordingly, each replication is a realisation of all the $a_{i,j}$*'s* in the decision hierarchy followed by the standard AHP calculation. Replicating *n* times provides estimates of the probabilities associated with the vector of priorities (Rosenbloom, 1996). Based on this principle, the author created a SAHP model shown in Figure 8. The resultant vector of priorities, can be treated using statistical tools and techniques in order to obtain the statistical significance of the results.

The methodology of Stochastic Analytic Hierarchy Process (SAHP) was applied to the original selection bearing in mind the above issues learned from the first application of the AHP. The group of fifteen people involved in the first application of AHP, carried out the SAHP by strictly following the four phases of SAHP methodology. For more information on this application of SAHP please refer to Submission 4 and Bañuelas and Antony, (*under review*). As a result of SAHP implementation, a probabilistic "c" composite priority vector shown in Figure 9 was created.

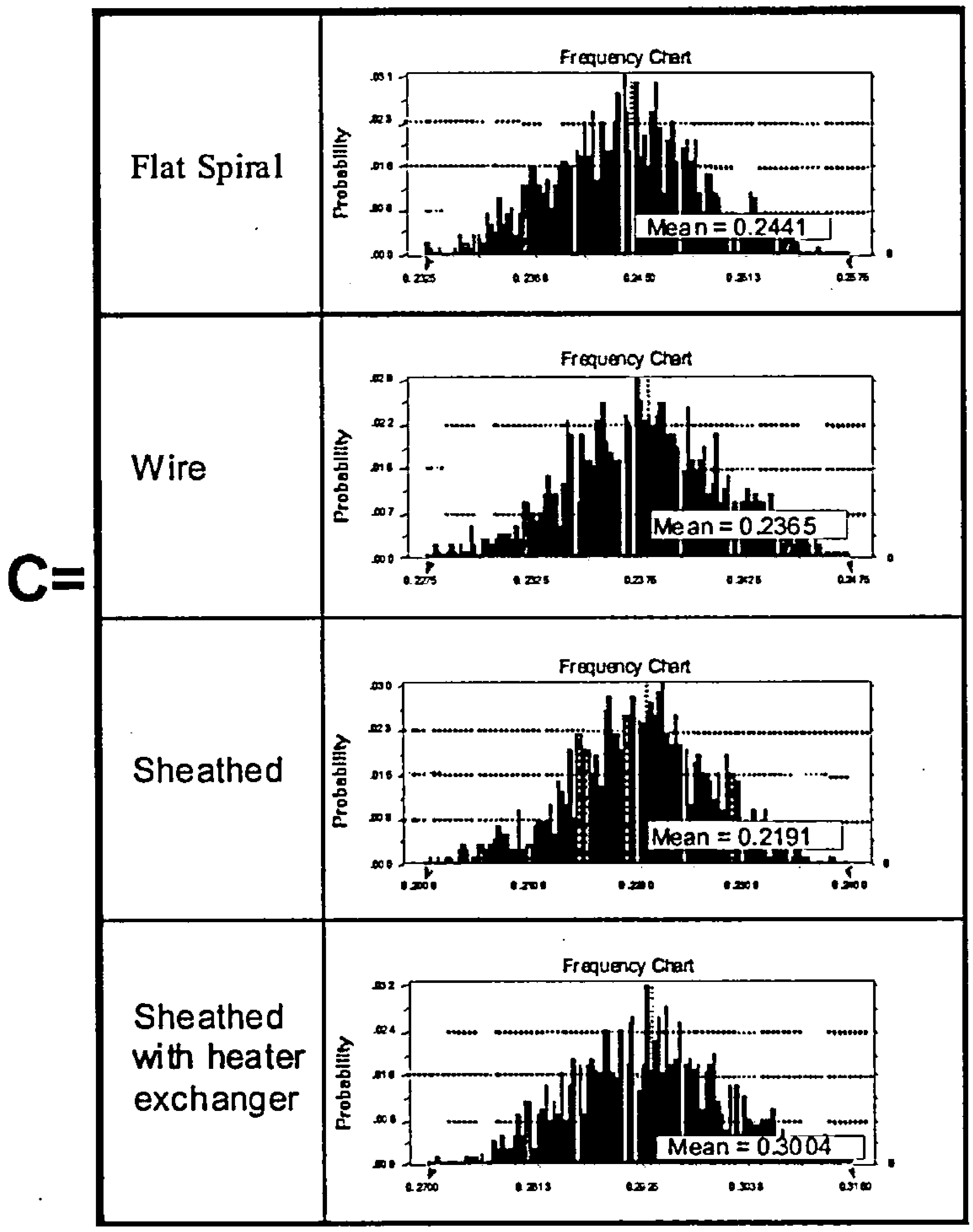


Figure 9: The probabilistic "c" composite priority vector

The probabilistic "c" composite priority vector provides a measure of statistically significant differences between the alternatives that led to prioritising order of alternatives. Using one way ANOVA, it was possible to investigate the question: "Are the means in the "*c*" vector (*ci*) statistically different?" In this case the means of the c_i

were considered significantly different; thus, the design concept with the higher utility (sheathed with heater exchanger) was selected over the current design concept (flat spiral) and two design concepts used by competitive products (wire and sheathed). Since the current design was not selected, a major redesign took place in which different design parameters were optimised. Nevertheless, if the current design concept were to be selected using SAHP, the team would have proceeded to improve the current design thereafter with the use of the IDOV methodology. In other words, during a design project it is possible to improve the design by minor improvements or optimisations. After the design concept was selected the team moved to the optimisation phase of the IDOV methodology.

The optimise phase had the objective of optimising the selected design concept and making trade-offs between competing requirements. A screening experiment was employed to discover the critical few "X's" that affected the heat element performance. Having identified the critical variables, Response Surface Methodology (RSM) was utilised to determine the settings of the design parameters that produce the optimal response(s) (Khuri and Cornell, 1996). A Multiple Response Optimiser was then employed to assist with the identification of the combination of factor settings that jointly optimise two responses (i.e. drying time and energy consumption of the tumble dryer). The redesigned heat element was then validated in the last phase of the IDOV methodology to confirm that the pilot experiments build the predictions made during the RSM. As a result, the product achieved 8% energy consumption improvement and improved assembly time by 5%, at the same cost and with the required level of safety. For more information about the optimisation phase please refer to Submission 4 and 6.

4.2.4 Reflection upon the DFSS project and outcomes

During this second action research cycle a DFSS project was carried out to select, design and optimise the heat element technology in order to achieve "B" energy consumption for the new platform of tumble dryers. In this case the calculated sigma level short term for the CTQ characteristic energy consumption was 2.9 (1.67 long term). Thus, according to the Six Sigma literature the product can be improved by means of DMAIC (Pyzdek, 1998; Breyfogle, 1999; Harry and Schroeder, 2000; Pande *et al.,* 2000; Eckes 2001; Chowdhury, 2002). Conversely, in this project the change of the current product specification to a higher level left the inherited technology incapable of reaching the new customer demands, thus a DFSS approach was employed.

Although the project was initially focused on redesigning the current heat element technology, the decision to improve or redesign was raised during the evaluation of four design concepts (flat spiral, wire, sheathed and sheathed with heater exchanger). Since the current design (flat spiral) was not selected, a major redesign took place in which performance and drying time were optimised; the product was designed for manufacturing; it was tested to meet the safety requirements; and value analysis exercises were carried out to reduce cost. Nevertheless, during a design project it is possible to improve the design by minor improvement or optimisations. In fact, the last designs in the collaborative company have been, to some degree, product updates with minor improvements using the design methodology. Moreover, before DFSS was launched in the company, the design department used to apply Six Sigma by following the DMAIC approach in their design activities.

In line with the first action research cycle, this project was redesigned based on multi-criteria rather than on sigma level alone. Risk, cost and cash avoidance again played an important role along with improved product safety, reliability, performance and the ability of the product to be recycled. In the same manner as the first case, AHP was introduced for the selection of the requisite Six Sigma approach. However, a reflection of the applicability of AHP dictated the need to incorporate uncertainty in the pairwise comparisons and managerial aspects in order to successfully apply this technique. The SAHP technique is capable of taking into consideration quantitative, qualitative, and multiple dimension information under uncertainty, which are powerful and necessary characteristics for the selection of the requisite Six Sigma approach. In addition the process of planning, simulation, analysing and confirming the SAHP improved and refined the debate and the decision process, making it easier to select the alternative suggested by the SAHP. For these characteristics the collaborative company foresaw the applicability of SAHP and promptly adopted and implemented it for various multi-criteria decisions.

Although SAHP is more complex than the original AHP, the subject matter experts do not require advanced knowledge of either mathematics, statistics or AHP to construct the hierarchy and perform the pairwise comparisons. It is recommended that the rest of this model is undertaken using a spreadsheet with Monte Carlo macros (e.g. Excel with Crystal Ball software). The incorporation of uncertainty through a simulation and statistical approach provide the SAHP with a means to test the final scores. Table 3 compares the SAHP with the traditional AHP.

Table 3: The foundation of SAHP

Dimension	Traditional AHP	Other AHP modifications	SAHP
Incorporation of uncertainty	Delphi method	Using probabilistic judgements (Hauser and Tadikamalla, 1996; Rosenbloom 1996; Levary and Wan, 1998) fuzzy sets (Ruoning and Xiaoyan, 1992; Chang, 1996; Lee *et al.*, 2001) and intervals (Zahir, 1991; Arbel and Vargas, 1993).	Using probabilistic judgements
The method to estimate the underlying rankings	Principal eigenvector (without replication)	Principal eigenvector (Saaty, 1988; Kumar and Ganesh, 1996), the multiplicative method (Stam and Duarte, 2003) and the logarithmic least square method (Fichtner, 1986; Kwiesielewicz, 1996).	Replicating *n* times the principal eigenvector using Monte Carlo simulation
Interpretation of the results	Utility theory, sensitivity analysis	Fuzzy interpretation (Ruoning and Xiaoyan, 1992; Chang, 1996; Lee *et al.*, 2001), statistical interpretation (Hauser and Tadikamalla, 1996; Rosenbloom 1996; Levary and Wan, 1998)	Statistical interpretation using confidence intervals, ANOVA and Mean Square Deviation. Sensitivity analysis is also carried out.
Soft/managerial issues	Brainstorming, Delphi method	Barely researched	Combines several methods (affinity diagrams, stakeholder analysis, brainstorming) in a systematic way in order to deal with soft/managerial aspects.

Similar to the first action research cycle, the tools, techniques and methods employed on this IDOV project did not differ significantly to those employed on the DMAIC project. Moreover, a comparison of the Six Sigma and Design for Six Sigma training materials highlights significant similarities. Not all the tools employed in this IDOV project are exclusive to the DFSS toolkit. Team charter, design of experiments, response surface methodology, hypothesis testing, rational sub-grouping and Multiple Response Optimiser are all tools that can be employed in both methodologies.

Before extrapolating the findings of the first two action research cycles, a third action research cycle was carried out aimed at identifying the factors surrounding the selection of the requisite Six Sigma approach in a non-manufacturing project and testing the applicability of SAHP in a non-manufacturing environment.

4.3 Selection of the requisite Six Sigma approach; Using the Stochastic Analytic Hierarchy Process in a Six Sigma non-manufacturing project

Six Sigma has been predominantly used to improve manufacturing processes. However, in recent years Six Sigma is increasingly applied to a wide variety of non-manufacturing[10] processes. Quality in non-manufacturing process and products differ in three fundamental ways from goods in terms of how they are produced, consumed and evaluated; they are intangible, heterogonous, and inseparable (Zeithalm, 1990). As a result, quality applied to non-manufacturing can be more difficult to evaluate than in manufacturing processes; as it is difficult to measure it on the same basis as manufactured products; the criteria that customers use to evaluate the service perception is highly subjective and they cannot be tested before they are offered to the customer since they are performed at the same time that they are bought (Zeithaml, 1990, Bergman and Klefsjo, 1994). Bearing in mind these differences, this project was carried out in a non-manufacturing process in collaboration with Land Rover. The researcher aimed at extending the research domain to a non-manufacturing process.

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[10] Non-manufacturing is a term to describe any business process that does not produce a physical product but directly or indirectly supports the business mission (Does, Van den Heuvwl, De Mast, and Bisgaard, 2002).

4.3.1 Background to the case

The third action research cycle took place at Land Rover Solihull. This company develops, designs, manufactures and commercialises premium automotive 4X4 vehicles. Land Rover has not escaped industry trends and has been affected by the forces of globalisation, overcapacity, the challenges posed by Japanese producers and the emergence of new segments as the market for cars has become increasingly fragmented (Donnelly and Morris, 2003). In recent years, Land Rover embarked on a corporate revitalising plan aimed at achieving profitability through improved market share and reduced costs. The company adopted Six Sigma as one of the foundation business initiatives aiming at transforming the company in the coming years. Six Sigma DMAIC methodology is employed during Six Sigma improvement projects and the Define, Concept, Optimise and Verify (DCOV) methodology during DFSS projects. The selection of the requisite Six Sigma approach in the collaborative company is based on whether the project intent is to eliminate defects or prevent defects in either business processes or products. If the decision is made to eliminate defects, the project is carried out using the DMAIC methodology. On the other hand, if the decision is made to prevent defects, the project follows the DCOV methodology of the DFSS approach. Nevertheless, the company's Green Belt training material states that sometimes projects are originally identified as DMAIC, but later it may be necessary to put the project through DCOV methodology. According to the training material, this can happen during the analysis and improvement phases of the DMAIC when the process cannot provide sufficient improvement or sensitivity to noise of the process/product needs to be reduced. Conversely, DFSS projects can move to the DMAIC methodology during the optimisation and verification phases of the DCOV methodology for projects requiring capability improvement. The focus of the project presented here was to eliminate defects and increase customer satisfaction for the current process, thus DMAIC was initially employed.

4.3.2 Story and outcomes

Engineering change transactions are some of the most expensive of any a company undertakes (Vollman, Berry and Whybark, 1997). A typical engineering change requires a meeting of people from different departments, the change needs to be approved, documented, scheduled and monitored for execution. The engineering change process in the collaborative company is designed to manage change and serves the purpose of communication, finding of solutions, decision-making and the tracking of those decisions and their associated consequences to the point of measuring their success. However, variation of the process leads to poor quality output, misunderstanding and constant re-learning. Problems caused by the engineering change process are manifested in long implementation time and differences between the actual use of parts and the Bill of Materials (BOM) statement. An initial review of these differences by the Six Sigma team highlighted that the handover from engineering to release is the highest source of discrepancies. A handover problem occurs when the instruction from the engineer is not correctly understood or implemented in the system by the release analyst. A project was launched aimed at identifying, quantifying and eliminating the source of variation that leads to unsuccessful handover from engineering to release. The details of the project are shown in Submission 5. In the initial phases of the DMAIC methodology a Six Sigma team identified the number of discrepancies (i.e. between BOM statement and actual manufacturing use) assigned to the handover point and the time to reject for approval at the handover point as the main critical-to-quality characteristics. The process was mapped and standardised during the first stages of the DMAIC methodology. During the measurement phase the process was baselined using rational sub-grouping. Accordingly, the time to implement a change performed at a level of 0.88 Sigma level (long term). For the CTQ quality, the sigma level long term was estimated at 1.12 Sigma (long term) or 261,673 DPMO.

During the initial phases of the DMAIC project, it was found that mass inspection was the main approach used to promote quality in the handover process. The Six Sigma team argued that quality cannot be inspected into a process as quality has to be built into the process. As part of the improvement phase the Six Sigma team brainstormed potential alternatives to ensure quality in the handover process. The Six Sigma team identified two main routes of action to enhance it, they were categorised as improvement and redesign alternatives. The improvement option will focus on enhancing the detection of failures in health check, whereas the redesign option prevents the failures occurring in the first place. Similar to the first action research cycle, this decision is subject to multiple and conflicting criteria. Implementation risk, the initial investment and the potential level of improvement are thought to be different in each alternative. The researcher, with the support of the Six Sigma team, decided to apply the Stochastic Analytic Hierarchy Process (SAHP) to select between redesigning the handover or improving it. SAHP was applied to solve the improve or redesign issue following the methodology shown in Figure 8.

To ensure that the cross-functional team needed to perform the SAHP possesses the blend of skills, knowledge and personalities for optimum effect, six people selected from the logistics, engineering, release and Information Technology (IT) departments carried out the SAHP methodology (the researcher facilitated the SAHP session). The problem decomposition was carried out during a brainstorming session in which decision-makers and subject matter experts organised and summarised the natural grouping from the large number of brainstormed objectives using affinity diagrams producing the hierarchy structure shown in Figure 10.

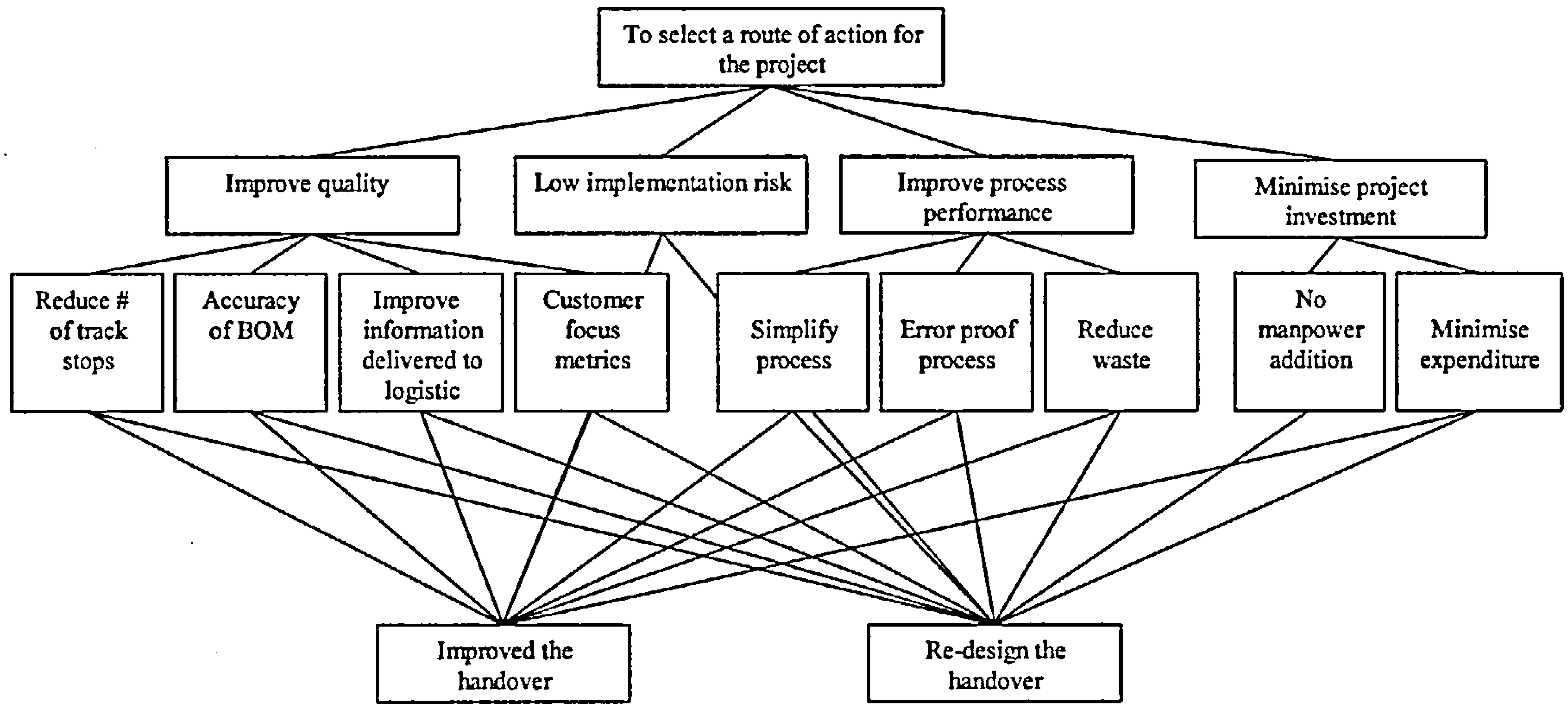

Figure 10: Hierarchy of the improve or redesign issue in a non-manufacturing project

To produce probabilistic distributions, the judgements of a group of subject matter experts and decision-makers were collected using individual questionnaires and their answers incorporated in the SAHP procedure. In addition each question was discussed before actually answering it, to facilitate the convergence of judgements. Data collected from the questionnaire was analysed and plotted producing triangular and uniform distributions using Crystal Ball simulation software. Monte Carlo simulation was employed to estimate the "c" composite vector from the probabilistic judgements (s_{ij}). Following the procedure developed during Submission 4, the s_{ij} probability judgements were replicated 1000 times to estimate the "c" composite priority vector using Crystal Ball software. The probabilistic "c" composite priority vector is represented in Figure

11 using Box plots. As can be seen, the redesign option produced the higher utility for the objectives set; thus, according to SAHP this option should be selected.

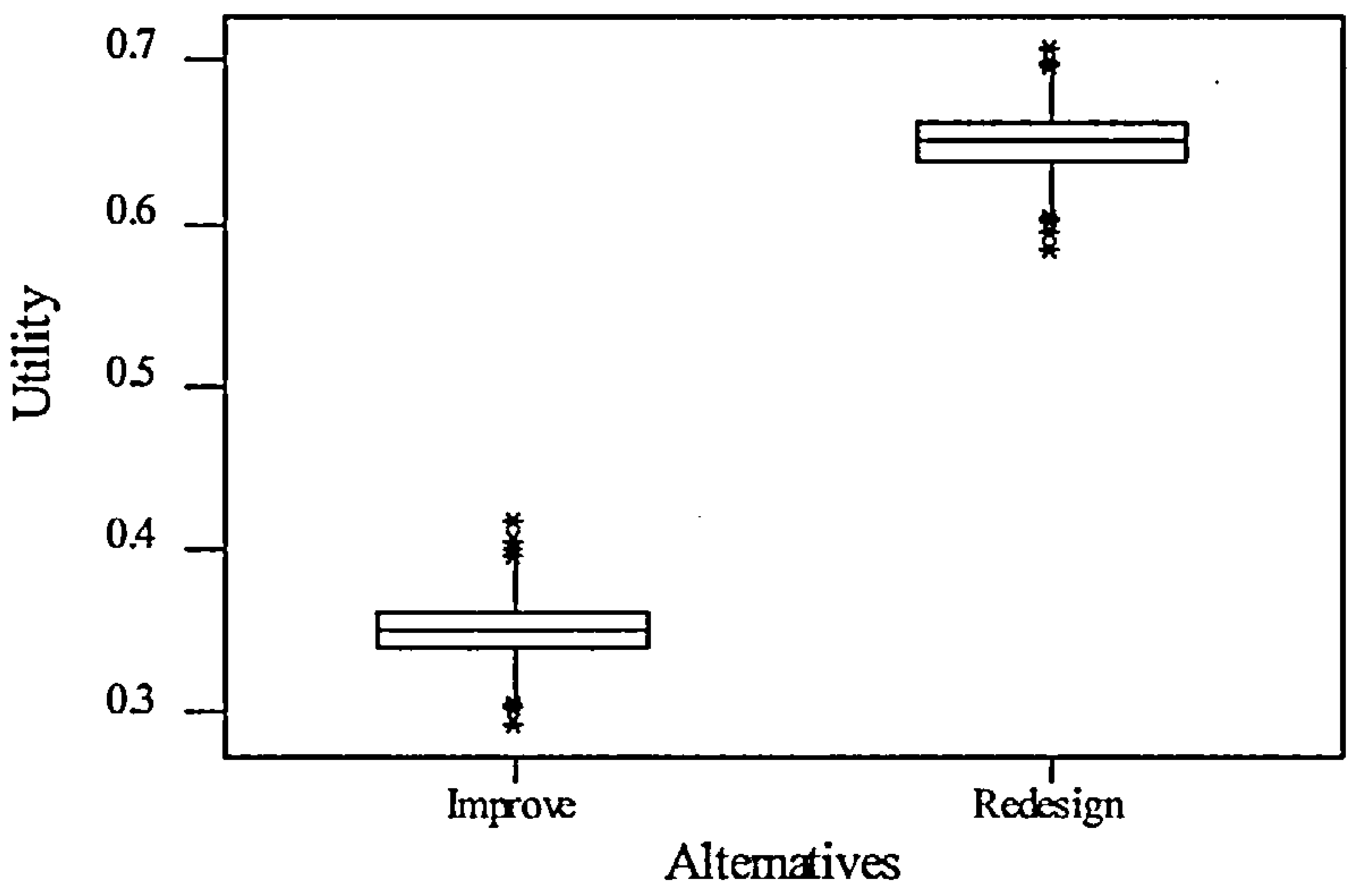

Figure 11: Box plots for alternatives

As a consequence, the Six Sigma team decided to redesign the handover process. The first step of the redesign effort consisted of the application of the Design Failure Mode and Effect Analysis (DFMEA) in order to identify the various failures modes, their causes and to recommend actions in order to improve the prevention of such failures using alternative design configurations. The researcher and the Six Sigma team decided to reduce or eliminate the failure modes using a preventive focus rather than a reactive one, where inspection is on the process rather than the process itself, and process standards and scheduled training are in place. The process owner agreed with the recommended actions and decided to implement the solution in less than a month. At the time of writing this document, this proposed solution was not yet implemented. The process owner argued that there had not been time to implement the solution due to work overload. Nevertheless, from the research point of view, the researcher was able to identify different criteria affecting the improve or redesign issue and to test the applicability of the SAHP in a non-manufacturing project, which were the initial objectives of this project.

4.3.3 Reflection upon the Six Sigma project and outcomes

During this third action research cycle the process was performing at a level of 0.88 Sigma in terms of time and 1.12 in terms of quality. The initial decision in this project was made to eliminate defects, thus the DMAIC methodology was used. However, during the analysis and improvement phases the process could not provide sufficient improvement, thus the project adopted a preventive approach. A similar decision was taken during the DMAIC manufacturing project carried out in Submission 3.

As the route cause of the problem was understood and special causes of variability were identified, the Six Sigma team was able to propose two main routes of action for the project: redesign or improve it. To solve this issue the team considered several factors including quality, risk, performance and project costs. These criteria were further subdivided into attributes. The redesign option was believed to enhance quality criterion better than the improve alternative and change the existing process by eliminating special causes and minimising common causes. On the other hand, implementation risk was believed to be lower in the improve option, than that of the redesign alternative. In addition, the team perceived the redesign option as riskier because it involved a radical approach to handover of an engineering change, thus the chances of not delivering the expected performance and quality might be higher. Similar to the quality criterion, the expected performance associated with the redesign alternative is perceived to be higher than that of the improve option. The project investment was perceived as lower in the improve version than that of the redesign alternative.

To cope with this multi-criteria decision the SAHP was applied bearing in mind the issues learned from the first application of the SAHP. The researcher also aimed at introducing SAHP in a different environment (e.g. different industry sector) to test its applicability. The process of planning, simulating, analysing, and confirming SAHP improved the understanding of the process and refined the debate and the decision-making to select the alternative suggested by the SAHP was made easier. As a result, the redesigned alternative was selected over the improvement option and the team proceeded to find potential ways to prevent defects. The SAHP as a technique was successfully applied and did not require further modifications.

Similar to the previous action research cycles, the tools and techniques and methods employed on this DMAIC project present a degree of similarity to those used during DFSS projects. However, it can be said that during this project the tools and techniques employed in the initial phases were predominantly part of the DMAIC toolkit. After the decision redesign/improve was made a DFSS tool was employed, i.e. DFMEA. At Land Rover, Six Sigma and DFSS are seen as adaptable processes that require the use of specified tools and techniques at every phase. Each project may select methods and tools according to their ability to fulfil key Six Sigma or DFSS elements.

5 Discussion and Main Findings

The purpose of the discussion and final reflection is not only to align the three action research projects with the theory but also to extend the theory through an innovative application of knowledge. This reflection was carried out by analysing the outcome of the three action research cycles with the literature in regard to each of the hypotheses formulated.

5.1 Sigma level

"The sigma capability of products/processes has a positive association with the selection of redesign or improvement efforts within Six Sigma, however the Five Sigma level cannot necessarily dictate the use of one approach over the other."

According to the Six Sigma literature, adopting Six Sigma DMAIC processes can be improved up to Five Sigma (Pyzdek, 1998; Breyfogle, 1999; Harry and Schroeder, 2000; Pande *et al.,* 2000; Eckes 2001; Chowdhury, 2002). In this research, the first action research cycle employed DMAIC Six Sigma to improve the process from 1.29 Sigma to 2.06 Sigma long term. After that, the process was redesigned achieving 2.64 Sigma long term. Similarly, the third action research cycle decided to redesign the process to surpass the 1.12 Sigma level (0.88 Sigma for the CTQ time) after initially employing DMAIC Six Sigma. The second action research project (Submission 4) performed at a 1.67 Sigma long term. Thus, according to the Six Sigma literature the product can be improved by means of DMAIC, however, the change of the current product specification to a higher level left the inherited technology incapable of reaching the new customer demands, thus the process was redesigned.

Instead of the "Five Sigma wall", (3.5 Sigma long term) the three action research cycles presented here employed a redesign approach to surpass the "2.06 Sigma wall", "1.67 Sigma wall" and "1.12 Sigma wall" (or the "0.88 Sigma wall" for the CTQ time) respectively, as Table 4 shows.

Table 4: Capability level when redesign was selected

	Literature	First action research cycle (Submission 3)	Second action research cycle (Submission 4)	Third action research cycle (Submission 5)
Sigma level achieved before redesign	3.5 sigma long term (5 sigma short term)	2.06 sigma long term	1.67 sigma long term	0.88 sigma* 1.12 sigma' long term
Initial Six Sigma methodology employed	DMAIC	DMAIC	DFSS (IDOV)	DMAIC
Industry sector	Various	Abrasives	White goods	Automotive

**CTQ time*
'CTQ quality

During Submission 1 the researcher argued that the "Five Sigma" wall to define the improve or redesign issue as an affirmation is highly arguable because of the lack of data to support the claim and the absence of assumptions to formulate it. The three action research cycles evidence enables the author to state that the "Five Sigma wall" cannot necessarily dictate the use of the requisite Six Sigma approach. Nevertheless, the sigma capability of products/processes had a positive association with the selection of redesign or improvement efforts within the Six Sigma projects presented here. The project presented in the first action research cycle (Submission 3) considered the process capability as one of the main criterion when selecting redesign of the re-winder. Indirectly, Submission 5 took into account process capability when considering improving quality and performance in the engineering change, and thus increasing the sigma level.

It is important to state that the evidence presented in this research is not random and accurate statistical evidence on the selection of the requisite Six Sigma approach within the UK industry. Instead, this research aims at capturing the essence of the improve or redesign issue by extracting data from three Six Sigma projects, which contain in-depth explanation and analysis. Refer to chapter 7.

5.2 Numerous criteria

"Numerous process/product factors are associated with the decision as to when to embark on redesign efforts."

For some authors (Pande *et al.*, 2000; Eckes 2001; Truscott, 2003), the issue of whether to improve or redesign is usually subject to different factors. They affirm that factors such as risk, process capability, technology availability and change in the company's strategy may be considered for the selection of the requisite Six Sigma approach. During each of the cycles of the action research spiral conducted the processes under study were redesigned considering criteria such as performance, risk, capability/entitlement, performance, financial benefit, cash avoidance, reliability, cost, recyclability, safety and assemblability. These criteria were further sub-divided into attributes or sub-objectives. Table 5 shows the different criteria used during the three action research cycles and those found in the literature. The criteria identified during this research are not exhaustive for the improve or redesign issues. The researcher expects that different factors will emerge for different Six Sigma projects. Moreover, they can vary depending on the prevailing conditions and the interactions amongst them, as achieving any criterion individually might affect the desired outcome of other criteria.

Table 5: Criteria affecting the selection of the Six Sigma approach

[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
Risk	Pande *et al.*, 2000	✓	✓	✓
Capability/ entitlement	Harry and Schroeder, 2000; Tennant, 2001; Chowdhury, 2002	✓		
Performance			✓	✓
Chaotic process	Pande *et al.*, 2000; Eckes, 2001.			
Financial benefit		✓		
Cash avoidance		✓		✓
Reliability			✓	
Cost			✓	
Recyclability			✓	
Safety			✓	
Assemblability			✓	
Quality				✓

From the evidence of this research, it can be said that numerous process/product factors are associated with the decision as to when to embark on redesign efforts. The identification and understanding of such factors increases as the root cause of the problem is identified. In addition the process of implementing the AHP or the SAHP sharpen up the debate and decisions and lead to the identification of new factors.

5.3 Provision of MCDA technique

"The provision of a consistent methodology and techniques, for representing and analysing the decision system for a Six Sigma approach selection, has a positive association with an effective Six Sigma approach assortment."

One of the hypotheses to test in this research is the selection and application of a consistent MCDA technique for representing and analysing the decision system for the Six Sigma approach selection. The researcher, by taking into consideration the problem content, the intervention system and intellectual resource systems as suggested by Mingers (2001) selected the Analytic Hierarchy Process as a suitable MCDA for the selection of the requisite Six Sigma approach.

The work detailed in Submission 3 discovered AHP was a suitable method for the selection of improve or redesign for the re-winder. The AHP provided the decision-maker with an understanding and awareness of the problem under consideration and with a measurement of consistency. However, during Submission 4 analysis of the applicability of the AHP dictated the incorporation of uncertainty, managerial aspects and statistical significance into the results. The improve or redesign issue is multidimensional where technical or physical aspects, social and political aspects and personal ones can be present, including the relationship between people, and their differential willingness and ability to adjust to the changed circumstances of the desired solution of the problem. In addition, different people and departmental factions can have different conceptions as to what the problem is. All these might affect reaching consensus and converging ambiguous judgments to a Likert scale (Hauser and

Tadikamalla, 1996). Therefore it is important to understand the problem and its structure prior to attempting to solve it through the AHP.

To deal effectively with the full richness of the problem, it is necessary to deal with this multi-dimensionality under uncertainty and incorporate managerial issues into the AHP. By doing so, the following benefits can be achieved:

- An understanding of the context of the problem.
- Structuring of the problem to be solved.
- Management of the relationship between people, and their differential willingness and ability to adjust to the changed circumstances of the desired state of the problem.
- Facilitation of consensus, generate new insights and provide more confidence in the results.
- Employment of more than one method in tackling real world problems (i.e. link the AHP with other "soft" methods).

The Stochastic Analytic Hierarchy Process (SAHP) was developed and applied to the original selection bearing in mind the issues learned from the first application of the AHP. Submission 5 also employed SAHP to select between improving and redesigning the handover process. For the selection of the requisite Six Sigma approach the researcher and the collaborative companies found, in SAHP, a suitable MCDA technique. The SAHP was specially developed to select the requisite Six Sigma approach while considering both uncertainty and managerial aspects. The methodology for SAHP has established a systematic framework that can be applied to different multi-criteria problems for the selection or justification of various decisions. A major contribution of this research lies in its development. SAHP has the potential of being applied to problems previously solved using AHP offering a means of incorporating uncertainty and the statistical significance of the results. Some of the areas where SAHP can be employed, as a general multi-criteria decision analysis technique, include: selection of projects; selection of design concepts; make or buy decisions; resource allocation; and manufacturing plant selection. However, the broader applicability of the SAHP has yet to be tested and represents a direction for further research (refer to section 8.4).

Even though the SAHP as a model becomes more and more complex and may become resource consuming, the benefits of selecting a better alternative by taking into account quantitative and qualitative information under uncertainty are expected to outweigh the costs. The time required by an organisation to implement the SAHP will decrease as additional learning occurs along with reuse of static data portions of the model.

5.4 Symbiosis between Six Sigma and DFSS

"Six Sigma improvement efforts have traces of redesign activities and vice-versa."

In Submission 2 DFSS and Six Sigma were differentiated in terms of their philosophy, methodology and the tools and techniques that they employ. Although this distinction of Six Sigma and DFSS is not claimed to be "correct" in some sense, and inevitably some latitude will be required in applying this distinction, it is necessary to test this hypothesis. Accordingly, it is possible to compare DFSS and Six Sigma in terms of their philosophical assumptions, the methodologies employed and the tools and techniques that they use.

During Submission 2 it was stated that Six Sigma can be considered a reactive and defensive philosophy to solve problems. On the other hand, Design for Six Sigma is an offensive, preventive and proactive philosophy. Accordingly, the first and third action research cycles initially focused on eliminating defects and enhancing performance on current processes assuming that current design is essentially correct, thus the use of DMAIC Six Sigma was justified. The second action research opted for a redesign approach, thus the IDOV DFSS methodology was followed. However, during the DMAIC manufacturing project carried out in Submission 3, the ageing of the process, the cost of maintaining the current technology and the expected benefits of introducing a redesign process established that redesigning the process was a more feasible solution than trying to improve it. A similar decision was also taken during the analysis and improvement phases of the third action research project, the process could not provide sufficient improvement, thus the project adopted a more preventive approach. These projects were originally identified as DMAIC, but later it was necessary to put them through the IDOV methodology as processes could not provide sufficient improvement.

Conversely, the DFSS project presented in Submission 4 opted for a DFSS approach, consequently the IDOV methodology was employed. However, the decision to improve or redesign was raised during the concept design selection where four different design alternatives, including the current design, were evaluated. As the current design was not selected, a major redesign took place. But it was noticed that it was possible to improve the design by minor improvement or optimisations following the IDOV methodology. This approach has been adopted by GDA during previous products designs by updating through minor improvements their products.

From an examination of the collaborative companies training materials and the projects carried out with them some similarities were perceived in terms of the tools and techniques used in DFSS and Six Sigma. The Appendix shows a comparison of the tools and techniques taught during Six Sigma and DFSS training at 3M, GDA and Land Rover. In 3M, for example, most of the DMAIC tools and techniques are also incorporated on either the DFSS assembly or DFSS chemical toolkit. Seventeen out of the twenty main topics taught on the DMAIC course are also taught during the DFSS training. Only "Cost of Poor Quality", "Standard Operation Procedures" and "Mistake Proofing" are exclusive of DMAIC practice. In addition, in the collaborative companies Six Sigma and DFSS are seen as adaptable processes that require the use of specified tools and techniques at every phase. Accordingly, each of the projects conducted in this research selected tools and techniques according to their ability to fulfil the project deliveries regardless of the origin of each individual technique. This makes it difficult to establish a clear boundary between redesign and improvement versions of Six Sigma in regards of the tools and techniques employed by each approach

From the evidence collected in the action research spiral it can be said that the Six Sigma and DFSS are linked in an enduring symbiosis; each requires the other and each interfaces with the other to contribute effectively and efficiently to achieve the targets set during Six Sigma projects. In addition there is a degree of overlap between both approaches in terms of their methodologies, tools and techniques. Consequently, the selection between Six Sigma and DFSS is within in a spectrum since Six Sigma improvement efforts have traces of redesign activities and vice-versa.

6 Innovation Statement

The concept and implementation of SAHP is new to the selection of the requisite Six Sigma approach and as such it constitutes the main innovation to result from this research. It extends the selection of the requisite Six Sigma approach beyond the sigma level case and the general guidelines, towards a systematic multi-criteria decision considering multiple and usually conflicting criteria under uncertainty. Furthermore, while the SAHP was originally conceived as a specific aid to the improve or redesign issue within Six Sigma, this research indicates that it is potentially much more widely applicable (e.g. project and design concept selections).

This research also demonstrates innovation in the study of factors to select the requisite Six Sigma approach through action research. Contrary to other studies (Harry and Schroeder, 2000; Pande *et al*, 2000; Eckes, 2001), this research provides actual data and background information of how different criteria were considered for the selection of the requisite Six Sigma approach during three Six Sigma projects in three different collaborative companies. This assisted the collaborative companies and provided innovation as few authors have raised the issue and their views fundamentally differ.

To establish areas of innovation, either in developing new processes or applying established processes in different application, the following framework in Table 6 was used.

Table 6: Innovation framework

Test	Response	Section
1) What aspects of the project are entirely new?	This research extends the selection of the requisite Six Sigma approach beyond the sigma level case and the general guidelines towards a multi-criteria decision using the Stochastic Analytic Hierarchy Processes.	Section 2.5 and section 4.
2) What aspects of the project have been done elsewhere but not yet applied to your own industry or business situation?	The application of MCDA techniques is widely reported in the literature. However, the literature does not report the use of MCDA for the selection of the requisite Six Sigma approach.	Section 2.3
3) Are there significant alternatives ways of tackling the task, "thus allowing greater scope for innovation" or is the main path already determined?	This research indicates the potential broader applicability of SAHP beyond specific industrial settings. This hypothesis however requires testing through empirical work.	Section 8.4
4) What do you perceive as the main areas of innovation?	The concept and implementation of SAHP is new to the selection of the requisite Six Sigma approach and as such it constitutes the main innovation to result from this research.	Section 6.
5) How relevant is the innovation to: a) Your own company? b) Your own industry? c) All industries	The innovation is considered relevant regardless of the company or industry constraints.	Section 35.
6) What new processes/ materials/ techniques, procedures will arise from this project that will create better options for action in the future?	Although SAHP was originally conceived as a specific aid to the improve or redesign issue within Six Sigma, this research indicates that it is potentially much more widely applicable.	Section 8.4
7) How will the project contribute to a greater understanding of the subject area and its contribution to the business environment?	By identifying and quantifying the different factors affecting the selection of the Six Sigma versus DFSS as well as by testing the applicability of MCDA for solving this issue.	Section 73.
8) Will the outcome of the project be worthy of wider dissemination e.g. through publications and conferences?	The outcome of the project has been published in various journals and presented at a conference.	Section 1.2.1 and Submission 6.
9) What would be the effects on the business of NOT going ahead with the project?	During this research it was argued that it is pointless to try to improve a process by means of DMAIC where the fundamental design of the process is inadequate; therefore it is compulsory to identify conditions where the effectiveness of processes can be improved by employing redesign efforts or where the efficiency of a process needs to be improved through Six Sigma.	Section 26
10) On what information/experience have you based your answers to the above questions? For example, do you know what other companies and research institutions, or parts of your organisation have tackled similar problems?	Based on a literature review in Six Sigma and parallel areas of the research. In addition, three project in three organisations were studied. The findings of the researcher were put in the public domain so they can be debated and defended.	Chapters 2 and 4.

7 Validity of the Research

In research much of the achievement of rigour is embodied in the concepts addressing the many dimensions of validity (Mentzer and Flint, 1997). Validity is a hierarchy of procedures to ensure that what is concluded from research can be stated with some confidence, i.e. the conclusions are valid (Mentzer and Kahn, 1995). There is a popular belief that the methods of a positivist approach can be more easily generalised and validated with the aid of objective and rigorous statistical analysis. On the other hand, phenomenological research strategies such as action research, are subjective, therefore unreliable and the solutions they claim cannot be generalised (McNiff, 1988). In this research the sample was neither randomly selected from the population nor was its size statistically selected, thus no statistical conclusions about the population can be drawn. However, researchers argue that the fact that action research arises from a different background means that it cannot be judged using the same criteria as other research methods (Waterman, 1998; Badger, 2000; Kelly and Simpson, 2000). Consequently, the full access to the knowledge and meaning of informants give a degree of internal validity (Easterby-Smith, *et al.,* 1999). Conversely, external validity is evaluated by the degree of generalisation of the findings through conceptual replication and industrial application (Mentzer and Flint, 1997).

7.1 Internal validity

Because this research assesses the effects of interventions, internal validity is of primary consideration. Action research intends to capture the essence of the phenomena by extracting data which is rich in its explanation and analysis, and the researcher has full access to the knowledge and the meaning, thus internal validity is aimed to be higher under action research than in other methods (Coghlan and Brannick, 2001). In action research a special concern is whether or not the data collected and reported are a true reflection of what was studied (Waterman, 1998). This problem can be mitigated by making available to the reader the details of each core action research cycle. In this way the reader can interpret how the researcher tested the research hypotheses during each Submission. In addition, internal validity was enhanced by means of triangulation[11] (Hussey and Hussey, 1997; Baskerville and Wood-Harper, 1996; Coghlan and Brannick, 2001). In this research a full variety of evidence - documents, reports that the collaborative companies routinely produce; artefacts, informal interviews and observations were employed.

7.2 External validity

It is recognised that this research only claims some degree of external validity since it is implicit that within action research unique situations are being studied, and generalisation is not normally inferred (Kelly and Simpson, 2000). Nevertheless,

[11] *Triangulation* is the use of different research approaches, methods and techniques in the same study. *Triangulation* can avoid the potential bias and sterility of a single method approach (Hussey and Hussey, 1997).

although a situation may be individual, unique and specific, it is "of a kind", that through nomo-logical deductions[12] and industrial applications some findings may be generalised to other situations (Badger, 2000). That is; generalisation is based on contextual similarity rather than statistical significance (Meyer, 2000).

7.2.1 Conceptual replicability

During this research different hypotheses were tested and MCDA techniques were implemented for the selection of the requisite Six Sigma approach. For Mentzer and Flit (1997) a way to add certainty is to have others to replicate the study. Thus, only by giving others full access to the research methods and encouraging replication by means of publication can the research be replicated (McNiff, 1988; Coghlan and Brannick, 2001). Consequently, this research was placed in the public domain so that conceptual replicability can be promoted and the research can be debated and defended. The researcher aimed at having a broad range of audiences, thus he published the research in different journals which target different audiences, including practitioners and academics.

In an effort to be more able to provide a higher degree of generalisation the researcher selected polar cases, as studies conducted under varying conditions of time, company, industries and persons demonstrate empirical support of the conclusions and the external validity is enhanced. In addition, by using theoretical sampling the core action research projects were chosen to replicate previous cases, to extend theory, to fill

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[12] Nomo-logical deductions has the following form: If action of type "A" by the collaborative companies always produces consequences of type "C" in a given class of situations, then company "X" takes action "A" in a particular situation then a consequence of type "C" occurs. This contrasts with the inductive – statistical approach, which asserts that if a certain specifiable conditions are realised, then a particular event will occur with certain statistical probability.

theoretical categories and/or provide examples of polar cases (Eisenhardt, 1989; Zuber-Skerrit and Perry, 2002). Accordingly, each action research cycle was carried out in different industry sectors (abrasives, white goods and automotive) by different organisations (3M, GDA and Land Rover), people and in different organisational settings (manufacturing, design and engineering departments). In this form, replicability was gradually enhanced and was not limited to a single industry or organisation.

7.2.2 Industrial application

The author implemented the AHP and the SAHP in three industrial applications. The three action research cycles conducted during this research simultaneously assisted in practical problem solving in industry and helped to innovatively apply knowledge to new or unusual circumstances. The introduction and testing of MCDA techniques for the selection of the requisite Six Sigma approach required its real application in industry. Thus, a significant part of this research was undertaken at the collaborative companies and therefore all hypotheses were tested in industry.

The validity of the SAHP as a technique is primarily demonstrated by its industrial application. The purpose of the SAHP is to provide insights and understanding, sharpen debate and finally select an alternative considering multiple criteria. The right decision is considered to be that choice reached by decision-makers after a holistic assessment of the available alternatives (Larichev, Olson, Moshkovish and Mechitov, 1995). In addition, the alternatives suggested by AHP and SAHP were fully implemented in two of the three cases. At the time of writing, the third case was in the implementation process.

8 Conclusions

Six Sigma has focused on improving processes by eliminating variation using a well-structured methodology. Although initially employed to improve existing products and processes Six Sigma has started to focus upon design and redesign of products and processes capable of achieving Six Sigma levels using a different approach known as Design for Six Sigma (DFSS). In this research it was argued that companies can apply Six Sigma and DFSS approaches, thus yielding more improvements than if only one of them was used on its own. However, there is a lack of unanimity in the literature to determine when one approach becomes a priority over the other, in order to improve the efficiency and effectiveness of processes and products.

8.1 Conclusions about each research question

The lack of unanimity raised the following research question: *What influences the selection of the requisite Six Sigma approach, i.e. Six Sigma versus DFSS?* To answer this question, three projects in three different industry sectors were carried out using action research as a method of investigation. During the three projects of the action research spiral an initial decision was made to employ Six Sigma or DFSS for a particular project. This decision was based on whether the original design of the process/product under study was essentially correct, the delivery partners' needs were satisfied with that design and; the current product/process configuration satisfies the functional requirements of the market and customer or delivery partner. Nevertheless, as special causes were identified and eliminated using Six Sigma the status quo was changed by means of DFSS. From an analysis of the three projects it was found that the sigma capability of products/processes has a positive association with the selection of redesign or improvement efforts within Six Sigma. The project presented in the first action research cycle considered the process capability as one of the main criterion when selecting redesign of the re-winder. Indirectly, the Six Sigma project carried out in collaboration with Land Rover took into account process capability when it considered improving quality and performance on the engineering change, and thus increasing the sigma level. Nevertheless, in the DFSS project, the sigma capability criterion to define the use of a redesign approach was ignored. The change of the current product specification to a higher level left the inherited technology incapable of reaching the new customer demands. In contrast with the literature, which suggests that the only way to surpass the "Five Sigma wall" is by redesigning the process, the projects analysed during this research employed a redesign approach after the causes of poor quality were understood and to surpass a lower level of quality than the "Five Sigma wall". Consequently, the Five Sigma level cannot necessarily dictate the use of one approach over the other.

During the three projects analysed in this research, numerous product or process criteria influenced the decision as to when to embark on redesign efforts. Each of the cycles of the action research spiral conducted during this Engineering Doctorate, the processes under study were redesigned considering multi-criteria. In the DMAIC project financial benefit, cash avoidance, risk reduction and capability level were the main criteria affecting this decision. In the DFSS project, the criteria considered in the decision were cost, safety, performance, quality and reliability, assemblability and recyclability. During the DMAIC project in a non-manufacturing process the criteria involved were quality, risk, performance and investment. The criteria identified during this research are not exhaustive and it is expected that other criteria will emerge for different Six Sigma projects. Moreover, the importance of specific criterion in this decision can vary depending on the prevailing conditions and the interactions amongst the criteria involved. In order to select the requisite Six Sigma approach by considering the criteria involved in this decision, this research tested the applicability of MCDA techniques to deal with this decision, and consequently answered the question: *how effective is the use of Multi-Criteria Decision Analysis (MCDA) techniques in the selection of the requisite Six Sigma approach?* The operational research field has a number of MCDA techniques suitable for the selection of the requisite Six Sigma approach. From a number of MCDA techniques, the researcher chose the Analytic Hierarchy Process. Although, during the first action research project AHP was successfully applied to the selection of the requisite Six Sigma approach, during the second project AHP failed to deal with the decision of whether to redesign or improve. This was attributed to the uncertainty that decision-makers have in converging single point scale judgments used in the AHP construction. In order to deal with this uncertainty a SAHP was developed and applied to the problem at hand. SAHP proved to be a more robust method, because management of uncertainty using probabilistic judgments provided the decision-makers with a means to test the final scores statistically. This method was also successfully applied to select between redesign the current process or improve it, during the third action research cycle in collaboration with Land Rover.

From the evidence presented in this research it can be concluded that the provision of SAHP for representing and analysing the decision system for a Six Sigma methodology selection, has a positive association with an effective Six Sigma approach assortment. The effectiveness of the SAHP in this research is related to the degree in which it produces the desired outcome. That is, whether or not the use of SAHP can incorporate the key elements of the problem (the alternatives, criteria, decision makers and uncertainties) to select the Six Sigma approach after a holistic assessment of the available alternatives and their implications. SAHP provided insights, understanding and sharpened debate. The process of attempting to structure the process by means of SAHP was useful in achieving the goals, and the numeric output of SAHP provided confidence in the results.

From an analysis of the three projects it was also found that Six Sigma projects may have traces of redesign activities and DFSS projects may have traces of continuous improvement activities. In addition, a degree of commonality in the tools and techniques employed on each approach exists. Nevertheless, as the root causes of variation were understood, teams were able to identify redesign and improvement alternatives to reduce variation.

8.2 Implications for practice and theory

The author argues that it is important to identify conditions where the effectiveness of processes can be improved by employing redesign efforts or where the efficiency of a process needs to be improved through Six Sigma. During this research, three projects identified these conditions using the AHP and the SAHP respectively. This facilitated the collaborative companies in making an appropriate resource allocation and to maintain an effective balance between the two approaches. The development and application of the SAHP to deal with the research problem represents a major departure from existing guidelines by taking into account measurements and judgments under uncertainty as well as systematic multi-objective performance evaluation. In addition, the study of factors through action research to select the requisite Six Sigma approach, assisted the collaborative companies and provided an innovative application of knowledge since few authors have raised the issue and they differ fundamentally. Contrary to other studies, this research provides actual data and background information of how different factors influenced the selection of the requisite Six Sigma approach. The main achievements of this research are:

- The development of SAHP into a technique for deciding between Six Sigma and DFSS;
- A study of the selection of the requisite Six Sigma approach in three different projects;
- The application of MCDA techniques for the selection of the requisite Six Sigma approach;
- The potential wider application of SAHP as technique;
- The financial benefits achieved as a result of the Six Sigma projects;
- The provision actual evidence of the criteria considered for the selection of the requisite Six Sigma approach in three cases.

8.3 Limitations

This research is limited to three organisations with operations in the UK, which are currently implementing Six Sigma and Design for Six Sigma. Due to these limitations generalisation is carried out through nomo-logical deductions and industrial applications, thus, generalisation depends on contextual similarity rather than statistical significance. The selection of the requisite Six Sigma approach was analysed at a project level. During this research AHP was selected from a number of MCDA techniques, thus the effectiveness of the use of these techniques to the selection of the Six Sigma approach is limited to the AHP and SAHP cases. Consequently, the applicability of other MCDA techniques for the selection of the requisite Six Sigma approach remains to be seen.

8.4 Directions for further work

As with any research effort, there are additional areas to investigate and improve. The proposal for further research is divided into the generalisation of the research findings and the further development of the SAHP as a technique.

8.4.1 Generalisation of the findings

An effort to generalise the findings of this research is advisable using a positivist method (e.g. surveys, interviews) in order to increase the sample size and to identify different factors affecting the use of Six Sigma over DFSS in a broader range of industries and settings (e.g. different countries or the selection of the requisite Six Sigma approach in Small and Medium Enterprises). In addition the matter of this research can be studied at different levels of the organisation or by organisations about to embark on Six Sigma or Design for Six Sigma. That is, the improve or redesign issue can be studied at a business level rather than a project level.

8.4.2 Development of SAHP software

The development of the SAHP technique produced a more complex approach than the AHP. Expert Choice software has been developed for the traditional AHP. A potential area of research and development is the creation of computer software for SAHP. Since SAHP is a group decision making technique it is important to take this into consideration when developing the software, allowing people to deploy the hierarchy structure over the web so decision-makers can evaluate the objectives and alternatives from different locations. Additional features of the software could include managing decisions with documentation, reports and sensitivity analyses, providing capability to accept judgments from multiple stakeholders in different geographic locations at the same time and evaluating outcomes based on team member demographics.

8.4.3 Extending the SAHP practice

It is important to note that at the time of submission, the broader applicability of the SAHP has yet to be tested. The application of SAHP in two different organisations indicates the potential broader applicability of SAHP beyond specific industrial settings. This hypothesis however requires testing through empirical work. Further implementation of SAHP is therefore planned in the following areas:

Industrial replications: Implementation of SAHP for the selection of the requisite Six Sigma approach in different projects for "fine tuning" e.g. cultural factors associated with differences in mode of operation, organisation structure and management style.

Six Sigma project selection: Six Sigma project selection is considered a complex and multi-criteria problem (Pyzdek, 1998; Breyfogle, Cupello and Meadows, 2001; Adams, Gupta and Wilson, 2003). SAHP has the potential of reducing the complexity of the selection of projects to a series of one-on-one comparisons and then synthesising the results using statistics.

Application of SAHP outside the Six Sigma field: AHP has been applied to a wide range of problems. SAHP also has the potential of being applied to problems previously solved using AHP offering a means of incorporating uncertainty and the statistical significance of the results.

Extending SAHP for systems with feedback: It remains to be seen if it is possible to apply the principles and mechanisms to estimate the rankings used by SAHP for systems with feedback (Analytic Network Process). That is, decision systems which do not have the linear top to bottom hierarchical form but look more like a network (Saaty, 1996).

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Appendix

Tables 7, 8 and 9compare the different tools and techniques taught during the Six Sigma and DFSS training in the collaborative companies. They were retrieved from the syllabus of the Black Belt trainings.

Table 7: Comparison of tools and techniques taught during DMAIC and DFSS trainings at 3M

Tools, Techniques and Topics	DMAIC	DFSS Assembly	DFSS Chemical
Project Chartering	✓	✓	✓
Business Plan	✓	✓	✓
Cost of Poor Quality	✓		
Customer Value Management		✓	✓
Market Segmentation		✓	✓
Process Maps	✓		✓
Cause and Effect Matrix	✓		✓
Measurement System Analysis	✓	✓	✓
Capability Analysis	✓	✓	✓
Basic Statistics	✓	✓	✓
Concept Engineering		✓	✓
QFD		✓	✓
Pugh Concept Selection		✓	
Design for Assembly		✓	
Design for Manufacture		✓	
Product Reliability		✓	
Statistical Tolerancing		✓	✓
Design Critical Parameter Flow		✓	
Failure Mode and Effect Analysis	✓	✓	✓
Modular Design		✓	
Multi-Vari Analysis	✓	✓	✓
Hypothesis test	✓	✓	✓
Multiple Regression	✓	✓	✓
Design of Experiments (DOE)	✓	✓	✓
Balanced ANOVA/Residuals	✓	✓	
Response Surface Modelling	✓	✓	✓
Critical Parameter Mgt		✓	✓
Sensitivity Analysis			
Robust Design Taguchi		✓	✓
Design Experiments Mixtures			✓
Optimisation for Multiple Reponses			✓
Final Capability Study	✓	✓	✓
Control Plans	✓	✓	

Tools, Techniques and Topics	DMAIC	DFSS Assembly	DFSS Chemical
Standard Operation Procedures	✓		
Statistical Process Control	✓		✓
Mistake Proofing	✓		

Source: 3M Six Sigma training material (3M, 2002)

Table 8: Comparison of tools and techniques taught during DMAIC and DFSS training at GDA

Tool/Technique	DMAIC Commercial	DMAIC Technical	DFSS
Team Charter	✓	✓	✓
Quality Function Deployment	✓	✓	✓
Process Map	✓	✓	
Failure Mode and Effect Analysis	✓	✓	✓
Cause & Effect	✓		
Brainstorming	✓	✓	
Structure Tree		✓	✓
Pareto Analysis	✓	✓	
Kano Model	✓		✓
Gauge R&R	✓	✓	✓
Rational Sub-groups	✓	✓	✓
Sampling	✓	✓	✓
Statistical Toleracing		✓	✓
Process Capability	✓	✓	
Monte Carlo simulation		✓	✓
Affinity Diagram	✓		
Design for assembly			✓
Transfer functions			✓
Graphing	✓	✓	✓
Hypothesis Testing	✓	✓	✓
Regression	✓	✓	✓
Confidence Intervals	✓	✓	✓
ANOVA	✓	✓	✓
Scatter diagram	✓		
Design of Experiments	✓	✓	✓
Response surface methodology		✓	✓
Multiple response optimiser		✓	✓
Cost/Benefit analysis	✓		
Implementation Plan	✓	✓	
Reliability theory and models			✓
Fault tree analysis			✓
Reliability block diagrams			✓
Design for reliability			✓
Design for manufacturing			✓
Statistical Process Control	✓	✓	✓
Mistake Proof	✓	✓	✓
Control Plans	✓	✓	
Procedures	✓	✓	
Training Plans	✓	✓	
Response Plan	✓	✓	

Tool/Technique	DMAIC Commercial	DMAIC Technical	DFSS
Communication Plans	✓	✓	
DFSS scorecard			✓
Action plans	✓	✓	

Source: GDA Six Sigma training material (GDA, 2002).

Table 9: Comparison of tools and techniques taught during DMAIC and DFSS training at Land Rover

Tools and Techniques	DMAIC	DFSS
Project Charter	✓	✓
Costs of Poor Quality	✓	
CTQ Tree	✓	
Pareto Analysis	✓	
Gap Analysis	✓	
High level process map (SIPOC)	✓	✓
Consumer Insight		✓
Market Research and Brand Analysis		✓
Kano Model		✓
Affinity diagrams		✓
Mind Maps		✓
Quality Function Deployment		✓
Quality Loss Function		✓
System Engineering-Target Setting & Verification		✓
DFSS Scorecard		✓
Cause and Effect Tools	✓	
Failure Mode and Effects Analysis	✓	✓
Basic Statistics	✓	✓
Benchmarking	✓	
Data Collection and Analysis	✓	✓
Measurement Systems Analysis	✓	✓
Concept Generation & Selection (i.e. Mind Maps)		✓
Theory of Inventive Problem Solving (TRIZ))		✓
Confidence Intervals	✓	
Morphological Matrix, Pugh Analysis, AHP)		✓
Hypothesis Testing	✓	✓
Analysis of Variance (ANOVA)	✓	✓
Correlation and Simple Regression	✓	
Multi Vari	✓	
Full Factorial Experiments	✓	✓
Fractional Factorial Experiments	✓	✓
Central Composite		✓
Latin Hypercube		✓
System & Functional Diagrams		✓
Axiomatic Design		✓
P-Diagram		✓
Cause and Effect Diagram	✓	✓
Cause and Effect Matrix	✓	✓
System Diagrams		✓
Function Structure Diagrams		✓
Hardware Interface Matrices		✓
Reliability and Robust Engineering Design		✓
Dimensional Variation Analysis		✓
Numeric/Heuristic Optimisation		✓

Tools and Techniques	DMAIC	DFSS
Parameter Design		✓
Tolerance Design		✓
Analytical Reliability & Robustness		✓
Statistical Tolerancing		✓
Process Capability		✓
Design for Manufacturing and Assembly		✓
Statistical Process Control	✓	✓
Reaction Plan	✓	
Mistake proofing operation	✓	
Training plan	✓	
Standarised work	✓	
Preventive Maintenance	✓	
Visual Process Environment (including 5S, charts, plots, pre-control)	✓	
Quality System controlled documented systems	✓	
Model Validation & Uncertainty		✓
Design Verification		✓
Robustness/Reliability Demonstration		✓
Control Plan		✓

Source: Ford/Land Rover Six Sigma training material (Ford, 2003).