Design for Six Sigma (DFSS): lessons learned from world-class companies

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Abstract: Design for Six Sigma (DFSS) is a powerful approach for designing products, processes and services to meet the needs and expectations of the customer while driving down quality costs. It involves the utilisation of powerful and useful statistical tools to predict and improve quality before building prototypes. This paper attempts to study DFSS and the associated experiences of world-class companies. For this purpose, DFSS methodologies are introduced and compared with Six Sigma methodology. The DFSS process is demonstrated and some examples of world-class companies are presented. Finally, some implementation obstacles are addressed and the DFSS training programme is described and emphasised. The findings imply that the methodologies for DFSS are enormous and companies employ different methodologies. Also, it has been found that the role of project leaders is essential for the success of projects and the training programme offered in DFSS should be flexible.

Keywords: Design for Six Sigma; DFSS; process; methodology; implementation; training.

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1 Introduction

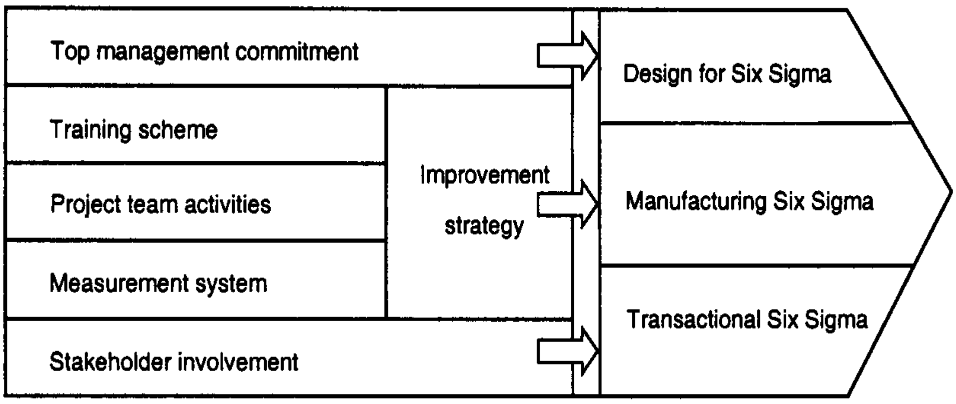
Six Sigma is a business performance improvement strategy that aims to reduce the number of mistakes/defects – to as low as 3.4 occasions per million opportunities. Sigma is a measure of the 'variation about the average' in a process (which could be in a manufacturing or service industry). According to Conlin (1998), most companies produce a defect rate of between 35 000 and 50 000 per million opportunities (where a defect can be anything from a faulty part to an incorrect customer bill). This defect rate equates to a sigma quality level of 3 to 3.5 sigma. Organisations that have adopted the principles and concepts of the Six Sigma methodology have become aware that, once they have achieved five sigma quality levels (*i.e.*, 233 defects per million opportunities), the only way to progress further (towards the elusive Six Sigma) is to redesign their products, processes and services (Harry and Schroeder, 2000; Chowdhury, 2001; Banuelas and Antony, 2003; Banuelas and Antony, 2004). This has led to the development of what today is termed 'Design for Six Sigma' (DFSS). On the other hand, for researchers such as Pande *et al.* (2000), it is not yet clear when redesign efforts should be used over continuous improvement. DFSS is a powerful approach to designing products, processes and services in a cost-effective and simple manner to meet the needs and expectations of the customer while driving down quality costs. It involves the utilisation of powerful and useful statistical tools to predict and improve quality before building prototypes. It is not a replacement for such techniques/approaches as New Product Introduction Process (NPIP); rather it is a methodology to make the introduction of new products, processes and services more efficient, reliable and capable of meeting high customer expectations and requirements. DFSS has the potential to simplify design configurations, eliminate non-value-added steps or processes in the design of a product or service, and hence reduce material costs, labour costs and overhead costs. The DFSS approach seeks inventive ways of satisfying and exceeding customer requirements and expectations. It seeks to optimise the function of the product/service design and then verify that the product/service meets the requirements specified by customers.

The aim of this paper is to study DFSS and the associated experiences of world-class companies. For this purpose, in the following, it is highlighted where DFSS fits in the corporate framework of the Six Sigma. The DFSS methodologies are introduced and compared with Six Sigma methodology. DFSS process is demonstrated and some examples of world-class companies are presented. Finally, some implementation obstacles are addressed and the DFSS training programme is described and emphasised.

2 Design for Six Sigma and the corporate framework of Six Sigma

The corporate framework of Six Sigma embodies the five elements of top-level management commitment, training schemes, project team activities, measurement system and stakeholder involvement, as shown in Figure 1. Stakeholders include employees, owners, suppliers and customers. At the core of the framework is a formalised improvement strategy with the following five steps: Define, Measure, Analyse, Improve and Control (DMAIC). The improvement strategy is based on training schemes, project team activities and measurement systems. Top-level management commitment and stakeholder involvement are both included in the framework. Without these two, the improvement strategy functions poorly. All five elements support the improvement strategy and improvement project teams. Most big companies operate in three parts: R&D, manufacturing and nonmanufacturing service. Six Sigma can be introduced into each of these three parts separately. In fact, the colour of Six Sigma could be different for each part. Six Sigma in the R&D part is often called 'DFSS', 'Manufacturing Six Sigma' in manufacturing, and 'Transactional Six Sigma (TSS)' in the nonmanufacturing service sector. All five elements in Figure 1 are necessary for each of the three different Six Sigma functions. However, the improvement methodology, DMAIC, could be modified in DFSS and TSS.

Figure 1 The corporate framework of Six Sigma



Source: Park (2003)

3 Design for Six Sigma methodologies

The original Six Sigma methodology developed for problem solving at Motorola is MAIC, which means measurement, analysis, improvement and control. Later, DMAIC instead of MAIC was advocated at GE, where D stands for definition. MAIC or DMAIC is mostly used as a unique problem-solving process in manufacturing areas. While Six Sigma is widely recognised by the DMAIC acronym, DFSS has no standard acronym. Therefore, organisations have adopted a variety of approaches that have resulted in acronyms, as follows (Park, 2003; Soderborg, 2004):

- Define, Measure, Analyse, Design, Verify (DMADV). MADV was suggested by Motorola for DFSS, and D was added to it for definition. DMADV is similar to DMAIC.
- Identify, Design, Optimise, Validate (IDOV). This was suggested by GE and has been used most frequently in practice.
- Define, Initiate, Design, Execute, Sustain (DIDES). This was suggested by Qualtec Consulting Company.
- Invent, Innovate, Develop, Optimise, Verify (IIDOV).

- Concept development, Design development, Optimisation, Verify, Certification (CDOV).
- Define, Characterise, Optimise, Verify (DCOV).
- Identify, Design, Evaluate, Assure, Scale-up (IDEAS).

Despite these naming differences, all versions of DFSS share fundamental strategies and tools that promote a common goal: to create a data-driven product development culture that efficiently produces winning products.

Some practitioners use different process phases for different categories of projects. For example, those who apply DFSS in technology and product development use IIDOV to describe DFSS for technology development and CDOV to describe product commercialisation (design). Some companies, such as Ford, use the DCOV abbreviation for all categories of DFSS projects to reduce confusion.

According to Park (2003), the above methodologies for manufacturing and R&D are not suitable for service areas. He emphasises that Define, Measure, Analyse, Redesign, Implement, Control (DMARIC) is an excellent problem-solving process for nonmanufacturing service areas, in which the 'redesign' phase addresses the redesign of the system of the service work towards the improvement of the service function.

More information on the DFSS methodologies and their comparisons can be obtained from Lönnqvist (2006).

4 Differences between Six Sigma and design for Six Sigma methodologies

The two philosophies differ in several ways. Six Sigma is considered reactive because it involves finding and fixing problems in existing processes. DFSS involves designing processes capable of reaching Six Sigma levels; thus it is considered a more aggressive quality approach. Moreover, Six Sigma and DFSS employ different methodologies. Six Sigma utilises the DMAIC methodology, which follows the phases define, measure, analyse, improve and control. In contrast, DFSS employs the DMADV methodology, which follows the phases define, measure, analyse, design and verify.

In practice, when DMAIC is used, Six Sigma teams tend to achieve constant incremental improvements by reducing or minimising the cause of variation in the existing processes. This approach of continuous improvement facilitates change on a steady and progressive basis. It seeks stability by reducing or even eliminating variation that leads to added costs and customer dissatisfaction (Finster, 2001). Six Sigma DMAIC projects work within the framework of the existing processes. The aim is to do what the company already does, but doing it efficiently and rigorously. These projects are developed from today's perspective and constrained by assumptions made during the development and design stages (Nave, 2002).

Most of the Six Sigma efforts are focused on taking variability out of the existing processes employing DMAIC methodology. However, at the same time variability is introduced in new products. In order to avoid this, DFSS efforts have been focused on predicting and improving quality before products and processes are launched. It can also be employed to redesign current processes and products. This approach can be seen as an effective way to obtain Six Sigma quality levels and avoid future problems in manufacturing and service. Contrary to the incremental improvement from the Six Sigma methodology, Design/Redesign for Six Sigma has the ability to discard existing processes and substitute them with radical new ones. Therefore, it is considered that DFSS could improve not only process efficiency but also process effectiveness.

Generally, DFSS methodologies, such as DMADV, intend to create designs that are (Harry and Schroeder, 2000):

- resource efficient
- capable of reaching very high yields
- independent of complexity and volume
- 'robust' to process variability
- highly linked to customer demands.

A comparison is made in Table 1 between Six Sigma and DFSS methodologies. Unlike the DMAIC methodology for Six Sigma, the phases or steps of DFSS are not universally recognised or defined. Almost every company or training organisation will define DFSS differently. Most of the time a company will implement DFSS to suit its business, industry and culture.

Table 1 Differences between Six Sigma and DFSS

Six Sigma	*DFSS*
Define, Measure, Analyse, Improve, Control	Define, Measure, Analyse, Design and Verify (DMADV) Define, Measure, Analyse, Design, Optimise, and Verify (DMADOV)
Looks at existing processes and fixes problems	Focuses on the up-front design of the product and process
More reactive	More proactive
Dollar benefits obtained from Six Sigma can be quantified rather quickly	Benefits are more difficult to quantify and tend to be more long term. It can take six to 12 months after the launch of the new product before one can obtain proper accounting on the impact

Source: Yang and EI-Haik (2003, pp.60–61)

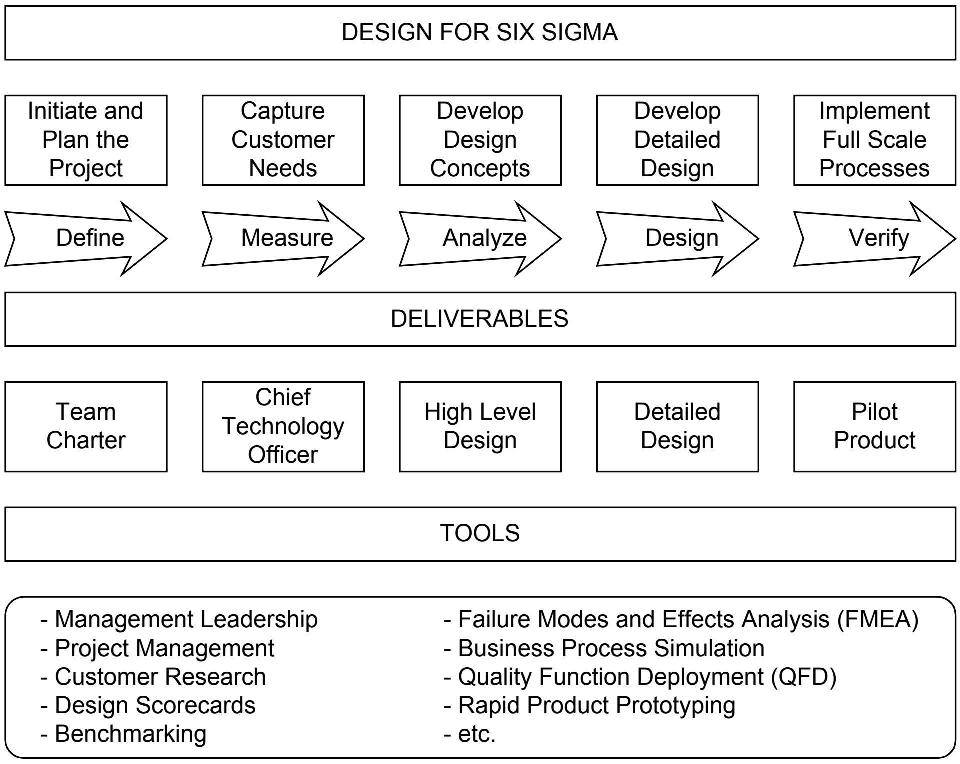
5 The Design for Six Sigma process

The process of DFSS is the systematic utilisation of tools, training and measurements to enable the organisation to design products and processes that meet customer expectations and that can be produced at Six Sigma quality levels (Mader, 2002). The goal of DFSS is to achieve minimum defect rates, Six Sigma level, and maximise the positive impact during the development stage of the products. It is used to develop new products or services with Six Sigma criteria, capability and performance (Tennant, 2002). It utilises a variety of quality-oriented tools and techniques to meet customer requirements and has shown an increase in life cycle profits. As Treichler *et al.* (2002) noted, the essence of DFSS is "predicting design quality up front and driving quality measurement and predictability improvement during the early design phases". Essentially, the DFSS process is focused on new or innovative designs that yield a higher level of performance. De Feo and Bar-El (2002) summarise seven elements of DFSS as follows:

1. drives the customer-oriented design process with Six Sigma capability
2. predicts design quality at the outset
3. matches the top-down requirements flow-down with the capability flow-up
4. integrates cross-functional design involvement
5. drives quality measurement and predictability improvement in early design phases
6. uses process capabilities in making final decisions
7. monitors process variances to verify that customer requirements are met.

DFSS has been used and proven successful at Dow Chemical (Buss and Ivey, 2001), W.R. Grace, (Rajagopalan *et al.*, 2004), Delphi Automotive (Treichler *et al.*, 2002), NCR Corporation (McClusky, 2000), General Electric (Weiner, 2004), and other process-oriented industries. Figure 2 depicts the five-step DFSS process.

Figure 2 Five-step DFSS process



Sources: De Feo and Bar-El (2002) and Kwak and Anbari (2006)

As illustrated, deliverables such as the chief technology officer capture customers' needs, using tools and techniques such as Quality Function Deployment (QFD), and address the priorities of design in the next stage, *i.e.*, 'Analyse'.

In the following, some of the DFSS process types used by world-class companies are demonstrated.

5.1 Samsung SDI

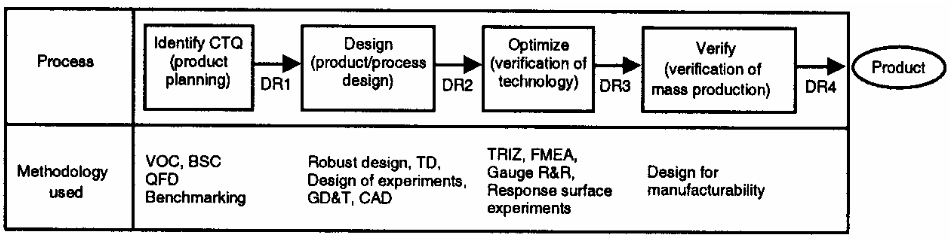
Samsung SDI is a company under the Samsung Group. Samsung SDI was founded in 1970 as a producer of the black/white Braun tube. It began to produce the color Braun tube from 1980, and now it is the number one company for Braun tubes in the world. The market share of Braun tubes is 22%. The major products are Color Display Tube (CDT), Color Picture Tube (CPT), Liquid Crystal Display (LCD), Vacuum Fluorescent Display (VFD), Color Filter (C/F), li-ion battery and Plasma Display Panel (PDP). The total sales volume is about $4.4 billion and the total number of employees is about 18 000 including 8000 domestic employees. It has six overseas subsidiaries in Mexico, China, Germany, Malaysia and Brazil.

The DFSS process of Samsung SDI follows the IDOV (identify, design, optimise, verify) process, and after each step, a Design Review (DR) helps to validate the process as shown in Figure 3.

There are four different types of DR. Each one reviews and validates the immediately previous step. For instance, DR1 reviews the product planning and decides whether the DFSS process can flow to the next step or not.

Another DFSS (R&D Six Sigma) example is presented in Table 2. The team consisted of eight persons (one is a Champion, and the other seven members are all Black Belts (BBs)). The duration of this study was from January to June of 2000. The team basically used the IDOV process. However, it added Recognise and Define (R-D) before IDOV, hence the process of team activities is R-D-I-D-O-V. Table 2 shows the project implementation steps used by this team at Samsung SDI.

Figure 3 The DFSS process in Samsung SDI



Source: Park (2003)

5.2 Suppliers of white goods in Europe

In another investigation, conducted by Banuelas and Antony (2004), the DFSS project was carried out in the home laundry appliance division of one of the largest suppliers of white goods in Europe. Table 3 summarises the tools employed in the DFSS process.

Table 2 Project implementation steps of a DFSS team in Samsung SDI

DFSS steps	*Detailed steps*	*Tools used*	*Design review for product development*
R (Recognise)	Analysis of CPT market trends	Customer review	
	Preparation of customer value map	Business planning	
D (Define)	Selection of Omega CPT CFR	QFD, CPM	DR1
	Theme selection of CPM flow-down	Concept engineering	
I (Identity)	Selection of project CFR	FMEA	
	Failure analysis	MSA	
	Measurement analysis	Benchmarking and gap analysis	
D (Design)	List of all input variables	Cause and effect matrix	DR2
	Design of basic shape and decision of prototype	Simulation, capability study	
	Tolerance analysis for yield improvement	Tolerance design	
O (Optimise)	Determination of big Xs which influence Y	DOE and ANOVA	DR3
	Determination of optimal levels of big Xs	Robust design	
	Quality check through pilot study	DFM	
	Completion of paper design		
V (Validate)	Verification for mass production	Process mapping	DR4
	Analysis of process capability	Capability study	
	Determination of final product quality	Reliability study	

Notes: CPM = Critical Parameter Method.
QFD = Quality Function Deployment.
CFR = Critical Function Responses.
FMEA = Failure Mode and Effect Analysis.
MSA = Measurement System Analysis.
DOE = Design of Experiments.
ANOVA = Analysis of Variance.
DFM = Design for Manufacturability.
Source: Park (2003)

5.3 Ford Company

In the Ford Company, a tool matrix was developed to outline which tools might be applied at each project phase (Figure 4).

It is important to note that not all the specialised tools presented would apply to a particular project. For those that would – due to the extended length of DFSS projects – the team members worried they would forget much of the training by the time they needed to apply it. They concluded it was inefficient to train all team members in all tools.

In conclusion, it should be noted that different companies employ different sets of DFSS tools and there is no agreement on the issue.

Table 3 An example for DFSS tool usage

Phase	*Task number*	*Specify tasks*	*Tools employed*
Identify	1	Identify customer CTQs	Team charter; critical to quality tree; quality function deployment; benchmarking; CTQ flow-down
	2	Perform CTQ flow-down	
	3	Analyse measurement system capability	
	4	Generate and validate systems/subsystems models	
	5	Build scorecards prediction, parts, process and performance	
Design	6	Roll up scorecards for all subsystems	Analytic hierarchy process; regression analysis, baselining, rational subgroups; design for assembly
	7	Capability flow-up	
	8	Identify the gaps	
	9	Low Zst on scorecard	
	10	Lack of transfer function	
	11	Unknown process capability	
Optimise	12	Use DOE to find transfer function and the critical few Xs	Full factorial DOE; response surface methodology; multiple response optimiser
	13	Parameter and tolerance design	
	14	Generate purchase and manufacturing specifications	
	15	Specify mean, variance and limits	
Verify	16	Confirm that pilot studies match predictions	Baselining; rational subgroups
	17	Mistake proofing process	
	18	Develop manufacturing and supplier control plans for CTQ	
	19	Refine models, scorecards, process characterisation database	

Source: Banuelas and Antony (2004)

Figure 4 Ford DFSS tools matrix

<table>
<tr><td>D</td><td>Consumer insight</td><td>Market research</td><td>Brand analysis</td><td>Noriaki Kano model</td><td>Quality Function Deployment</td><td>Bench-marking</td><td>Quality history: surveys</td><td>Quality history: repairs</td><td>Quality loss function</td><td rowspan="4">System engineering

Target setting and verification</td><td rowspan="4">DFSS scorecard</td></tr>
<tr><td>C</td><td>Concept generation and selection</td><td rowspan="2">Design of Experiments</td><td>P-diagram</td><td>System and functional diagrams</td><td rowspan="2">Reliability and robust engineering design</td><td>Axiomatic design</td><td>Dimensional variation analysis</td><td>Failure Modes and Effects Analysis</td><td>Measure-ment system analysis</td></tr>
<tr><td>O</td><td>Numeric/ heuristic optimization</td><td>Parameter design</td><td>Tolerance design</td><td>Analytical reliability and robustness</td><td>Statistical tolerancing</td><td>Design for manufacture / assembly</td><td rowspan="2">Process Capability Assessment</td></tr>
<tr><td>V</td><td colspan="2">Model validation and uncertainty assessment</td><td colspan="2">Design verification plan and report</td><td colspan="3">Robustness/ reliability demonstration</td><td>Control plan</td></tr>
</table>

Source: Soderborg (2004)

6 Implementation obstacles

There are several problems to be tackled for DFSS implementation. These problems must be solved for a smooth introduction of DFSS. They are summarised as follows (Park, 2003):

- Engineers tend to resist the introduction of any new scientific methodology into their research activities. Hence, their understanding and cooperation or approval should be sought before introducing the DFSS into their activity.
- Green Belts (GB) or BB education/training is especially necessary, since there are many scientific tools for R&D including QFD, DOE, simulation techniques, robust designs and regression analysis. For such education/training, textbooks that contain real and practical examples should be carefully prepared in order to make researchers understand why DFSS is a very useful tool.
- Project team activities might be difficult in R&D departments. In this case, BBs should be assigned as full-time project leaders. It is desirable that the company gives time, space and the necessary financial support to the BBs to solve the projects.

7 Design for Six Sigma training

One of the key DFSS implementation challenges is training. Ford, as an example, first applied a typical BB training model to entire teams. Team members attended two weeks of classroom training during the early months of a project. They studied a curriculum that included in-depth coverage of process and tools. As a result of the feedback, the DFSS training was restructured. To enhance continued adherence to the process, teams then met periodically in workshops corresponding to each project phase (D, C, O and V). By the end of each workshop, the team has a written work plan for the project's next steps. A team process leader, typically a trained BB, guides the application of Six Sigma tools. An Master Black Belt (MBB) facilitates the workshops, collaborates with team leaders throughout the project and provides additional training in advanced DFSS tools as required. To supplement knowledge of basic DFSS tools already provided through the Ford Technical Education Program (FTEP), Ford's Office of the Technical Fellow in Quality Engineering sponsors reliability and transfer function seminars for the engineering community at large and targeted at DFSS teams. Baseline DMAIC skills are also reinforced as engineering organisations near the completion of a corporate mandate requiring all engineers to achieve DMAIC Green Belt status. The current flexible training model in Figure 5 rationally leverages existing training programmes while driving projects forward on a just-in-time basis.

As shown, almost all of the team members are involved in the training programme. Also, some prerequisite courses of DMAIC should be handled before launching DFSS courses. Another lesson learned is that the courses are offered in three different levels, *i.e.*, required, recommended and optional courses.

Figure 5 Training to support DFSS at Ford (see online version for colours)

		Audience				
	Kind of training	All engineers	DFSS team members	DFSS team Black Belts (BBs)	DFSS Master Black Belts (MBBs)	**Delivery**
DMAIC prerequisites	Green Belt course (two to three days)	Req	Req	N/A*	N/A	Classroom
	BB course (20 days)			Req	Req	Classroom
	MBB course (10 days)				Req	Classroom
DCOV	Ford technical education program: introduces basic DCOV tools	Req	Req	Req	Req	Online with test
	Seminars in reliability and transfer functions (two days each)	Rec	Rec	Rec	Req	Classroom
	Team workshops (one-half to one day at each phase)		Req	Req	Req	Classroom
	Advanced classes**		Opt	Rec	Req	Classroom
	Shadowing a working DFSS MBB				Req	On-the-job

* Not applicable, BB training supersedes this requirement.
** DFSS process (one day), analytical reliability and robustness (two days), structured inventive thinking (three days)

Key
Req Required
Rec Recommended
Opt Optional

Source: Soderborg (2004)

8 Conclusions

In this paper, the concept of DFSS was precisely studied and the experiences from world-class companies were demonstrated and learned. The findings imply that implementing DFSS can be challenging for any organisation. It seems that it is not easy for a company to adopt DFSS. However, once it is fully adopted, the net effect and cost savings can be enormous.

With respect to the lessons learned, it is concluded that although a relatively unique methodology, such as DMAIC, could be considered as a Six Sigma methodology, the methodologies for DFSS are numerous and different companies employ different methodologies. Consequently, this might be a reason why the tools and techniques used by companies in the DFSS process are different. The role of project leaders and DFSS training programmes are found to be essentials for the success of DFSS projects. Finally, in the DFSS training programme, some DMAIC prerequisites should be considered and the program should be offered in a flexible manner, consisting of required, recommended and optional courses.

However, DFSS is the most effective means of realising the full benefits of the Six Sigma capability. It ensures that the concepts and principles of Six Sigma are applied at the production design and development stages for enhanced customer satisfaction, improved long-term profitability, increased product reliability, improved profit margin, *etc.* This has been a simple introduction to the underlying approach. In practice, of course, it is a more complex procedure which, like many others, depends crucially on the selection of team members and on ensuring that they have a supportive environment in which to work. However, successfully applied, DFSS is expected to enforce the best design practices to achieve competitive advantage and business excellence.

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