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A Program Level Application of Design for Six Sigma in the Aircraft Industry

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Abstract. Design for Six Sigma (DFSS) has been implemented in many companies to enhance their business performance and customer satisfaction. However, DFSS has not been widely applied to the aircraft industry which operates large, complex development programs. In this paper, the characteristics of an aeronautical product development program are analyzed to figure out the limitations of current DFSS methodology and the prerequisite to deployment of DFSS at the program level is suggested.

Keywords: Design for Six Sigma(DFSS), Large Complex System, Aeronautical Product, Program Level

1. INTRODUCTION

Since Michael Harry of Motorola introduced Six Sigma, many companies around the world have applied this methodology to their business processes. Six Sigma has enabled them to dramatically reduce defect rates and quality costs in their products and services. It has also enhanced customer satisfaction and given a potential edge over competitors. Six Sigma rewards stakeholders with its success.

Beginning in 1995, the Division of Medical Systems in General Electric (GE) applied Six Sigma for 3 years to its New Product Introduction (NPI) of a newly developed computerized tomography (CT) scanner. This was the first attempt to apply the Six Sigma process to development of a new product, and GE aimed to improve the robustness of the product against variations in the manufacturing and usage environment. This Design for Six Sigma (DFSS) approach enabled GE to introduce a light speed medical CT scanner which was nine times faster and ten times more reliable than other contemporary scanners. From the successful deployment of DFSS for the new scanner, GE expanded the application of this DFSS process to all corporate areas (Harry and Schroeder, 2000). Nowadays companies have been adopting DFSS not only in product design and development but also in service systems design.

In the meantime, the aircraft industry has applied Lean Six Sigma methodology to achieve operating excellence (Arkell, 2003; Joyce and Schechter, 2004). DFSS has not been widely and fully applied at program level in the aircraft industry. Only the prerequisite for deployment of DFSS at the program level has been addressed (Creveling *et al*., 2003; Judd, 2005; Yang and El-Haik, 2003; Treichler, 2005).

This paper examines the reason why DFSS could not be deployed at program level in the aircraft industry. Aspects such as complexity, organizations, resources, process, schedules, and traceability are addressed, as well as comparisons between a typical development program in the aircraft industry and a general DFSS project.

In section 2, DFSS is outlined for its applicability to any product development program. The quality level and program size of an aeronautical product is described in section 3. Section 4 deals with the generic development process of an aeronautical product, and introduces the intrinsic attributes of the aircraft industry where major companies deploy Six Sigma or Lean. In section 5 some key aspects are considered to figure out the prerequisite for full application of DFSS to program level deployment in the aircraft industry. Concluding remarks are presented in section 6.

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2. THE OUTLINE OF DFSS

Six Sigma DMAIC (Define, Measure, Analyze, Improve, Control) process focuses on the improvement of manufacturing or servicing processes. DFSS is required to exceed five sigma levels of performance because campaigns to improve existing products and processes encounter a barrier as they approach five sigma (Chowdhury, 2002). Figure 1 shows that the relative cost of design change at production stage is approximately one thousand times higher than that of design change at research stage (Kiemele, 2003). This requires the introduction of a new process which handles quality from the beginning of a product development program.

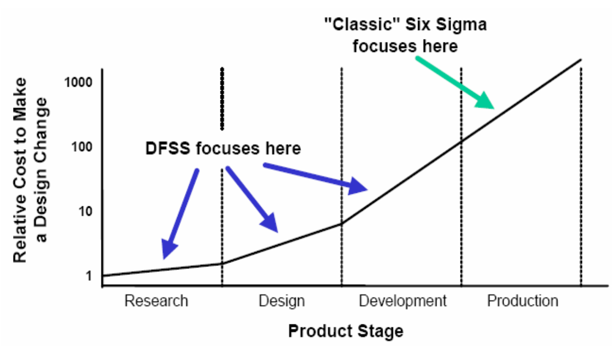

Figure 1. Relative Cost of Design Change (Kiemele, 2003).

Figure 2 shows that DFSS can dramatically reduce the number of engineering changes after the drawing release and product delivery (Kiemele, 2003). While the traditional product development process is the reactive design, where frequent firefighting against quality issues occurs, DFSS is a proactive design to prevent the fire (Chowdhury, 2002). The former provides quality "tested in," but the latter has quality "designed in."

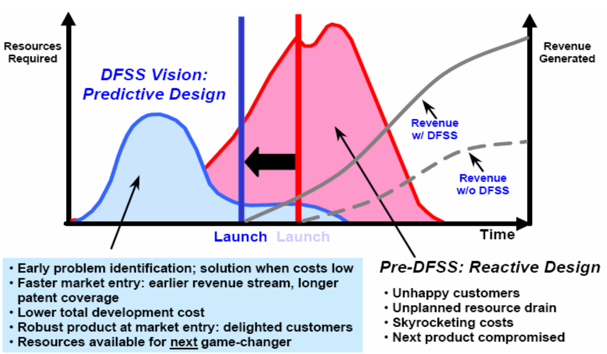

Figure 2. Benefits of DFSS Deployment (Kiemele, 2003).

While Six Sigma has a well-defined roadmap of DMAIC, Design For Six Sigma has various roadmaps like IDOV (Identify, Design, Optimize, Validate), DMADV (Define, Measure, Analyze, Design, Verify), DMADOV (Define, Measure, Analyze, Design, Optimize, Verify), CDOV (Concept, Design, Optimize, Verify), ICOV (Identify, Characterize, Optimize, Verify), and etc. Figure 3 shows several of these DFSS roadmaps, plus a few more (Advanced Integrated Technology Group, 2005). This diversity originates from the fact that each company has been trying to adopt the DFSS process in alignment with its own respective product development process under its own business environment.

IDOV	Identify, Design, Optimize, Validate (or 'Verify')
IDDOV	Identify, Define, Develop, Optimize, Validate
DIDOV	Define, Identify, Design, Optimize, Validate
DIDOVM	Define, Identify, Design, Optimize, Verify, Monitor
DMADOV	Define, Measure, Analyze, Design, Optimize, Verify
DMADV	Define, Measure, Analyse, Design, Verify
DMEDI	Define, Measure, Explore, Design, Implement

Figure 3. Various DFSS Processes (Advanced Integrated Technology Group, 2005).

A DFSS project normally consists of more CTQs (Critical-To-Quality), larger manpower demands, more project teams, longer schedules, and longer time to reward than those of a DMAIC project (Tennant, 2002).

A program is a group of projects managed in a coordinated way to obtain benefits not available from managing them individually (Duncan, 1996). The characteristics of DFSS according to the level in the aircraft industry can be explained as shown in Table 1.

Table 1. The Characteristics of DFSS Level in the Aircraft Industry.

Category	DMAIC project	Project level DFSS	Program level DFSS
Duration	3 to 6 months	6 to 12 months	2 to 7 years
Manpower	small team of 4 to 6	larger team of 10 or more	whole program team
Number of CTQs	1 or 2	Up to 40+	several tens or more
Time to reward	shorter	longer	much longer
Focus	solve problem	prevent problem	satisfy customer

3. CHARACTERISTICS OF THE AIRCRAFT INDUSTRY

Companies in the aircraft industry are more conservative than automotive companies because the highest priority in aeronautical product development is to ensure the required flight safety aspects are embedded in the product for the protection of the lives of crews and passengers on board. The required system safety level does not allow any catastrophic disaster per million flight hours, which is higher than 6 sigma level. There are only a few major commercial aircraft manufacturers in the world due to the high competition and high level of risk associated with the development of new aircraft.

Most aircraft manufacturers have their own legacy processes which define the detailed process of product development. Furthermore, the development of a new large transport aircraft requires a time frame of over ten years, a development budget of more than $10 billion, thousands of engineers working together, hundreds of subcontractors and suppliers, and assembly of millions of parts.

4. DEVELOPMENT PROCESS OF AERONAUTICAL PRODUCTS

The development process of an aeronautical product is one of the most complex tasks in the world. Most aeronautical product development programs adopt the Integrated Product and Process Development (IPPD) approach as shown in Figure 4 (Whalen *et al*., 2000). With the IPPD approach, systems engineering process is the backbone to aeronautical product development.

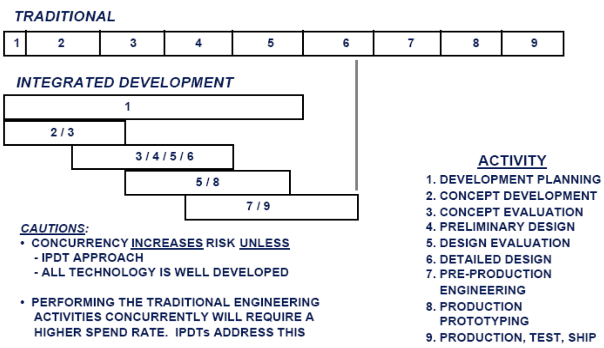

Figure 4. Integrated Product and Process Development (Whalen *et al*., 2000).

Some companies in the aircraft industry have been deploying a generic systems engineering process for the development of their highly complex systems. This process is generally divided into two sub-processes: the technical development sub-process and the technical management sub-process, as shown in Figure 5 (Dean *et al*., 1997). The technical development sub-process consists of several stages: analyze requirements (customer needs), define candidate architectures, optimize and evaluate alternatives, and verify the system. The technical management sub-process also consists of several stages: plan the technical effort, manage risks, assess and evaluate technical effort, and control technical baseline. Systems engineering and integration function plays a key role in these development processes (Creveling *et al*., 2003). "Analyze requirements" includes analyzing the custommer's operational mission requirements or system level requirements. "Define candidate architectures" encompasses functional analysis to break down system level requirements into required lower level functional requirements like subsystem and component level. It also incorporates the selection of candidate architectures of physical, functional, and interface baselines. "Optimize & evaluate alternatives" is to trade-off design parameters to achieve 'best system effectiveness' like lifecycle cost, reliability, etc. "Verify the system" is to ensure that the synthesis satisfies functional performance requirements at each level as shown in Figure 6 (DoD, 2001).

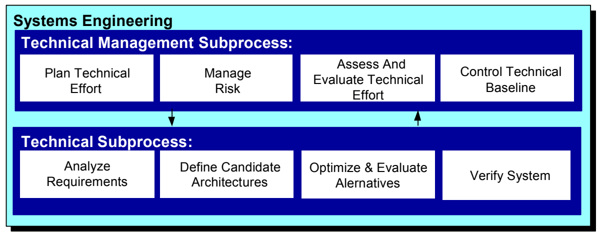

Figure 5. Generic Systems Engineering Module (Dean *et al*., 1997).

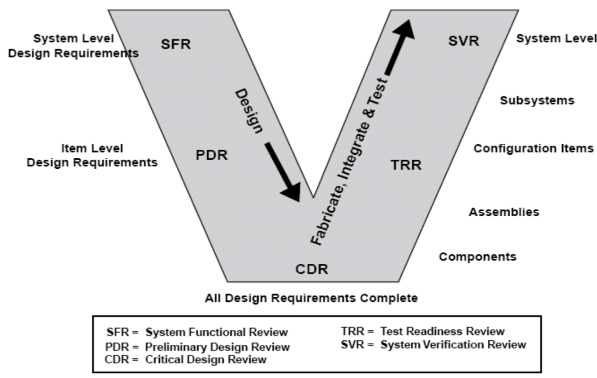

Figure 6. Requirement Flowdown and Verification (DoD, 2001).

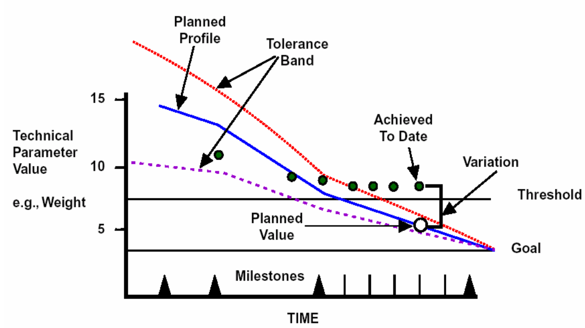

Figure 7. Technical Performance Measurement (DoD, 2001).

"Plan technical effort" is to have every task and plan associated with development defined, organized, coordinated, and integrated prior to implementation of program. "Manage risk" is to identify, assess, and handle risks associated with schedule/cost/performance for all phases of the development process. "Assess and evaluate technical effort" includes various kinds of design reviews, monitoring and controlling program-defined Technical Performance Measurements (TPMs), an example of which is shown in Figure 7 (DoD, 2001). "Control technical baseline" consists of configuration management.

Table 2. Six Sigma versus Lean (Westwood and Silvester, 2007).

Methodology	Lean	Six Sigma
Theory	Reduce waste	Reduce variation
Application Guidelines	Identify value Identify value stream Flow Pull Perfection	Define Measure Analyze Improve Control
Focus	Flow	Perfection
Assumptions	Waste removal will improve performance Many small improvements are better than system analysis	A problem exists Figures and numbers are valued System output improves if variation in all processes is reduced
Primary Effect	Reduced flow time	Uniform process output
Secondary Effect	Less variation Uniform output Less inventory New accounting System flow metrics Improved quality	Less waste Fast throughput Less inventory Variation metrics Improved quality
Criticism	Statistical or system analysis not valued	System interaction not considered Processes improved independently

Systems engineering is regarded as an established, sound practice. However, according to U.S. Government Accountability Office (GAO) and NASA studies of space systems, systems engineering is not always delivered effectively because of major budget and schedule overruns (Haskins, 2006). The majority of aircraft development budget is spent on post-launch support (Judd, 2005). The evolving practice of DFSS will aid engineers in developing producible designs, since DFSS reduces development cycle time and saves money by making less design changes (Choudri, 2004; Murman *et al*., 2002).

Major aircraft manufacturers like Boeing and Lockheed Martin have applied Lean methodology for eliminating waste and defects in their products. In 1999 Boeing adopted Six Sigma methodology on the basis of Lean, called Lean+. Lockheed Martin has applied Lean with Six Sigma, which is called LM21 (Joyce and Schechter, 2004; Bush, 2005). Both companies have considered that Lean and Six Sigma complement each other, providing synergy for the product and process improvement, although each methodology has a different application as shown in Table 2 (Snee and Hoerl, 2007; Westwood and Silvester, 2007).

Although the aircraft industry is implementing a lot of aeronautical product development programs in which strategic planning, marketing, engineering, manufacturing, sales, and support divisions are involved, yet the industry deploys mostly DFSS black belt projects in order to design and optimize isolated subsystems within their program. However, program level application of DFSS woven into the product lifecycle will yield a tremendous reduction in the post-launch "fire fighting" effort (Judd, 2005).

Since DFSS projects are black belt projects (not program level) in most companies, most companies of the aircraft industry have not performed program level DFSS (Judd, 2005). The following considerations are to be discussed to figure out the prerequisites for companies of the aircraft industry to apply program level DFSS to their legacy product development process.

5. CONSIDERATIONS FOR PROGRAM LEVEL DFSS DEPLOYMENT

5.1 Program Structure

Aeronautical product development programs are intrinsically large and complex with huge resources, different tasks, complicated schedules, critical milestones, high-frequency communication, large data flows, thousands of drawings, and hundreds of thousands of assembly parts. They require well-defined program structures in which the roles and responsibilities of each discipline are assigned. The Work Breakdown Structure (WBS) is established to allocate and monitor performance, cost, and schedule. Top-level requirements are allocated to each discipline according to the WBS. Every task should be accomplished without negatively affecting critical milestones. There has never been room for schedule delays.

Program level DFSS requires that DFSS program organization should be the same as that which is in charge of its objectives of performance, schedule, and cost. This requires a number of DFSS projects interrelated hierarchically to achieve the program goals. The DFSS program should be structured to allow subdivision into many DFSS projects which are to be implemented as one body. Charters, organizations, schedules, tasks, interfaces, inputs, and outputs of all the DFSS projects should be interrelated and consistent.

5.2 Engagement of Top Management

An aeronautical product development process is systematic, and stipulated in the company procedures which define roles and responsibilities. Many inter-disciplinary activities are performed according to these procedures to develop an aircraft product. This process leads the participants to only react to the pre-defined process. This reactive environment keeps top management from being involved in the development process.

As Six Sigma enables top management to energize project team members, program level DFSS requires the provision that top management instill a proactive atmosphere, empower the participants, and promote accomplishment of high operational excellence.

5.3 Proper DFSS Roadmap

As mentioned before, companies in the aircraft industry have their own legacy process of systems engineering while there are various roadmaps available for DFSS. DMADV methodology can be applied to product improvement projects with the aim of reducing cost, and enhancing reliability, etc. IDOV/IDDOV methodology can be deployed for new product introduction in a new market.

Program level DFSS in the aircraft industry requires a DFSS roadmap which can be integrated into the legacy process of systems engineering. Since there is no standard DFSS roadmap, a proper one needs to be selected or created.

5.4 Phases and Gates

The aeronautical product development process is normally divided into phases and corresponding gates to ensure that the product being developed meets the necessary requirements. Major technical reviews include a System Requirement Review (SRR) to establish the functional baseline, a System Design Review (SDR) to establish an allocated baseline, a Preliminary Design Review (PDR) to begin detail design, a Critical Design Review (CDR) to begin manufacturing, a Test Readiness Review (TRR) to begin testing, and a Production Readiness Review (PRR) to initiate production.

DFSS methodology has its own phases. For example, IDOV includes identify, design, optimize, and verify phases. A number of DFSS tools corresponding to each phase are utilized. The program level DFSS needs to resolve how DFSS phases incorporate the above-mentioned technical reviews and how the pertinent DFSS tools for each phase need to be synchronized. Timely training and support appropriate to the corresponding phase need to be provided to the managers and engineers.

5.5 Traceability

The end product of an aeronautical product development program can be broken down into elements, subsystems, components, and parts. This product-oriented family tree is the Work Breakdown Structure (WBS). The system performance at the end product level is normally ensured by monitoring whether all critical parameters converge within preplanned value. Critical parameters are selected and managed by a systems engineering discipline with a control chart of the Technical Performance Measurement (TPM) parameters. The framework for a TPM parameter tree including the end product level to component level is developed from the corresponding WBS. TPMs show the performance of critical parameters at given times in a progressive manner.

Program level DFSS requires scorecards not only of TPM parameter performance but also design parameters and process variables, as these affect the pertinent performance. Critical Parameter Management (CPM) of program level DFSS needs to be structured to correlate all transfer functions from which stochastic prediction of system performance is possible with the variation of design parameters and process variables.

6. CONCLUSION

The reason why DFSS could not be deployed at program level in the aircraft industry is examined from the viewpoint of complexities, organizations, resources, schedules, and requirements. Companies of the aircraft industry which operate large, complex development programs need to have a DFSS methodology harmonize with their legacy development process. The highly complex and very conservative characteristics of a development program in the aircraft industry keep DFSS from being deployed at program level.

The pre-requisite to deployment of DFSS at program level is considered in the area of program structure, engagement of top management, phases and gates, and traceability. The program structure of program level DFSS requires many subdivided DFSS projects whose schedules and tasks need to be integrated into the DFSS program. The engagement of top management is needed to empower all participants from marketing, engineering, procurement, manufacturing, and quality control division. A proper DFSS roadmap needs to be selected or created and integrated into the legacy process of systems engineering. Phases and gates of program level DFSS need to incorporate the major technical reviews and pertinent DFSS tools for each phase. Traceability for Critical Parameter Management (CPM) of program level DFSS needs to have system performance correlated with the variation of design parameters and process variables.

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