Section

5

WARWICK MANUFACTURING GROUP

Product Excellence using 6 Sigma (PEUSS)

Design for X

DESIGN FOR X

Contents

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1 Introduction

Concurrent engineering is a contemporary approach to DFSS. DFX techniques are part of detail design and are ideal approaches to improve life-cycle cost, quality, increased design flexibility, and increased efficiency and productivity using the concurrent design concepts (Maskell 1991). Benefits are usually pinned as competitiveness measures, improved decision-making, and enhanced operational efficiency. The letter “X” in DFX is made up of two parts: life-cycle processes *x* and performance measure (ability) (Huang 1996).

The DFX family is one of the most effective approaches to implement concurrent engineering. DFX focuses on vital business elements of concurrent engineering, maximizing the use of the limited resources available to the DFSS team.

DFX tools include:

- Design for Manufacture and Assembly;
- Design for Reliability;
- Design for Maintainability;
- Design for Serviceability;
- Design for the Environment;
- Design for Life Cycle Cost;
- and so on.

DFX provides systematic approaches for analyzing design from a spectrum of perspectives. It strengthens teamwork within the concurrent DFSS environment. The Design for Manufacture and Assembly (DFMA) approach produces a considerable reduction in parts, resulting in simple and more reliable design with less assembly and lower manufacturing costs. Design for Reliability (DFR) enables the DFSS team to gain insight into how and why a proposed design may fail and identifies aspects of design that may need to be improved. When the reliability issues are addressed at early stages of DFSS, project cycle time will be reduced. A simplified product can be achieved through the sequential application of DFMA followed by Design for Serviceability (DFS), which is the ability to diagnose, remove, replace, replenish, or repair any component or subassembly, to original specifications, with relative ease. Poor serviceability produces warranty costs, customer dissatisfaction, and lost sales and market share due to loss loyalty. In Design for Life-Cycle Cost, the activity-based cost (ABC) is a powerful method for estimating life-cycle design cost to help guide the DFSS team in decision making to achieve cost-efficient Six Sigma design in the presence of market and operations uncertainty. Another DFX family member is Design for Maintainability. The objective of Design for Maintainability is to ensure that the design will perform satisfactorily throughout its intended life with a minimum expenditure of budget and effort. Design for Maintainability, DFS, and DFR are related because minimizing maintenance and facilitating service can be achieved by improving reliability. Design for the Environment (DFE) addresses environmental concerns as well as post-production transport, consumption, maintenance, and repair. The aim is to minimize environmental impact, including strategic level of policy decision-making and design development.

2 Design for Manufacture and Assembly

Designs that are constructed to be easy to manufacture during the conceptual stage of a product development are much more likely to avoid redesign later when the system is being certified for production readiness. The best way to ensure a concept can be manufactured is to have active involvement from the production and supply chain organizations during concept generation and selection.

DFM and DFA are systematic approaches that the DFSS team can use to carefully analyze each design parameter that can be defined as part or subassembly for manual or automated manufacture and assembly to gradually reduce waste. Waste, or *muda,* the Japanese term, may mean any of several things. It may mean products or features that have no function (do not add value) and those that should have been trimmed (reduced, streamlined). It may also mean proliferation of parts that can be eliminated. But the most leverage of DFX, beyond the design axioms, is attacking the following waste sources:

(1) Assembly directions that need several additional operations and
(2) Design parameters with unnecessarily tight tolerances.

With DFMA, significant improvement tends to arise from simplicity thinking, specifically reducing the number of standalone parts. The Boothroyd-Dewhurst DFA methodology gives the following three criteria against which each part must be examined as it is added to the assembly (Huang 1996):

(1) During operation of the product, does the part move relative to all other parts already assembled?
(2) Must the part be a different material than, or be isolated from, all other parts already assembled? Only fundamental reasons concerned with material properties are acceptable.
(3) Must the part be separate from all other parts already assembled because the necessary assembly or disassembly of other separate parts would otherwise be impossible?

A “Yes” answer to any of these questions indicates that the part must be separate or using DFA terminology, a *critical* part. All parts that are not critical, can theoretically be removed or *physically coupled* with other critical parts. Therefore, theoretically, the number of critical parts is the minimum number of separate parts of the design.

Next, the DFSS team estimates the assembly time for the design and establishes its efficiency rating in terms of assembly difficulty. This task can be done when each part is checked to determine how it will be grasped, oriented, and inserted into the product. From this exercise, the design is rated and from this rating standard times are determined for all operations necessary to assemble the part. The DFA time standard is a classification of design features that affect the assembly process. The total assembly time can then be assessed, and using standard labour rates, the assembly cost and efficiency can be estimated. At this stage, manufacturing costs are not considered, but assembly time and efficiency provide benchmarks for new iterations.

After all feasible simplification tasks are introduced, the next step is to analyze the manufacture of the individual parts. The objective of DFM within the DFMA is to enable the DFSS team to weigh alternatives, assess manufacturing cost, and make trade-offs between physical coupling and increased manufacturing cost. The DFM approach provides experimental data for estimating cost of many processes. The DFSS team is encouraged to consult with the following studies where deemed appropriate: Dewhurst (1988) for injection molding, Dewhurst and Blum (1989) for die-cast parts, Zenger and Dewhurst (1988) for sheetmetal stamping, and Knight (1991) for powder metal parts.

The DFMA approach usually benefits from poka-yoke (errorproofing) techniques, which may be applied when components are taking form and manufacturing and assembly issues are considered simultaneously. *Poka-yoke* is a technique for avoiding human error at work. The Japanese manufacturing engineer Shigeo Shingo developed the technique to achieve zero defects and came up with this term, which means "errorproofing." A defect exists in either of two states: (1) it already has occurred, calling for defect detection, or (2) is about to occur, calling for defect prediction. Poka-yoke has three basic functions to use against defects: shutdown, control, and warning. The technique starts by analyzing the process for potential problems, identifying parts by the characteristics of dimension, shape, and weight, detecting processes deviating from nominal procedures and norms.

3 Design for Reliability

Reliability is the probability that a physical entity delivers its functional requirements (FRs) for an intended period under defined operating conditions. The time can be measured in several ways. For example, time in service and mileage are both acceptable for automobiles, while the number of open-close cycles in switches is suitable for circuit breakers. The DFSS team should use DFR while limiting the life-cycle cost of the design. The assessment of reliability usually involves testing and analysis of stress strength and environmental factors and should always include improper usage by the end user. A reliable design should anticipate all that can go wrong.

Design for reliability breaks down into two board categories:

- Knowledge-based engineering is the science of designing things to bear applied loads or transfer heat.

- Variation control is the science of adequately accounting for the sources and effects of variation that can affect design functional performance.

DFR adapts the law of probability to predict failure and adopts:

1. Measures to reduce failure rates in the physical entity by employing design axioms and reliability science concurrently.
2. Techniques to calculate reliability of key parts and design ways to reduce or eliminate coupling and other design weaknesses.
3. *Derating*—using parts below the specified nominal values.
4. Design failure mode–effect and criticality analysis (FMECA), which is used to search for alternative ways to correct failures. A "failure" is the unplanned occurrence that prevents the system or component from meeting its functional requirements under the specified operating conditions.
5. Robustness practices by making the design insensitive to all uncontrollable sources of variation (noise factors).
6. Redundancy, where necessary, which calls for a parallel system to back up an important part or subsystem in case it fails.

Reliability pertains to a wide spectrum of issues that include human errors, technical malfunctions, environmental factors, inadequate design practices, and material variability. The DFSS team can improve the reliability of the design by:

- Minimizing damage from shipping, service, and repair
- Counteracting the environmental and degradation factors
- Reducing design complexity. (See El-Haik and Young 1999.)
- Maximizing the use of standard components
- Determining all root causes of defects, not symptoms, using DFMEA
- Controlling the significant and critical factors using SPC (statistical process control) where applicable
- Tracking all yield and defect rates from both in-house and external suppliers and developing strategies to address them

To minimize the probability of failure, it is first necessary to identify all possible modes of failure and the mechanism by which these failures occur. Detailed examination of DFR is developed after physical and process structure development, followed by prototyping; however, considerations regarding reliability should be taken into account in the conceptual phase. The team should take advantage of existing knowledge and experience of similar entities and any advanced modelling techniques that are available. Failure avoidance, in particular when related to safety, is key. Various hazard analysis approaches are available. In general, these approaches start by highlighting hazardous elements and then proceed to identify all events that may transform these elements into hazardous conditions and their symptoms. The team then has to identify the corrective actions to eliminate or reduce these conditions. One of these approaches is called *fault-tree analysis* (FTA). FTA uses deductive logic gates to combine events that can produce the failure or the fault of interest. Other tools that can be used in conjunction with FTA include FMECA as well as the fishbone diagram.

4 Design for Maintainability

The objective of Design for Maintainability is to assure that the design will perform satisfactorily throughout its intended life with a minimum expenditure of budget and effort. Design for maintainability (DFM), Design for Serviceability (DFS), and Design for Reliability (DFR) are related because minimizing maintenance and facilitating service can be achieved by improving reliability. An effective DFM minimizes:

(1) The downtime for maintenance,
(2) user and technician maintenance time,
(3) personnel injury resulting from maintenance tasks,
(4) cost resulting from maintainability features, and
(5) logistics requirements for replacement parts, backup units, and personnel.

Maintenance actions can be preventive, corrective, or recycle and overhaul. Design for Maintainability encompasses access and control, displays, fasteners, handles, labels, positioning and mounting, and testing. The DFSS team needs to follow these guidelines:

- Minimize the number of serviceable design parameters (DPs) with simple procedures and skills.
- Provide easy access to the serviceable DPs by placing them in serviceable locations. This will also enhance the visual inspection process for failure identification.
- Use common fasteners and attachment methods.
- Design for minimum hand tools.
- Provide for safety devices (guards, covers, switches, etc.)
- Design for minimum adjustment and make adjustable DPs accessible.

The DFSS team should devise the criteria for *repair* or *discard* decisions within the context of life-cycle costing. The major maintainability cost factors to consider include transportation, shipping, and handling; training of maintenance people; and repair logistics, which encompasses the design of service, production, distribution, and installation of repairable DPs (components and sub-ssemblies).

The “repair” procedure should target:

- Enhancing the field repair capability to react to emergency situations
- Improving current repair facilities to reflect the design changes
- Reducing cost using modularity and standard components
- Decreasing storage space

The “discard” procedure should consider:

- Manufacturing cost

- Simplifying maintenance tasks (e.g., minimum skills, minimum tools, and standard attachment methods)
- Work site reliability: training technicians to avoid damaging the repair equipment
- Repair change adjustment to enable plug-in of new parts rather than field rework

5 Design for serviceability

After the DFSS team finished DFR and DFMA exercises, the next step is to embark on Design for Serviceability, another member of the DFX family. *Design for Serviceability* (DFS) is the ability to diagnose, remove, replace, replenish, or repair any DP (component or subassembly) to original specifications with relative ease. Poor serviceability produces warranty costs, customer dissatisfaction, and lost sales and market share due to loss loyalty. The DFSS team may check their VOC (voice-of-the-customer) studies such as QFD for any voiced serviceability attributes. *Ease of serviceability* is a performance quality in the Kano analysis. DFSS strives to have serviceability personnel involved in the early stages, as they are considered a customer segment. The DFSS team should visit the following considerations of DFS:

(1) Customer service attributes
(2) Labor time
(3) Parts cost
(4) Safety
(5) Diagnosis
(6) Service simplification
(7) Repair frequency and occurrence
(8) Special tools
(9) Failures caused by the service procedures

6 Design for the Environment

In an effort to meet the world's growing energy needs, the dependence on fossil fuels has become a necessary endeavor. Since the first oil crisis in 1973 and the Gulf War in 1991, the world's energy perspective has changed significantly. Since then many countries have attempted to reduce their dependence on oil by investigating alternative energy sources. More importantly, however, there has been an increased awareness concerning environmental pollution and efforts to reduce the effects of fossil fuel emissions. Global studies have concluded that increased fossil fuel consumption has led to increased carbon dioxide release, which in turn causes atmospheric heating. These theories, known as "the greenhouse theory" and "global warming," are both environmental concerns that have strongly affected the design and manufacturing industries. For example, increased legislation concerning automotive emission levels has driven the automotive industry to look for alternative fuel sources that would limit fossil fuel consumption while focusing on energy savings and lowering environmental impacts. Therefore, the motivation for environmentally friendly design is coming from the recognition that sustainable economic growth can occur without necessarily consuming the earth's resources. This trend opens the door for an evaluation of how the environment should be considered in design. *Design for the Environment* (DFE) (Myers 1984, Bussey 1998) addresses environmental concerns as well as post-production transport, consumption, maintenance, and repair. The aim is to minimize environmental impact, including strategic level of policy decision-making and design development. Since the introduction of DFE, one can view the environment as a customer! Therefore, the definition of defective design should encompass the designs that negatively impact the environment. As such, DFE usually comes with added initial cost, causing an increment of total life cost.

For the most part, the technology gained since the early 1990s has proved itself able to contribute substantially to sustainability in many design applications. With companies concerned with short-term versus the long-term benefits, and until there is widespread use and mass marketing of these designs, commercial environmentally friendly designs will probably continue to be a conversation piece rather than a routine practice. In addressing the question of whether DFE will be lucrative in a given DFSS project, it is imperative to consider designs that are optimal relative to other components in which they are used, specifically, datum technologies. Economic evaluation is required both for maximum economic benefit and to estimate what the expected financial savings (or losses) will be. The major purpose of using economic analysis techniques is to consider environment concerns and profit concerns jointly in an attempt to reduce the use of nonrenewable energy and maximize recyclability. These techniques usually clarify the financial value of limiting nonrenewable energy use. The actual financial value of any proposed solution can easily be evaluated according to the established economic criteria for the project. For example, solar economics deals with optimizing the trade-off between solar system ownership and operating costs and the future cost of the fuel saved by the solar system during its anticipated useful life. *Life-cycle cost* (LCC) is a term commonly used to describe a general method of economic evaluation by which all relevant costs over the life of a project are accounted for when determining the economic efficiency of a project. Lifecycle cost requires assessment of the following types of related costs:

(1) System acquisition and installation costs (capital costs)
(2) System replacement costs
(3) Maintenance and repair costs
(4) Operation cost (e.g., energy costs)
(5) Salvage or resale value net of removal and disposal costs

A life-cycle costing approach can be implemented by applying any or all of the following evaluation techniques:

(1) *Total life-cycle-cost* (TLCC) analysis, which sums the discounted value of all the equivalent costs over the time horizon.
(2) *Net present worth* (NPW) analysis, which calculates the difference between the TLCC of a proposed project and its alternative as a dollar measure of the project's net profitability.

(3) *Internal rate of return* (IRR) technique, which gives the percentage yield on an investment. (See Bussey 1998).
(4) *Activity-based costing* (ABC) with or without uncertainty measures.

With its emphasis on costs, DFE is a suitable method for evaluating the economic feasibility of projects such as energy conservation or solar energy, which realize their benefits primarily through fuel cost avoidance.

Questions to Ask in a Pre–Economic Evaluation of DFE:

(1) Amount of available funds for financing the project. Will the DFSS team have to ask for more budgets?
(2) What is the minimum attractive rate of return (MARR)? What discount rate should be used to evaluate the project? What is investment timeframe?
(3) What is the economic lifetime of the project?
(4) Is the lifetime of the project the same as the customer's timeframe so that the investment will prove feasible?
(5) What are the operating costs associated with the environmentally friendly design? For example, in the automotive industry, the escalation rate of fuel is a consideration. Will fuel inflate at a higher rate than the dollar?
(6) Government incentives (federal/state/local). Will any incentives play a role in the overall economic evaluation?

7 Design for life-cycle cost

Life-cycle cost is the real cost of the design. It includes not only the original cost of manufacture but also the associated costs of defects, litigations, buybacks, distributions support, warranty, and the implementation cost of all employed DFX methods. *Activity-based cost* (ABC)* is a powerful method for estimating life-cycle design cost, in particular when coupled with uncertainty provisions (Huang 1996). The method employs process action and sensitivity charts to identify and trace significant parameters affecting the LCC. The ABC method assumes that the design, whether a product, a service, or a process, *consumes activities.* This assumption differentiates ABC from conventional cost estimation methods that assume *resources consumption.* The ABC objective is to identify activities in the design life, and then assign reliable cost drivers and consumption intensities to the activities. Probability distributions are given to represent inherent cost uncertainty. Monte Carlo simulation and other discrete-event simulation techniques are then used to model uncertainty and to estimate the effect of uncertainty on cost.

8 Summary

The table below provides a comprehensive list of all the DFX elements and points to the relevant reference material, note full references are given in the next section.

Product or process		
X	**DFX**	**Reference**
Assembly	Boothroyd-Dewhurst DFA	O'Grady and Oh (1991)
	Lucas DFA	Sackett and Holbrook (1988)
	Hitachi AEM	Huang (1996)
Fabrication	Design for Dimension Control	Huang (1996)
	Hitachi MEM	
	Design for Manufacturing	Arimoto et al. (1993)
		Boothroyd et al. (1994)
Inspection and test	Design for Inspectability	Huang (1996)
	Design for Dimensional Control	
Material logistics	Design for Material Logistics	Foo et al. (1990)
Storage and distribution	Design for Storage and Distribution	Huang (1996)
Recycling and disposal flexibility	Design for Ease of Recycling	Beitz (1990)
	Variety reduction program	Suzue and Kohdate (1988)
Environmental repair	Design for Environmentality	Navichandra (1991)
	Design for Reliability and Maintainability	Gardner and Sheldon (1995)

Service		
X	**DFX**	**Reference**
Cost	Design for Whole Life Costs	Sheldon et al. (1990)
Service	Design for Serviceability	Gershenson and Ishii (1991)
Purchasing	Design for Profit	Mughal and Osborne (1995)
Sales and marketing	Design for Marketability	Zaccai (1994)
Use and operation	Design for Safety	Wang and Ruxton (1993)
	Design for Human Factors	Tayyari (1993)

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