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Design for manufacture and design for ‘X’: concepts, applications, and perspectives[☆]

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Abstract

The implementations of design for assembly and design for manufacture (DFM) led to enormous benefits including simplification of products, reduction of assembly and manufacturing costs, improvement of quality, and reduction of time to market. More recently, environmental concerns required that disassembly and recycling issues should be considered during the design stages. The effort to reduce total life-cycle costs for a product through design innovation is becoming an essential part of the current manufacturing industry. Therefore, researchers begin to focus their attention on design for environment, design for recyclability, design for life-cycle (DFLC), etc. These studies are sometimes referred to as Design for X (DFX). Since the late 1990s, hundreds of papers have been published pertaining to DFX applications in manufacturing. Most of them are widely distributed over many different disciplines and publications. This makes it very difficult for one to locate all the information necessary for the application of DFX in manufacturing. A paper that can help researchers and practitioners applying this emerging technology is highly desirable. The objective of this paper is to present the concepts, applications, and perspectives of ‘DFX’ in manufacturing, thus providing some guidelines and references for future research and implementation. © 2001 Elsevier Science Ltd. All rights reserved.

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1. Introduction

As early as the 1960s, several companies developed manufacturing guidelines for use during product design. One of the best known examples is the *Manufacturing Producibility Handbook* published for internal use by General Electric Corp. (MPH, 1960). In this handbook, manufacturing data were

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accumulated into a large reference volume with the idea that designers would be able to acquire the manufacturing knowledge for efficient and effective design. However, the emphasis was only on design of individual parts for 'producibility' and very little attention was given to the manufacturing and assembly processes. Beginning from the late 1970s, Boothroyd and Dewhurst conducted a series of study on design for assembly (DFA), which considers the assembly constraints (i.e. assembly methods and costs) during the design stages (Boothroyd & Dewhurst, 1983; Boothroyd, Poli & March, 1978). By using DFA, the estimated assembly time can be used as a guideline to find out the design changes that can lead to the reduction of the final cost (Waterbury, 1985). Expanded from DFA, Stoll (1988a,b) developed the concept of design for manufacture (DFM) to simultaneously consider all of the design goals and constraints for the products that will be manufactured. Several review papers about DFA, DFM, or DFMA (DFM and assembly) can be found in the literature (Andreason, Kahler & Lund, 1983; Scarr, 1986; Kobe, 1990). The implementations of DFA and DFM led to enormous benefits including simplification of products, reduction of assembly and manufacturing costs, improvement of quality, and reduction of time to market. More recently, environmental concerns required that disassembly and recycling issues should be considered during the design stages. In fact, the effort to reduce total life-cycle costs for a product through design innovation is becoming an essential part of the current manufacturing industry. Therefore, researchers begin to focus their attention on design for environment (Leonard, 1991), design for recyclability (Henstock, 1988), design for life-cycle (DFLC) (Alting, 1991; Ishii & Eubanks, 1993), etc. These studies are sometimes referred to as Design for X (DFX).

Since the late 1990s, hundreds of papers have been published pertaining to DFX applications in manufacturing. Most of them are widely distributed over many different disciplines and publications. This makes it very difficult for one to locate all the information necessary for the application of DFX in manufacturing. A paper that can help researchers and practitioners applying this emerging technology is highly desirable. The objective of this paper is to present the concepts, applications, and perspectives of DFX in manufacturing, thus providing some guidelines and references for future research and implementation.

2. Historical background

Engineering design is a process of developing a system, component, or process to meet desired needs. It is a decision making process in which basic sciences, mathematics, and engineering technologies are applied to convert resources optimally to meet a stated objective (ABET, 1988). Engineering design had usually been completed purely based on the consideration of product functionality. The design was then passed from the design department to the process-planning department and then to the manufacturing department. These activities were completed in a sequential manner with no feedback given to the designer. Sometimes the designed product is extremely difficult to manufacture and the manufacturing cost is unnecessarily high. To solve this problem, two approaches are used to help the designer reducing the product cost after a design is completed. They are value engineering and producibility engineering.

Value engineering is primarily concerned with product function and costs. Producibility engineering, on the other hand, assures that product specifications can be met with available or potentially available techniques, tooling, and test equipment at costs compatible with the product's selling price (Howell, 1982). By using value and producibility engineering, design engineers attempt to optimize the design to maximize the profit of accomplishing intended functions. However, three problems are encountered in the traditional manufacturing system using value and producibility engineering. First, such optimization, if not carefully monitored, could be accomplished at the expense of product manufacturability. Second, implementation of value engineering is usually stated as a company policy but not strictly followed in a scientific manner; therefore, the most significant savings may not be achieved (Corbett, Dooner, Meleka & Pym, 1991). Third, although value engineering and producibility engineering are highly valid methods in themselves, they enter into consideration too late in the traditional manufacturing system, i.e. after the product design has been completed. This makes it more expensive to modify the design (at a later stage) and it also delays the launch of a new product to the market. A new approach of DFM, integrates the manufacturing considerations into the design process to overcome these shortcomings.

The concept of DFM is inspired by the successful application of DFA in manufacturing practice. Initially, DFM is concerned with the identification of the appropriate materials and manufacturing processes for components in a product's design, based on the combination of various capabilities and limitations of the product, so that the product can be easily produced (Kirkland, 1988). As time went by, more and more researchers recognized that not only assembly and manufacturing constraints but also other life-cycle issues such as disassemblability, recyclability, and environmental concerns need to be considered before important design decisions can be made. This practice will lead to more optimal designs when the entire life-cycle of a product from conception to disposal is considered.

3. DFX applications

3.1. Design for assembly

The research on DFA is pioneered by Boothroyd and Dewhurst and is based on the premise that the lowest assembly cost can be achieved by designing a product in such a way that it can be economically assembled by the most appropriate assembly system. There are three basic types of assembly systems, namely, manual, special-purpose machine, and programmable machine assembly. Boothroyd and Dewhurst provided a *Product Design for Assembly* Handbook (Boothroyd & Dewhurst, 1986) indicating ratings for each part in the assembly, based on the part's ease of handling and insertion. The techniques described in this handbook are concerned with minimizing the cost of assembly within the constraints imposed by the other design features of the product. Using the DFA computer program provided, a designer answers a series of questions about the fastening method, symmetry of the parts, size of the parts, and angle of insertion. The evaluation obtained in terms of assembly time and assembly efficiency can be used to reveal the required design changes from the viewpoint of assembly (Ishii & Eubanks, 1993).

The DFA method developed by Boothroyd and Dewhurst (1987) is summarized as follows:

1. Through the use of basic criteria, the existence of each separate part is questioned and the designer is required to provide the reasons why the part cannot be eliminated or combined with others.
2. The actual assembly time is estimated using a database of real-time standards developed specifically for the purpose.
3. A DFA index (design efficiency) is obtained by comparing the actual assembly time.
4. Assembly difficulties are identified which may lead to manufacturing and quality problems.

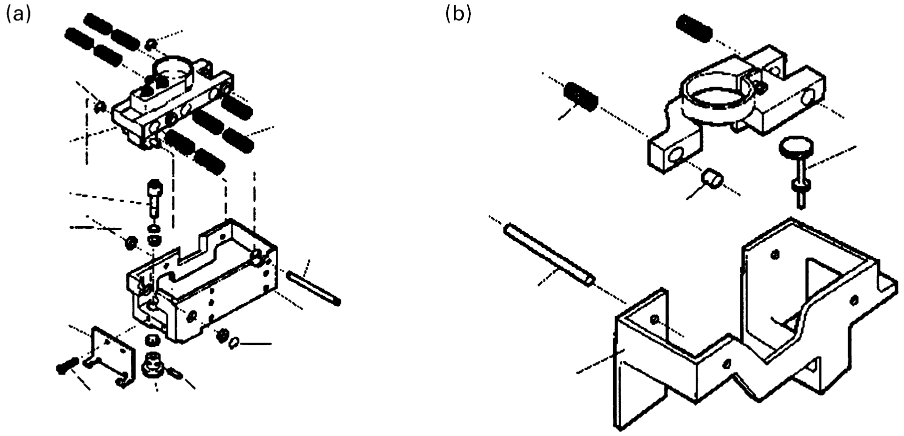

Fig. 1. Reticle assembly (Stoll, 1988a,b), (a) traditional reticle design (b) reticle design using DFA.

In the assembly, two factors that influence the assembly cost of a product or subassembly: (1) the total number of parts, and (2) the ease of handling, insertion, and fastening of the part. Therefore, in the DFA method, the basic alternatives for the designer to reduce the cost of assembly are either to avoid certain assembly operations altogether or to simplify them. Fig. 1 shows the comparison of a reticle design using a non-DFA method (Fig. 1a) and the other using a DFA method (Fig. 1b). It is evident that a DFA method provides numerous guidelines to reduce the number of parts.

Warnecke and Bassler (1988) developed an approach called *Assembly-Oriented Product Design*. The authors assessed each part's usefulness or functional value to evaluate the combined rating. This means that parts which have little functional value, such as separate fasteners, and which are difficult to assemble are given the lowest ratings. Finally, the ratings are used as guidelines to redesign the products. Poli & Knight (1984) developed a spreadsheet approach to rating design on the basis of their ease for automatic assembly. The results showed those parts and product features that tend to increase assembly costs. Myers (1987) described an algorithm that computed the manual handling time of the various components using Boothroyd's theory and data. In this work, the features needed are extracted from solid model boundary representations. Scarr (1986) emphasized the need to provide the information on a CAD-based workstation. The author concentrated on developing design rules for which automated assembly and robotics assembly techniques are appropriate.

In order to achieve design for efficient assembly, Hitachi (Boothroyd & Alting, 1992) developed a system that uses the *Assembly Evaluation Method* (AEM). AEM is based on the principle of 'one motion for one part'. In addition, approximately 20 symbols are used to represent assembly operations. Each symbol has an index that can be used to assess the assemblability of the part under consideration. The Sony Cooperation developed a unique set of rules for increasing productivity in 1980, involving design for assembly cost effectiveness (DAC) (Yamigiwa, 1988). In the DAC method, factors for evaluation are classified into 30 keywords. The evaluations are displayed on a diagram using a one-hundred-point system for each operation; thus making judgment at a glance easy. General Electric's Cooperate Engineering and Manufacturing staff have also conducted a total of 42 design for assembly workshops with the goal of redesigning products for ease of both manual and automatic assembly (Maczak, 1984).

Although various DFA approaches have been developed since the late 1970s, the basic guidelines remain the same, i.e. to reduce the number of parts and ensure the ease of assembly. The following is a list of DFA criteria (Corbett, 1987):

1. Minimize the number of (1) parts and fixings, (2) design variants, (3) assembly movements, and (4) assembly directions.
2. Provide (1) suitable lead-in chamfers, (2) automatic alignment, (3) easy access for locating surfaces, (4) symmetrical parts, or exaggerate asymmetry, and (5) simple handling and transportation.
3. Avoid (1) visual obstructions, (2) simultaneous fitting operations, (3) parts which will tangle or 'nest', (4) adjustments which affect prior adjustments, and (5) the possibility of assembly errors.

Another issue in the DFM is the modularity design. Given a family of modular products, designing low cost assembly systems is an important problem. The ability to produce a variety of products through the combination of modular components is a meaningful benefit during product design stage. Therefore, modularity design is to produce different products by combining standard components and sharing the same assembly operations for a part of their structure. Several modularity designs have been extensively researched recently to reduce the delay of product development. Suh (1990) promotes the decoupling of functional requirements in design. The independence of functional requirements allows design parameters to have a controllable effect on a specific functional requirement and minimal negative impact on other functional requirements. Pahl and Beitz (1988) provided two modules from the aspects of technology development and production capacity, respectively. One is function module that is constructed by the signal functions. The other is the production module that is formed either by one component or by assembly of many components. Huang (1998) developed a matrix approach to represent various types of module, e.g. component-swapping, component-sharing, and bus modularity, etc. Tsai and Wang (1999) presented a methodology of modular-based design in the conceptual stage of systems to support concurrent engineering. In the research, the functions are classified into different types of modules according to the correlation in design by using fuzzy cluster identification. Second, the optimal module type is selected based on the considerations of manufacture and assembly complexities of the system. Third, the design priority of functions within a module is scheduled by measuring the information content of functions.

3.2. Design for manufacture

The selection of appropriate processes for the manufacture of a particular part is based upon the matching of the required attributes of the part and the various process capabilities. These processes include raw material selection, process selection, modular design, standard component usage, multi-use part development, separate fasteners usage, and assembly direction minimization. Kirkland (1988) provided the factors which influence a designer's selection of a particular material which includes (1) raw material selection, (2) process selection, (3) develop a modular design, (4) use standard components, (5) design parts to be multi-useable, (6) avoid separate fasteners, (7) minimizing assembly directions. All parts should be assembled from one direction whenever possible. Extra directions mean wasted time and motion as well as more transfer stations, inspection station and fixture nests. The best possible assembly is when all parts are added in a top–down fashion to create a Z-axis stack. Multi-motion insertion should be avoided.

Stoll (1988a,b) cited a checklist of DFM guidelines that represented a systematic and identified list of statements concerning good design practice. Typically, the design guidelines are stated as directives that act to stimulate creativity and show the way to good DFM. Since 1980, DFM approaches have been used to obtain cost estimation for parts during the early design stage. Many DFM studies have been completed for machining parts (Boothroyd & Radovanovic, 1989), injection molding (Dewhurst, 1987), sheet metal stamping (Zenger & Dewhurst, 1988), die cast parts (Dewhurst & Blum, 1989) and powder parts (Knight, 1991).

DFM applications can be carried out with great efficiency via a CAD/CAM system that has a built-in cost estimation function. Designers can develop a computer representation of their design using a CAD model. Feature information of the CAD model can then be extracted (Eversheim & Baumann, 1991) and the cost of machining the features can be estimated. The information is fed back to the designer instantly. By modifying the CAD model using DFM guidelines, the designer can obtain cost information for design alternatives and choose a favorable design.

3.3. Design for disassembly and design for recyclability

Recently, recycling became an emphasis in most industrial countries due to the fact that the quantity of used products being discarded is increasing dramatically. It has been recognized that disassembly of used products is necessary in order to make recycling economically viable in the current state-of-the-art reprocessing technology. Disassembly is defined by Brennan, Gupta and Taleb (1994) as "the process of systematic removal of desirable constitute parts from an assembly while ensuring that there is no impairment of the parts due to the process".

In the past, products and machines were designed with only the assembly operations considered (Boothroyd, Dewhurst & Knight, 1994). Now, designers need to consider in terms of disassembly and parts recycling as well. Leonard (1991) reported that two basic methods of disassembly could be used: reverse assembly and brute force. In the case of reverse-assembly, if a fastener is screwed in, then it is screwed out; if two parts are snap fit together, then they are snapped apart. While in the case of brute force, parts are just pulled or cut. Seliger, Zussman and Kriwet (1993) identified some obstacles that made disassembly difficult for today's manufactured products. First, it is difficult to gain all the information necessary to plan the disassembly. Parts of the product might have been modified during repair, and wear can make joined elements difficult to remove. In addition, many consumer products are not designed for ease of disassembly.

The determination of disassembly sequence is another critical problem encountered. Subramani and Dewhurst (1991) developed an approach for disassembly sequence determination. Three issues associated with disassembly sequence determination are (1) freeing the part of all attachments, (2) finding the succeeding part in the disassembly sequence, and (3) disassembly of the succeeding part. Beasley and Martin (1993) reported that in order to obtain proper disassembly motion, both local and global geometric information should be considered. The local geometrical feasibility of a motion depends on whether an infinitesimal motion can be made or not. The global geometrical feasibility of a motion, on the other, depends on whether a finite motion can be made in a particular direction.

Gu and Yan (1995) presented a graph-based heuristic approach for automatic generation of disassembly sequence from a feature-based database. Four major stages are involved in generating the sequence: (1) create connective graphs based on the product feature representation, (2) decompose an assembly into subassemblies (represented as sub-graphs) using the connective graphs, (3) generate the disassembly sequence for each sub-graph formed at stages 2, and (4) merge the disassembly sequences of the sub-graphs into a complete disassembly sequence. Instead of emphasizing non-destructive disassembly, Lee and Gadh (1996) proposed a computerized design for disassembly approach based on destructive disassembly (DD). Kuo, Zhang and Huang (2000) provided a graph-based heuristic approach to perform disassembly analysis for electromechanical products. The components of a product and their assembly relationships are represented using a component-fastener graph. A cut-vertex search procedure is used to split the graph into sub-graphs representing modular sub-assemblies. Disassembly precedence analysis is then applied to generate a disassembly tree, from which a disassembly sequence can be derived. The results of the analysis can be used by designers to evaluate the disassemblability and recyclability of products which are designed by them. Desirable changes can then be made at the early stage of design.

Many industrial processes have been proposed for extracting these valuable elements from components on printed-circuit boards (PCBs) (Roy, 1991). One intangible benefit arising from recycling is a ‘green’ image. As environmental conscious increases, many consumers like to buy green products that create less environmental problems. Many governments now have official ecolabelling schemes to inform consumers about environmentally friendly products. For example, the Environmental Protect Agency published guidelines for use of the terms ‘recyclable’ and ‘recycled’ and the use of the recycling emblem in environmental marketing claims (EPA, 1991).

It is not possible or economical to recycle a product completely; therefore, the aim of recycling should be to maximize the recycling resources and to minimize the mass and pollution potential of the remaining products. Zussman, Kriwet and Seliger (1994) proposed three objectives that should be considered during design evaluation: (1) maximization of profit (benefits-costs) over a product’s lifespan, (2) maximization of the number of parts reused, and (3) minimization of the amount (weight) of landfill waste. Simon (1991) proposed a hierarchy of possible destinations for items removed during disassembly. From top to bottom, the hierarchy consists of re-use, remanufacture, recycle to high grade material, recycle to low grade material, incinerate for energy content, and dump in landfill site. In this hierarchy, the higher the level, the more of the investment of raw materials, source and energy in the component is conserved.

Research conducted in the CIM Institute of Georgia Tech (Rose & Evans, 1993) focuses on disassembly oriented life-cycle analyses, where recyclability of a product is evaluated under possible future trends in the development of recycling technology and economy. At the Swiss Federal Institute of Technology, an evaluation procedure has been proposed in order to support product design based on conflicting DFD criteria (Zust & Wagner, 1992). Each criterion is weighted and the final decision is made based on the scaling of all relevant criteria.

Several researchers have addressed the issue of design for manufacturing of plastics that can be easily recycled, particularly in injection molding. Ishii, Hornberger and Liou (1989) focused on designs for tooling and created a training tool based on design compatibility analysis. Navinchandra (1991) conducted an extensive survey of the implications of design for environmental compatibility. It not only addressed the recycling, but also the inevitable disposal. The author also clarified the costs associated with the overall product and material recycling loop.

Two engineering problems associated with DFR are dismantling techniques and recycling costs. Simon (1991) pointed out that dismantling required the knowledge of the destination or recycling possibility of the component parts disassembled. Here lies a difficulty, because between the time a product is designed and the time it reaches the end of its life, techniques would have advanced in recycling and re-engineering. Simon suggested two solutions to this problem: (1) remove the most valuable parts first, and (2) maximize the 'yield' of each dismantling operation. Henstock (1988) reviewed recycling practices for various metal based items with focus on steel scrap in automobiles. The study generated some general principles of DFR including: simplify mechanical assembly, avoid self-contaminating combinations of materials, standardize materials used, and separate high copper content items from steel items.

Ishii, Lee and Eubanks (1995) proposed the concept of clumping for disassembly and recycle. A clump is a collection of components and/or subassemblies that share a common characteristic based on user intent. Material compatibility is a major issue in clumping for product retirement. The designer may need to clump components that are not compatible due to certain constraints. If the post-life intent of the product is to be recycled and if materials in the clump are not compatible, then the mechanical connections among the components should be easily broken, i.e. using snap fits, press-fits, screws, and screw insert. If the intent of the designer is to clump for disposal, neither the material nor the fastening method is important.

Material recognition is another interesting approach for DFR. It requires technology capable of identifying materials, including the proportion and type of filler materials used. Ideally, the technology should be cheap, hand-held for use on different components, and significantly durable for use in a workshop-type of environment. A number of researchers have been working in this area with varying successes. Shergold (1994) indicated that the Fourier Transform Infra-Red (FTIR)-based equipment that Rover and Bird developed is good at identifying plastics and some filler materials.

Design for the ease of disassembly and recycling is a challenging problem to researchers and practitioners in the automotive industry. Shergold (1994) indicated that, in the automotive industry, currently only about 75% of the weight of each vehicle disposed of can be recovered for recycling. In addition, the author explained that parts removed by a dismantler are defined by market demand, and will generally include items such as the engine, the gearbox and other mechanical parts, as well as electronic components. Wittenburg (1992) proposed the concept of *recycling path* of components and materials, as envisaged by BMW. It entails a 'cascade model' of decreasing values, in which attention is first given to the disassembled parts suitable for re-use which have the highest value. BMW is the leader in design for recycling and disassembly in the automobile industry. The Z1 model is a two-seat automobile with an all-plastic skin that can be removed from the metal chassis in 20 min (Burke, Belter & Ishii, 1992). The doors, bumpers, and the front, rear, and side panels are made of recyclable thermoplastics produced by GE. The BMW 3251 also uses recyclable plastic parts and targets environmentally conscious customers (Braunstein, 1991). Through these efforts, BMW has identified some guidelines that make disassembly and recycling easier.

3.4. Design for environment

Fiksel and Wapman (1994) defined design for environment (DFE) as "the systematic consideration, during new production and process development, of design issues associated with environmental safety and health over the full product life-cycle". The scope of DFE encompasses many disciplines, including environmental risk management, product safety, occupational health and safety, pollution prevention, ecology, resource conservation, accident prevention, and waste management (MCC, 1993).

Horvath, Hendrickson, Lave and McMichael (1995) stated three main goals of DFE: (1) minimize the use of non-renewable resources, (2) effectively manage renewable resources, and (3) minimize toxic release to the environment. Mizuki, Snadborn and Pitts (1996) explained that DFE requires the coordination of several design- and data- based activities such as environmental impact metrics, data and database management, and design optimization (including cost assessments). The environmental impact metric is defined by Veroutis and Fava (1996) as "an algorithmic interpretation of levels of performance within an environmental criterion". The environmental criterion is the environmental attribute of the product. All of these environmental criteria can be translated into metric, and can be used to assist decision-making when the product is being developed.

The environmental accounting method includes activity-based costing (ABC) and cost benefit analysis. Bras and Emblemsvag (1995) proposed an ABC system to perform analysis in different life-cycle processes of products. In this system, costs are traced from activities to products based on each product's consumption of such activities. Traditional cost systems assume that each unit of a given product consumes resources, while ABC systems assume that products or services do not directly use up resources, but instead consume activities. The Hewlett-Packard (Korpalski, 1996) provides DFE tools for the company's use such as DFE guidelines, product assessments, and product stewardship metrics. The guidelines cover product use, product consumable and supplies, shipment packaging, manufacturing processes, and end-of-life product strategies. The product assessments are tools used by product stewards, which helps to measure results and target improvement opportunities. The product stewardship metrics include material conservation and waste reduction, energy efficiency, and design for environmental and manufacturing process emissions.

3.5. Design for life-cycle

DFLC is sometimes referred to as life-cycle engineering or life-cycle design. An outstanding analysis of life-cycle design that provides design support from the environmental point of view was provided by Alting (1991). Several papers about life-cycle design can be found in the literature (Riggs & Jones, 1990; Tipnis, 1993; Ishii & Eubanks, 1993; McCue, 1993; Weule, 1993; Govil, 1992). DFLC is based on the early product concept, including product/market research, design phases, manufacturing processes, qualification, reliability, customer service, maintainability, and supportability issues. Boothroyd and Alting (1992) distinguished six phases in the product life-cycle: (1) need recognition, (2) design development, (3) production, (4) distribution, (5) use, and (6) disposal. Keys (1988) noted that during the conceptual design phase, various design and simulation models of the product can be generated. From these conceptual models, requirements, specifications, and analyses will evolve decisions for breadboard/brassbound models.

Life-cycle assessment is a family of methods for assessing materials, services, products, processes, and technologies over the entire life of a product. The definition of product life-cycle assessment, developed by the Society of Environmental Toxicology and Chemistry (SETAC, 1991), is "an objective process to evaluate the environmental burdens associated with a product or activity by identifying and quantifying energy and materials used and wastes released to the environment, to access the impact of those energy and material uses and releases to the environment". Life-cycle assessment is the major tool used for DFLC. It is based on the analysis of the life-cycle costs of a product. Life-cycle cost analysis is based on product-specific costs that occur within the life-cycle framework. The life-cycle cost of a product can be divided into two parts: cost of product development and manufacturing, and cost of operation, maintenance and/or service. During the product development, product manufacturing and product usage, there is a society cost incurred, including waste, pollution, and health damage (Huthwaite, 1989).

Table 1
Product life-cycle cost (Jovane, 1993)

Life-cycle phase	Company costs	User costs	Society costs
Need	Market recognition		
Design	Development		
Production	Materials, energy, facilities, wages and salaries		Waste, pollution and health damage
Distribution	Transportation, storage, waste	Transportation, storage	Waste, pollution, packings and health damages
Use	Warranty service	Energy, materials, maintenance	Waste, pollution and health damages
Disposal		Disposal dues	Waste handling, disposal, health damages, pollution
Recycling		Recycling dues	Waste, pollution and health damages

An accurate estimation of costs to develop and use a product are crucial to life-cycle design (Shen, 1995). Kuo (2000) presented a disassembly sequence and cost analysis for the end-of-life products during the design stage. The disassembly cost is categorized into three types: target disassembly, full disassembly, and optimal disassembly. Material and energy flows identified during inventory analysis provide a detailed template for assigning costs to individual products. In an effort to be more complete, life-cycle cost analysis also uses an extended time scale, from the time of production through procurement, storage, use, and disposal (Keoleian, 1993). The *EPA Pollution Benefits Manual* (Keoleian, 1993) provides a financial analysis approach to compare alternatives for pollution prevention. From Keoleian's classification, life-cycle costs can be shared among manufacturing companies, users, and society, although their distribution can vary considerably from product to product. Table 1 shows the life-cycle costs of a product.

Lee and Tapiero (1987) developed a framework to identify the interaction between quality control parameters and product service in order to reduce product service cost. Assuming a linear cost structure, Hegde and Karmarkar (1993) derived an economic structure to be observed in the market for product support. They incorporated the discounting issues and the nonlinear cost structure of the product failure cost, and established altogether different relationship between design parameters and customer costs. Hegde (1994) divided failure costs into four categories (1) failure cost to the customer as the sum of fixed and variable costs of failure, (2) failure cost of downtime proportional to a power of the length of downtime, (3) failure cost as a storage device, and (4) failure cost as almost zero to calculate the total discount cost.

3.6. Design for quality

Since inspection and statistical quality control can never fully compensate for poor design, quality must be designed in the product (Bendell, 1988). According to Crow (1983), the objectives of design for Quality (DFQ) are: (1) design of a product to meet customer requirements, (2) design of a robust product that can counter or minimize the effects of potential variation in manufacture of the product and the product's environment, and (3) continuously improve product reliability, performance, and technology to exceed customer expectations and offer supervisor value. The concept of DFQ exists for a long time. However, it was not implemented until Taguchi method (1986) was introduced. Taguchi methods advocate a philosophy of quality engineering that is broadly applicable. Taguchi (1993) considers three stages in a product's or process's development: (1) system design, (2) parameter design, and (3) tolerance design. In system design, an engineer uses scientific and engineering principles to determine the basic configuration. In the parameter design stage, the specific values for the system parameters are determined. Tolerance design is used to determine the best tolerances for the parameters (Kackar, 1985; Phadke, 1989).

The Quality Function Deployment (QFD) is an important technique to implement DFQ because QFD carefully considers the customer requirements and transfers them into specification before manufacturing. QFD is a means of ensuring that customer requirements are accurately translated into relevant technical requirements throughout each stage of the product development process. In addition to QFD, benchmarking is also a tool used by enterprises in DFQ. Benchmarking is defined as a process of learning from the best in terms of business strategies, business operations, and business processes (Madu & Kuei, 1993). Zairi (1992) pointed out that there are three types of benchmarking: (1) internal, (2) external, and (3) generic. Internal benchmarking studies the best performance in an organization. External benchmarking deals with the best competitors in an industry. Generic benchmarking studies the best business practices in the world. Benchmarking is a powerful tool for the purpose of competitive analysis and continuous improvement.

3.7. Design for maintainability

Kapur and Lamberson (1977) defined maintainability as "the probability that a failed system can be repaired in a specific interval of downtime". The basic objective of Design for Maintainability (DFMt) is to assure that the product can be maintained throughout its useful life-cycle at reasonable expense without any difficulty. Maintainability requirements can be classified as qualitative and quantitative. Both qualitative and quantitative maintainability requirements are used to define the maintainability characteristics in a system or equipment. Qualitative requirements take the form of maintainability design guidelines. These guidelines describe such requirements as: (1) accessibility, (2) ability to detect and isolate failure, (3) weight limitations of replaceable units, (4) dimensional limits to allow replaceable units to be transported from their installed location to a repair shop or for shipment to their manufacturer's facility, and (5) design requirements to make replaceable units compatible with robots for removal and replacement in remote locations or hazardous environments.

Moss (1985) developed some fundamental principles of maintainability to obtain the objective of DFMt, such as standardization and interchangeability. Unger (1980) performed a system analysis to superimpose control sector for total maintenance and minimize the maintenance cost. The author classified the maintenance cost into four categories: (1) total costs of failure-related repairs, (2) total costs for condition-monitoring maintenance, (3) permanent costs for safety-related maintenance to meet legal criteria and (4) special maintenance.

The following is a list of DFMt guidelines that provides designers with specific guidance regarding qualitative design requirements.

1. General design features
    - The design shall preclude the possibility of damage to the equipment during maintenance and servicing.
    - Minimize the needs for special tools.
    - Part reference designations shall be located next to each part legibly and permanently.

  - Keying, size, or shape shall be used to ensure that removable parts are reassembled in the correct position.
  - Guide pins shall be provided for alignment of modules or high-density connectors.
  - Handles shall be provided for removable units weighting over 10 pounds or whose shape makes them difficult to handle.
  - Sharp edges, corners, or protrusions that could cause injury to personnel shall be avoided.
2. Mounting and location of units
   - Provide for the removal and replacement of line replaceable unit (LRU) without removal of unfailed units.
   - Provide for the removal and replacement of LRUs without interrupting critical functions.
   - Provide clear access to all LRU locations. Mount units to chassis or structure rather than on other units.
   - Mount heavy units as low as possible. Label access for units.
3. Test, checkout, calibration
   - Fault isolation test circuitry shall not cause failure of the circuit under test.
   - Test points on printed circuit boards shall be located to permit in-circuit testing.
   - Calibration and adjustment controls that are intended to have limited motion shall be provided with adequate stops to prevent damage.
   - All adjustments shall be designed to be common in their replacement response (i.e., clockwise, right, or up to increase).
4. Cables, leads, wiring, connectors
   - Provide clearance around connectors for adequate viewing and hand access.
   - Route cables to facilitate tracing, removal, and replacement.
   - Provide service loops in cables and harness to facilitate installation, checkout, and maintenance.
   - Code or label wires and cables throughout their length for easy identification.

3.8. Design for reliability

Reliability is comprised of four factors: (1) probability, (2) specified function, (3) designated environment, and (4) length of time. According to the Advisory Group on Reliability of Electronic Equipment (1957), reliability is defined as “the probability of a product performing without failure a specified function under given conditions for a given period of time”.

In reliability engineering, system reliability consideration in the design stage is supported by reliability allocation. Reliability allocation is a procedure to allocate the entire target reliability of a product into its subsystem, and again, allocate the sub-target reliability of each subsystem into parts level. The purpose of reliability allocation is to establish target reliability for each level in product structure so that engineers and the management have a clear goal to strive for. Three basic methods of reliability allocation that are commonly used are: equal, AGREE (1957), and ARINC allocations.

1. Equal Allocation. Assume the reliability model of the product is in series. Then

$$R^* = \prod_{i=1}^{n} R_i^* \text{ or } R_i^* = (R^*)^{1/n}, \qquad i = 1, 2, \ldots, n \tag{1}$$

where R^* is the entire target reliability, R_i^* is the ith subsystem reliability allocated and n is the number of subsystems

2. AGREE Allocation. This method was developed by the Advisory Group on Reliability of Electronic Equipment (AGREE, 1957) in 1950s. This method assumes that the reliability model of a product is in a series and subjected to the exponential distribution.

$$\theta_i = \frac{NW_i t_i}{n_i[-\ln R^*(t)]} \text{ or } R_i^*(t_i) = \exp\left(\frac{-t_i}{\theta_i}\right) \tag{2}$$

   where $i = 1, 2, \ldots, k$, t is the operating time of the product (or the system), t_i the operating time of the ith subsystem, W_i the weighting factor of the ith subsystem, n_i the number of parts of the ith subsystem, N the total number of parts, $N = \sum_{i=1}^{k} n_i$, $R^*(t)$ the target reliability at operating time t, $R_i^*(t_i)$ the allocated reliability of the ith subsystem and θ_i is the allocated MTBF of the ith subsystem.

3. ARINC Allocation. The Aeronautical Radio, Incorporated (ARINC) allocation method calculates the failure rate for each subsystem. This method also assumes an exponential distribution that indicates the failure rate is constant during the operating period. There are five steps for reliability allocation.
   - Calculate the system failure rate λ^*
   - Estimate each subsystem's failure rate λ_i
   - Calculate the weight of each subsystem

$$W_i = \frac{\lambda_i}{\sum_{i=1}^{n} \lambda_i} \tag{3}$$

   - Calculate the allocated failure rate of each subsystem λ_i^*, where $\lambda_i^* = w_i \lambda^*$
   - Calculate the allocated reliability of each subsystem $R_i^* = \exp(-\lambda_i^* t)$

There are two types of reliability analysis: reliability analysis for electronic systems and reliability analysis for mechanical systems. Experience indicates that the failure behavior of many components follow the bathtub hazard rate function (Ertas & Jones, 1993). For electronic systems, the first and third phases of reliability bath-tub curve of a product are generally subjected to the Weibull distribution or log normal distribution. In the second phase, which is most valuable to customers, it is usually subjected to the exponential distribution. Therefore, if the relevant parameters of the distribution are known, system reliability is easily calculated. The failures that occur in the mechanical system, on the other hand, are usually caused by aged or worn-out materials, or over-stress. An aged or worn out material reduces its strength against stress. Therefore, the reliability analysis for mechanical system is basically a strength-stress analysis. In designing a mechanical system, it is imperative that the strength of a part be significantly greater than the applied stress to have an acceptable reliability.

Ireson and Coombs (1988) provided a list of guidelines for design for reliability (DFR) which are (1) simplicity, (2) use of proven components and preferred designs, (3) stress and strength design, (4) redundancy, (5) local environment control, (6) identification and elimination of critical failure modes, (7) detection of impending failures, (8) preventive maintenance, (9) tolerance evaluation, and (10) human engineering. Human activities and limitations can be very important to system reliability. The design engineer must consider factors that directly refer to human aspects, such as human factors, person–machine interface, and evaluation of the person in the system, and human reliability.

4. Summary

DFX research emphasizes the consideration of all design goals and related constraints in the early design stage. By considering all goals and constraints early, companies can produce better products. Furthermore, the product will enter the marketplace earlier because an inherently simpler product is designed correctly the first time without the introduction of problems, delays and changes of orders. Design for assembly and DFM make a product easier to produce with lower costs. Design for disassembly, design for recyclability, and DFLC make the designer plan ahead for product processing after its useful life. Design for environment focuses on environmental safety and health related issues and thus can help reduce the indirect cost of a product. Quality, maintainability, and reliability can also be assured by design and process controls rather than by expensive testing, diagnostics, and rework.

There are several successful examples in industry that exemplify the effectiveness of DFX approaches in the manufacturing environment (Hashizume, Matsunaga, Sugimoto, Miyakawa & Kishi, 1980; Kroll, Lenz & Wolberg, 1988; Rosairo & Knight, 1989). The implementation of DFX may require additional effort early in the design process. However, with the integration of the product and process into design through business practices, management philosophies and technology tools, the result is a more predictable product to better meet customer needs, a quicker and smoother transition to manufacturing, and a lower total life-cycle cost. The greatest challenge is not implementing new techniques, but overcoming organizational barriers and resistance to changing the way things are done. There is no doubt that DFX will play an important role in the current manufacturing industries, and it is expected that in the future, DFX will become a cutting edge technology.

5. Future trend

5.1. Integration issues in DFX

The application of DFX requires that engineers and designers work in teams rather than individually. This occasionally creates friction. Additionally, the designers' work is more closely scrutinized, as DFX analysis often reveals that their initial ideas may not be the most effective (Constance, 1992). This implies that more integration issues need to be addressed during the design process. The integration should occur from the machine-tool controller to the controller's office, and laterally, from the product design through process planning, component manufacture, assembly, and shipping. New management systems must be developed to help companies to adopt shorter product life-cycles and extreme market cycles, distribute decision-making, and develop shared goals with laborers (Francis, 1990). The future research of integration issues should include (Ishii & Eubanks, 1993):

1. Systematic identification of user's life-cycle requirements. Design for value and QFD provides the basis for the study. One also needs a method to propagate these requirements to detailed specifications as the design progresses.
2. Methods to represent, store, and retrieve design alternatives. Given the functional and other life-cycle

needs of the users, designers need to find the most appropriate design alternatives by specifying materials, configuration, geometry, and manufacturing process.

3. Comprehensive measure of goodness of a design. The current design compatibility approach (DCA) focuses primarily on case-based, experimental knowledge on a specific life-cycle value such as manufacturability. DCA needs to accommodate more quantitative measures of design such as estimated life-cycle cost.

5.2. Human factors engineering in DFX

DFX concepts are embraced by a commitment to design all human–technology elements and processes with full and deliberate consideration of user performance capabilities. The practice of systematically applying the principles of human performance (e.g. perceptual, learning, motivational, and attitudinal) to the design of the human–equipment interface is termed human factors engineering (HFE). Design for the user via HFE and implementation of systematic training programs are the principle means for developing and sustaining human performance effectiveness in view of the technology explosion.

Human–technology interfaces within DFX are becoming more crucial than ever because of the requirements for system monitoring, communication, data entry, processing, and retrieval. Optimal human performance results from controls that are easy to reach and operate, from comfortable work environment, and from displays that are compatible with their counter part controls and are easy to see and interpret. Hardware and software should be designed and arrayed to optimize human performance. This suggests that technology configurations should be driven by user capabilities and requirements rather than requiring people to adapt inefficient, awkward, or tedious technology.

Human performance improvement is a continuous process influenced by workplace design and performance-based training. Future research issues should include (Child, 1983):

1. Plant modernization effects on human performance: human performance issues associated with the automated workplace.
2. DFM and human factors engineering: general guidance for the design of human–equipment interfaces.
3. Human learning principles: learning concepts and principles that should be incorporated into the design of human training programs.
4. System-based training: methods and processes of systems-based training programs, and a model that incorporates evaluation and feedback.

5.3. Intelligent DFX systems

Today, it takes most designers years of practice to acquire the experience needed to make the right compromises and to generate a satisfactory design when considering DFX issues. A knowledge-based program that encompasses knowledge associated with not only our understanding of the functions and features of the product, but also with its life-cycle issues are very useful to designers. Thus, designers will greatly benefit from a computer program that retrieves information about the

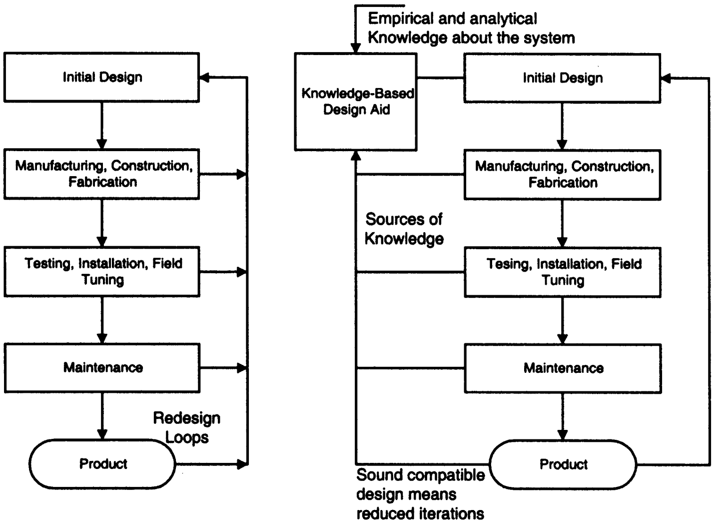

Fig. 2. Conventional design vs. expert system design.

design, design requirements, design process, evaluation of product compatibility, and makes suggestions for design improvement. Use of an intelligent system will result in a good design that is compatible with the various life-cycle aspects of the product. Ishii (1988) reported that the development of a knowledge-based system would provide better understanding of the relationship between the features embodied in the design and the life-cycle issues, such as performance and manufacturing.

The emerging field of artificial intelligence (AI) and the knowledge that engineering offers will allow designers to produce symbolic reasoning on computers. These techniques allow designers to model intuitive knowledge, judgment, and experiences that expert designers use, and to integrate them into available quantitative tools. Several researchers have explored the possibility of using expert system in engineering design (Brown, 1993; Makino, 1989; Bryan, Eubanks & Ishii, 1992). A comparison of conventional design versus expert system design is shown in Fig. 2. The research on intelligent DFX systems is still in its infancy. Only the use of expert system has been explored. Researchers should also explore the use of other AI techniques, including fuzzy logic, neural networks, genetic algorithms, and case-based reasoning in DFX. There is no doubt that these techniques can play a significant role in DFX research and development.

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