An Investigation of the Applicability of DfX Tools during Design Concept Evolution

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Abstract: Design stage is very critical as many decisions impacting the downstream development activities and the product cost are made in this stage. Over the years, numerous "Design for X (DfX)" concepts/methods have been developed in order to increase the efficiency at the design stage, and reduce the total cost and lead time of the product. Among these are design for manufacture, assembly, quality, maintenance, environment, obsolescence and recyclability. Despite these numerous concepts/methods, their application is challenging because of two reasons: (1) because methods have been developed with different foci (e.g., manufacturing vs. quality), it is difficult to know how different methods complement each other, and (2) in what sequence and where at the design stage they should be applied. In the paper, we address this challenge, with a review of DfX methods and the recommended design stages for their use. We also provide a thematic sequence for their application.

Keywords: Design for X, Engineering design process, Review.

1. INTRODUCTION

Many studies (e.g., Appelqvist *et al*, 2004; Dowlatshahi, 1996) pointed out that while design stage takes a very short period in a product life cycle, it dictates around 70-80% of product life cycle cost. Accordingly, how to well-utilize this prime time to create a successful product has been widely discussed. For example, Dowlatshahi (1996) presented a P:D ratio as a competitive advantage index of a product, where "P" is the total lead time to buy materials and process them into final products, and "D" is the customer's lead time from receipt of a customer's order until customer expects the delivery. A low P:D ratio represents the high service quality of the product. Many strategies can be applied to improve the P:D ratio. As shown in Table 1, some of these strategies have implications for the manufacturing and sales area, while others have for the design area. Dowlatshahi (1996) demonstrated the importance of the design via a case study of a bad stereo equipment design which caused long lead times and a high inventory level.

Table 1: The alternatives to improve the P:D ratio (adapted from Dowlatshahi,1996)

Choice	Responsible department		
	Mfg.	Design	Sales
Reduce P time	X	X	
Extend D time			X
Standardize raw materials		X	
Simplify product line		X	X
Sell what was forecasted			X
Forecast more accurately			X
Adding contingency (e.g., Safety stock	X		X

In this paper, we review the "Design for X" (DfX) concepts and methods with potential applications at different design phases. Overall, design stage activities can be divided into four phases: (1) Problem definition and customer needs analysis, (2) Conceptual design, (3) Preliminary design, and (4) Detail design. In the first phase, customer requirements for the new product are collected, and compiled. Then, the requirements are translated into product functions and features. In the second stage, concepts that can satisfy the requirements are generated, and selected. In the preliminary design stage, the computer aided design (CAD) models and prototype of the product are generated. The final design stage will determine the specification and parameters of the final product.

Our overall intent is to aid design practitioners in their application of DfX tools in providing cheaper products with high quality in shorter lead times.

2. DfX APPLICATIONS

In the paper, we present the DfX methods using two organizing themes (design for efficiency and green design) in order to show their complementary nature. In addition, we categorize the DfX methods using three ranges of perception: (1) product scope, (2) system scope, and (3) eco-system scope. In this context, we define efficiency as the ratio of the effective or useful design process output (e.g., designed artifact, and the process itself) to the total input to the design process and the designed artifact (e.g., information, materials). We review the DfX concepts relating to efficiency in two ranges of perception: product scope and system scope. Based on our review, we group design for manufacturing (DfM), design for assembly (DfA), design for quality (DfQ), design for reliability (DfR), design for disassembly (DfD), design for maintainability (DfMa) and design for obsolescence (DfO) within the product scope. The system scope covers design for supply chain (DfSC), design for logistics (DfL) and design for network (DfN). A summary of our review of these DfX concepts is presented in Section 2.1.

Green design is practicing engineering with the inclusion of natural system as a fundamental consideration (Ogot and Kremer, 2004). We review the DfX concepts relating to green design in Section 2.2. Based on our review, we group design for Recycle (DfRe), design for sustainability (DfS), design for environment (DfE), and design for life cycle (DfLC) in this category. As for the ranges of perception, we categorize DfRe to be at the product scope, and DfS, DfE, and DfLC to be at the eco-system scope. Figure 1 presents the overall structure of our categorization.

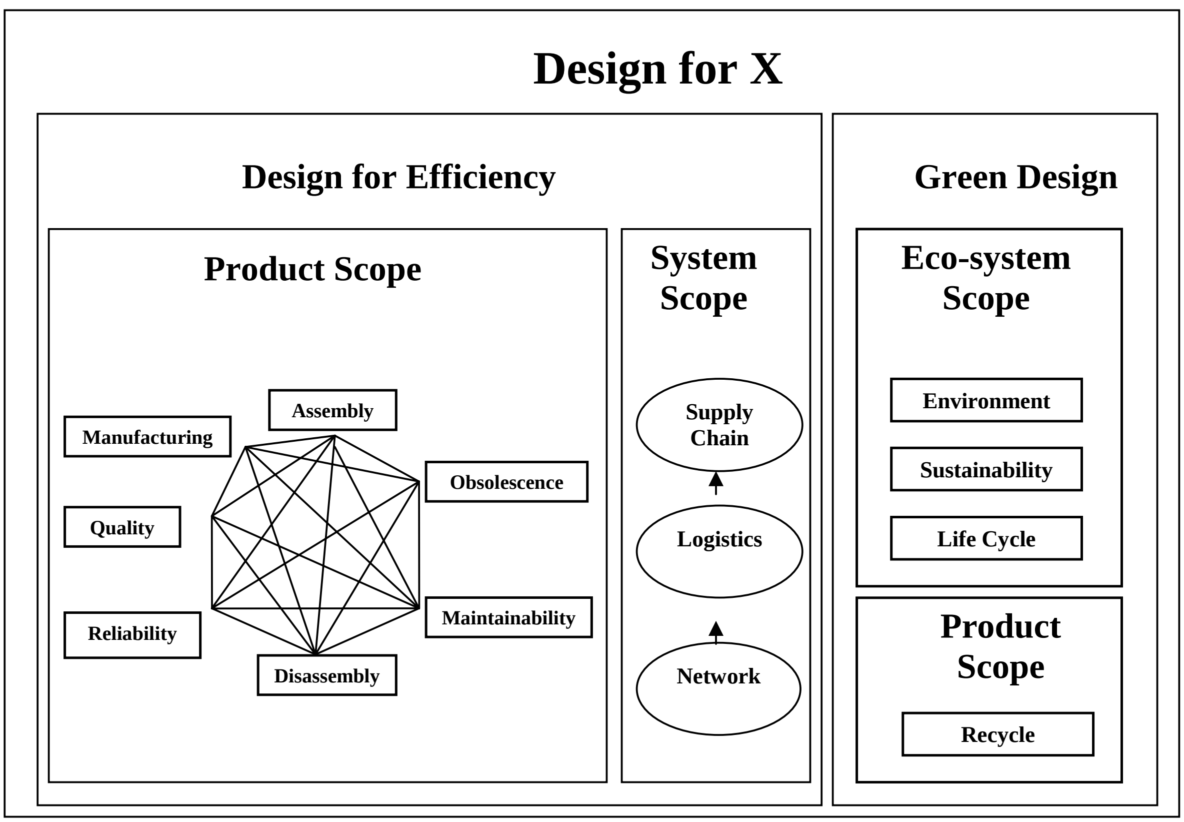


Figure 1. Structure of the DFX

2.1 Design for Efficiency

The main purpose of design for efficiency is expressed as reducing cost and lead time of a product while sustaining or improving its quality. Our review of design for efficiency concepts are divided into two ranges of perception: product scope and system scope. The product scope focuses on the product aspects which enable efficiencies at the shop-floor within a company (e.g., altering the design of a product to reduce machining time). The system scope concentrates on the integration and coordination of the value chain starting with the design stage and ending with the delivery and maintenance system.

2.1.1 Product Scope

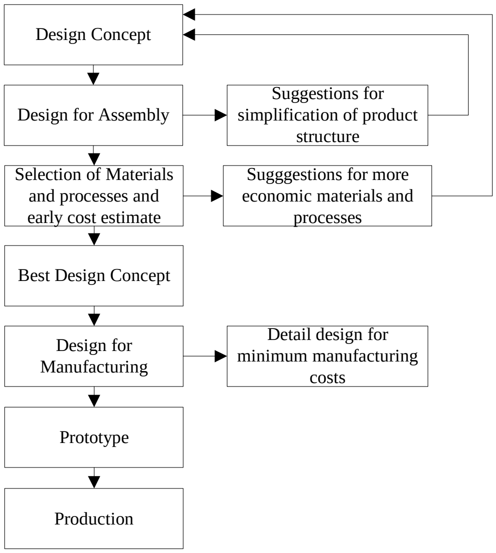
All DfX concepts we have grouped under this scope have varying level of interrelations among them. For example, while evaluating the design for assembly of a product, quality and reliability issues might affect the material and process choices. Likewise, design for manufacturing might be impacted by design for maintainability.

Among the design for efficiency concepts, assembly and manufacturing are the earliest discussed topics. According to Das *et al.* (2000), design for manufacturing was defined as "an approach for designing a product so that (i) the design is quickly transitioned into production, (ii) the product is manufactured at a minimum cost, (iii) the product is manufactured with a minimum effort in terms of processing and handling requirements, and (iv) the manufactured product attains its designed level of quality." Fabricius (1994) proposed a set of guidelines "Seven step procedure for design for manufacture" to enhance the linkage between design and manufacturing using a three-dimension model. The first dimension consists of the design phases. The second is the seven universal virtues, which are production costs, quality, flexibility, risk, lead time, efficiency and environment impact and the activity levels. In this context, activity level starts from the component level, then proceeds to the structural level, family level to corporate level. This set of guidelines goes through the four design phases to determine the best concept for DfM.

Different from guidelines proposed by Fabricius (1994), which are metric-based, Stoll (1988) described 13 DfM guidelines that are strategy-based and practice oriented. These guidelines focus on three strategies: (1) modular design, (2) multi-use parts with standardization, and (3) ease of assembly to increase the manufacturability. Warnecke and Babler (1988) presented an assembly-oriented design process (AODP) method that systematically applies design rules and evaluates the suitability for assembly to reduce the iterative loops in design phases. To achieve this goal, the AODP measures four aspects of the new product from top to down beginning with product structure, subassemblies components and joining techniques during design phases. There are methods, however, that are component-based rather than involving systematic reviews. For example, Boothroyd and Alting (1992) pointed out that the Assembly Evaluation Method (AEM) developed by Hitachi follows the "one motion for one part" principle. Two indices in AEM, evaluation score E and assembly cost ratio K are used in this method. The evaluation score E examines the difficulty of assembly and cost ratio K projects the assembly costs based on the current costs. These two indices support the analysis of the current assembly method and provide suggestions for the new product design. The three techniques, (guidelines by Stoll (1988), AOPD and AEM), summarized above are all applied in the preliminary and detail design phase.

Boothroyd (1994) claimed that product design for manufacture and assembly can be the key to high productivity in all manufacturing industries comparing to the automation. He proposed a design for manufacture and assembly (DfMA) method, which is illustrated in Figure 2 with an example, to shorten the time taken to bring the product to market. In his method, the concept of design for assembly was first indicated in the conceptual design phase to ensure the best design concept for materials and processes. Then, the concept was evaluated to minimize the manufacturing costs. Although this will slightly increase the time in conceptual design phase, considerable time savings would be achieved during preliminary design and detail design phases.

With regard to Design for obsolescence (DfO), Singh and Sandborn (2006) observed the sharp increase of maintenance cost in a complex system because of the obsolescence of a few components. They developed a proactive mitigation of obsolescence cost analysis (MOCA) model and applied it on the F-22 aircraft of US Air Force. MOCA model provides a predicted technology improvement timeline and a mix of obsolescence mitigation approaches ranging from lifetime buys to part substitution. This model generates the requirement of design refresh parts and respective schedules that would minimize the life cycle sustainment cost of a product under the uncertainties of cost analysis and dates in the detail design phase. It can help predict as early as possible how to best design and plan for system sustainment. The advantage of this method is that it can provide guidelines for how systems are modified, and how to allocate the budget more accurately, and thus improving the operational availability. However, there are two drawbacks in this model. First, it does not take into account software changes, which are initiated by hardware changes. Second, it does not have a real-time view of the parts inventory because it takes the original manufacturers' last order date as input data.



Item	Number	Theoretical Part count	Assembly time (sec)	Assembly Cost (US cent)
Base	1	1	3.5	2.9
Motor subassembly	1	1	4.5	3.8
Motor screw	2	0	12	10
Sensor subassembly	1	1	8.5	7.1
Set Screw	1	0	8.5	7.1
Thread Leads	-	-	5	4.2
Plastic cover	1	1	4	4.3
Total	**7**	**4**	**46**	**38.4**

Figure 2. Typical steps of DfMA method (left) and result of DfA analysis for redesign of motor-drive assembly as an example (right) adapted from Boothroyd (1994).

Desai and Mital (2006) pointed out that building maintainability into the product/system at the design stage is the only way to reduce maintenance requirements. Accordingly, they provide a set of guidelines to account for DfMa at the design stage:

(1). Accessibility: All equipment and subassemblies that require routine inspections should be located such that they can be accessed in a readily and easy manner. Moreover, they should be fitted with parts that can be connected rapidly to mechanical, air, electric and electronic connections.

(2). Modularity: Modularity requires grouping functionally similar parts into subassemblies, which then can be put together to form the product. Effective modularization can be achieved only if interfaces are standard.

(3). Simplicity: Simpler designs are inherently easier to maintain. Simplicity can be achieved by undertaking measures such as reducing the number of different parts or reducing the part variety.

(4). Standardization: Standardization allows for easy replacement of faulty components. It also assures designers of a certain quality level. Cost effectiveness is yet another advantage of using standard components because of their availability.

(5). Foolproofing: Precautions should be devised to prevent fitting to the wrong assembly.

(6). Inspectability: There should be an attempt to create a design that can be subjected to full, non-destructive, functional testing.

Desai and Mital (2006) proposed that a structured design review can be used to ensure design for maintainability (DfMa). The overall purpose of DfMa is to have designers consider maintainability during the conceptual design phase in order to reduce the maintenance time and frequency at shop floor.

The design for quality (DfQ) is generally deployed in the preliminary design phase when the first prototype is available. Das *et al.* (2000) developed a Design for Quality Manufacturability (DfQM) method to classify the defects and map them to the design parameters. This method first analyzes the influence factors in product design files and assembly sequences. These factors are then translated and classified into different group of defects through an “error catalyst” agent thus enabling users to foresee the possible defects and correct them at the design stage. Among other tools to ensure design for quality, designers can use Quality Function Deployment (QFD), and Failure Mode Effects Analysis (FMEA). QFD is used during the conceptual design phase to translate the customer requirements to the products functions (Kuo *et al.*, 2001; Herrmann *et al.*, 2004). FMEA is a tool to identify the root cause of the failure and thus certify the quality of the product in the detail design phase (Stoll, 1988; Herrmann *et al.*, 2004).

Reliability is another issue that is closely related to quality. Reliability is the probability of a product performing a specified function without failure under given conditions for a given period of time (Kuo *et al.*, 2001). Efforts regarding design for reliability (DfR) are by Ireson (1995) and Kuo *et al.* (2001). Ireson (1995) provided reliability guidelines. Kuo *et al.* (2001) proposed mathematical models for designers to estimate and control the reliability within a small likelihood.

Design for disassembly (DfD) is an important consideration, which focuses on repair and after delivery service situations. Zhang *et al.* (1996) developed a graph-based heuristic approach to generate a disassembly tree. The approach has three steps, which use the graph representation. First, disassembly analysis is undertaken to study the product structure and disassembly sequence. The next step is data (database) management to ensure recording of the physical properties of component such as weight, volume and recycling methods. The last step relates to recycling cost minimization, which determines the disassembly strategy and the ultimate recycling cost. Due to the nature of graph representations, quantitative analysis is possible. Based on the graph-based heuristic approach, Kuo (2000) presented a disassembly sequence and cost analysis method that classify disassembly cost into three parts: target disassembly, full disassembly and optimal disassembly. When to stop the disassembly operations is dependent on the break-even point of the cost and profit. The two methods presented above are generally used in the preliminary and detail design phase. A complementary concept to DfD is design for recycle (DfRe); DfD methods can be used for recycling purposes.

2.1.1 System Scope

Lee and Sasser (1995) defined Design for Supply Chain Management (DfSCM) with the aim of designing products and processes to more effectively manage supply chain related cost and performance. DfSCM utilizes product line structure, bill of materials and customization processes of a product in order to optimize the logistics costs and customer service performance. Lee and Sasser (1995) constructed a mathematical model to support the decision making for the supply chain (e.g., inventory levels, transshipment and product postponement). One other work relating to DfSC is by Appelqvist *et al. (*2004). They built a framework for supply chain decision making, and guidelines for designers to create the supply chain in the detail design phase.

Supply chain aims at service and product in the production cycle while logistics concentrates on the materials related issues such as acquisition, storage, transportation and delivery. Mather (1992, pg 7.) defined the design for logistics (DfL) as: "…to delight the customer with product when needed." He argued that some logistics issues resulting from product design cannot be solved by marketing and manufacturing techniques, and a redesign would be a reasonable and necessary solution. Accordingly, he provided two DfL guidelines for logistically effective design to be applied during the detail design phase. The first guideline recommends replacing unique components necessitating long lead times with standard components through redesign. When such a redesign is not possible, the second guideline recommends leaving the processing of unique components with long lead times to the final stages (e.g., form postponement). Given the importance of logistics Dowlatshahi (2006) proposed that logistics engineering, manufacturing logistics, design for packaging (DfP), and design for transportability (DfT) should be reviewed concurrently while designing for logistics. In his paper, Dowlatshahi (2006) provided detailed guidelines to accomplish this.

Design for network (DfN) is proposed as an extension for the DfM. Maltzman *et al.* (2005) described the goal of DfN to make a network more successful for both service providers and vendors which meet or exceed the customer expectations. DFN focuses on improving processes, tools, and components (i.e., network elements and software) so that a network is easier to integrate. DFN is a holistic, iterative and systematic approach to improve the design of a whole product and a network, without losing sight of the network requirements.

2.2 Green Design

Green design is practicing engineering with the inclusion of natural system as a fundamental consideration (Ogot and Kremer, 2004). Based on our review, we group design for sustainability (DfS), design for environment (DfE) and design for life cycle (DfLC) under green design related DfX concepts. The ultimate purpose of green design is to design a product, which will have minimum negative environmental impact during its life cycle. Howarth and Hadfield (2006) developed "Bournemouth University model" for designers to review the sustainability of a product in the detail design phase. This model contains two parts: The first part contains the set of guidelines for sustainable development which considers each element of the life cycle from raw materials, manufacture, distribution, use and final disposal from the views of "interested" parties in the preliminary design phase. Interested parties include customers, planning officers, material suppliers, environment agency, waste contractors, community, etc. The second part of the model provides three worksheets – one each for product, company and site. Users input the impact score in the worksheets and the worksheets will illustrate a graph with economic, environmental and social risks.

Ljungberg (2006) summarized the guidelines for sustainable products as below:

1. Reduce the materials and the use of energy for a product including services during its lifetime.
2. Reduce the emissions, dispersion and creation of toxic elements during its lifetime.
3. Increase the amount of recyclable materials.
4. Maximize the sustainable use of renewable resources.
5. Minimize the service intensity for products and services.
6. Extend the useful life for a product.

7. Assess and minimize the environmental impact over the product lifetime.
8. Having a “functional economy” by which company earns revenue by long term service instead of selling product only once.
9. Use “reverse logistics” which means that all efforts should be used in order to reuse products and materials.
10. Increase the efficiency of a product in the use phase.

Ljungberg (2006) observed that there are six groups of materials which cover approximately more than 99% used in mechanical, civil and electrical engineering. Among these materials are metals, ceramics, synthetic polymers, natural organic materials, natural inorganic materials and composites. Their advantages, disadvantages and classification of their sustainability are summarized in Table 2. Ljungberg (2006) further suggested a comprehensive yet generic set of sustainability strategies (guidelines) which can be used during all design phases. We provide these guidelines below.

1. Eco-design, which is known as design for the environment (DfE).
2. Modular design. Easy repair and change of components are important (e.g., copier or computer parts).
3. Design for material substitution. Substitution of materials of high environmental impact with superior materials in terms of sustainability.
4. Waste source reduction by design. Reduce the amount of materials that go into the product or its packaging.
5. Design for disassembly (DfDA). A product should be easy to disassemble in order to recycle materials (e.g., usage of snap fits, mechanical locks, etc).
6. Design for recycling (DfR). DfR focuses on maximum recyclability and a high content of recycled material in the product. Different materials should not be mixed if not necessary and different parts should be labeled for easy separation of materials.
7. Design for disposability. Assures that non-recyclable parts or materials can be disposed in an ecological way.
8. Design for reusability. Focuses on possible reuse of different components in a product. The reused parts could be freshened up and reused.
9. Design for service (DfS). The design of a product is done to enable easy service from the outer regions of the product.
10. Design for substance reduction. Undesirable substances, which are used during the products life cycle, should be minimized.
11. Design for energy recovery. The design uses materials suitable for burning with a minimum of toxic or harmful emissions.
12. Design for life extension. Reduced waste through prolonged life for components or products is the aim of this strategy.

The green design guidelines presented above can be applied in all stages of the design process.

Table 2: A Sample of Materials for Sustainable Design (Adapted from Ljungberg (2006))

Material group	**Examples on materials**	**Typical advantages**	**Typical disadvantages**	**Classification of the sustainability**
Metal	Steel (Fe + C)	Durable and strong	High cost of machining	Easily recyclable (e.g., re-meltable)
	Aluminum	Often plastically formable	Mostly corrosion sensitive	
	Bronze	Often cheap		
Ceramicss	Porcelain (clay)	Non-toxic	Brittle	Easy to deposit
…………….				

Korpalski (1996) proposed DfE guidelines as well as product assessment and product stewardship metrics to aid computer part manufacturing at Hewlett-Packard. He pointed out that these tools both mitigate the environment impact and reduce the product cost as a whole. To a similar end, Herrmann *et al.* (2004) also indicated that there is a balance point where both design for efficiency and green design goals would improve. Design for life cycle (DfLC) is another important factor in green design. Keoleian (1993) recommended that the life cycle consideration should be undertaken in the needs assessment phase. Life cycle assessment (LCA) method has been widely discussed (Keoleian, 1993; SETAC, 1993; EPA, 1994; Kuo *et al*, 2001; Guinée, 2002; Ljungberg, 2006). As for practical applications, Vezzoli and Sciama (2006) translated the general LCA rules into guidelines and checklists and customized them for vending machine industry. A related concept, deign for recycle (DfRe) focuses on maximizing the reuse of parts and minimizing the amount of landfill waste. Wittenburg (1992) presented a recycling path for Germany’s auto industry, which removes the most valuable parts first and then stops disassembling when the marginal return becomes uneconomical.

3. DISCUSSION

Based on our extensive review of DfX tools, we have compiled information responding to two questions for each DfX tool: (1) At what design phase the DfX should be used?, and (2) What does the DfX tool provide for application (derived from the published research)? The information collected as a response to question one is presented in Table 3. In the table, columns 2-5 include the DfX tools placed in appropriate columns, each indicating a design phase. This tabulation is based on published work, accordingly each V*# represents a unique reference listed in the references section.

The information collected as a response for question two is classified into five categories based on the nature of the DfX techniques published. These categories are: (1) guidelines, (2) checklists, (3) metrics, (4) methods, and (5)mathematical models. Guidelines provide the directions and ideas needed to be followed during the design phases (e.g., guidelines of Ljungberg (2006) for sustainable design can be found in section 2.2). Checklists give a list of items that require a "Yes", "No" response, judgments, and brief calculations to verify designs. Metrics might involve both guidelines and checklists; however, they are generally presented in quantifiable terms. A method has a systematic structure and procedures for users to verify design content (e.g., DfMA method (Boothroyd, 1994) in section 2.1.1). Finally, mathematic models involve equations and formulas that are validation. In Table 3, we represent different categories in different colors.

Upon review of Table 3, it is observed that only a few tools have been developed for the early stages in design (the needs analysis and conceptual design phases) in comparison to the later stages (the preliminary design and detail design phases). This might stem from the fact that variables such as functions, shape, materials, processes and machines of the product being designed are still undefined.

Table 3. The techniques applied in the four design phases

Phase / Factors	Needs Assessment/ Problem definition	Conceptualization	Preliminary Design	Detail Design
Assembly		V*3(**DFMA(d)**)	V*2(**AEM(c)**), V*3(**DFMA(d)**), V*33(**AOPD(d)**),	V*2(**AEM(c)**), V*3(**DFMA(d)**), V*33(**AOPD(d)**),
Manufacturing	V*11(**Seven steps procedures for DFM(a)**)	V*3(**DFMA(d)),** V*11(**Seven steps procedures for DFM(a)**)	V*3(**DFMA(d)**), V*11(**Seven steps procedures for DFM(a)**), V*31(**DFM guide- lines(a)**)	V*3(**DFMA(d)**), V*11(**Seven steps procedures for DFM(a)**), V*31(**DFM guidelines(a)**) ,
Quality		V14,21(**QFD(c)**)	V*6(**DFQM(d)**)	V*6(**DFQM(d)**),V*14,31(**FEMA(d)**)
Disassembly & Recyclability			V*35(**graph based heuristic approach(d))**, V*20 **(Disassembly sequence and cost analysis(d)),** V*21(**Recycling path(a)**),	V*35(**graph based heuristic approach(d))**, V*20**(Disassembly sequence and cost analysis(d)),** V*21(**Recycling path(a)**),
Maintain-ability			V *7(**Structure design review procedure(b)**)	V *7(**Structure design review procedure(b)**)
Reliability				,V*17(**Reliability guidelines(a)**), V*21(**Reliability allocation(e)**)
Obsolescence				V*28(**MOCA methods(d)**)
Supply chain				V*1**(DSC guideline(a)**), V*22(**SC Model(e)**)
Logistics				V*8(**CE guidelines(a)**), V*25(**DFL guidelines(a)**)
Network	V*24 (**Process mngt architecture(d)**)	V*24 (**Process mngt architecture(d)**)	V*24 (**Process mngt architecture(d)**)	V*24 (**Process mngt architecture(d)**)
Sustainability	V*23 (1. **guidelines for sustainable product design(a)**, 2.**sustain-ability strategies for design(a)**)	V*23 (1. **guidelines for sustainable product design(a)**, 2. **sustainability strategies for design(a)**)	V*15 .(**Bournemouth University model(d)**) , V*23 (1. **guidelines for sustainable product design(a)**, 2.**sustainability strategies for design(a)**),	V*15 .(**Bournemouth University model(d)**) , V*23 (1. **guidelines for sustainable product design(a)**, 2.**sustainability strategies for design(a)**),
Environment	V*19(**DFE guide-lines(a)**, **product assessment (b)**, **product stewardship metrics(c)**)	V*19(**DFE guidelines(a)**, **product assessment (b)**, **product stewardship metrics(c)**)	V*19(**DFE guidelines(a)**, **product assessment (b)**, **product stewardship metrics(c)**)	V*19(**DFE guidelines(a)**, **product assessment(b)**, **product stewardship metrics(c)**)
Life Cycle	V*9,12,18,21 (.**LC assessment(a)**)	V*9,12,18,21 (**LC assessment(a)**) , V*32(**Guidelines and checklist for LC design(c)**)	V*9,12,18,21 (**LC assessment(a)**) , V*32(**Guidelines and checklist for LC design(c)**)	V*9,12,18,21 (**LC assessment(a)**) , V*32(**Guidelines and checklist for LC design(c)**),

a. Guideline **b.Checklist** **c. Metrics** **d. Method** e. **Math Model**

One other noteworthy observation is that most of the product scope related DfX concepts are emphasized in the preliminary design and detail design phases, while system scope related concepts concentrate in the detail design. During detail design phase, the variables become fixed. Moreover, eco-system scope related concepts are applicable for all four design phases. Some studies (Korpalski, 1996; Vezzoli and Sciama, 2006) mentioned that some products are redesigned because of environmental considerations. That is to say, the environmental factor itself is one of the requirements in the problem definition phase. However, wide coverage of environmental factors results in the absence of specific guidelines for most industries. Another observation is that the concentration of research work in this area shifted from product scope to system and eco-system scope after 1990s. This might reflect the development of international enterprises and the awareness of the global village.

From a cost point of view, starting from operational cost and ending with end-of-life cost; the DfX concepts and methods, overall, benefit (reduce) the cost items. However, the actual percentage of each DfX concept can not be precisely measured because of the variety of the product type and required production system. Moreover, an increase in cost at the design phase should be expected. Figure 3 shows this overall reduction in cost. In the figure, the direction of arrows represents the cost variation where pointing upwards means an increase and downwards means a decrease. Moreover, the size of the arrow represents the amount of monetary savings or expenditure.

In addition to the DfX tool presented in Table 3, there are software tools that aid design and design for manufacturing. For example, computer-aided design (CAD) software (e.g., Inventor, Solidworks, Unigraphics, etc.) and Computer-Aided Manufacturing (CAM) software (e.g., MasterCAM, PowerCAM) are widely used in design during design phases. In general, CAD software provides parametric modeling and dynamic simulations to support designers to plan and verify the geometry, process sequences and so on. There are also software, which links design and manufacturing to an extent. For example, Smith *et al.* (2003) proposed a Manufacturing Advisory Service (MAS) system, which is a concept level manufacturing process and material selection tool, designed to educate designers in basic process capabilities and inform experienced designers about new technologies. Gupta *et al.* (2003) developed Wizard for selection of processes and materials (WiseProM) that can be used by designers during the preliminary design stage. This system helps designers in selecting the proper combination of materials and processes to meet design requirements. Esawi and Ashby (2004) applied Cambridge Engineering Selector (CES) as a tool for the rational selection of engineering materials such as metals, ceramics, polymers, composites, woods and manufacturing processes such as shaping, finishing, joining, and surface treatment. The newest release of CES adds eco-design features, which can help estimate the environmental impact of product components. IDEMAT is a tool for material selection, which puts emphasis on environmental information. It provides a database with technical information about materials, processes and components. Finally, SimaPro is a free LCA software package, which follows ISO 14040. It provides modeling functions and scenario analysis such as complex waste treatment and recycling scenarios.

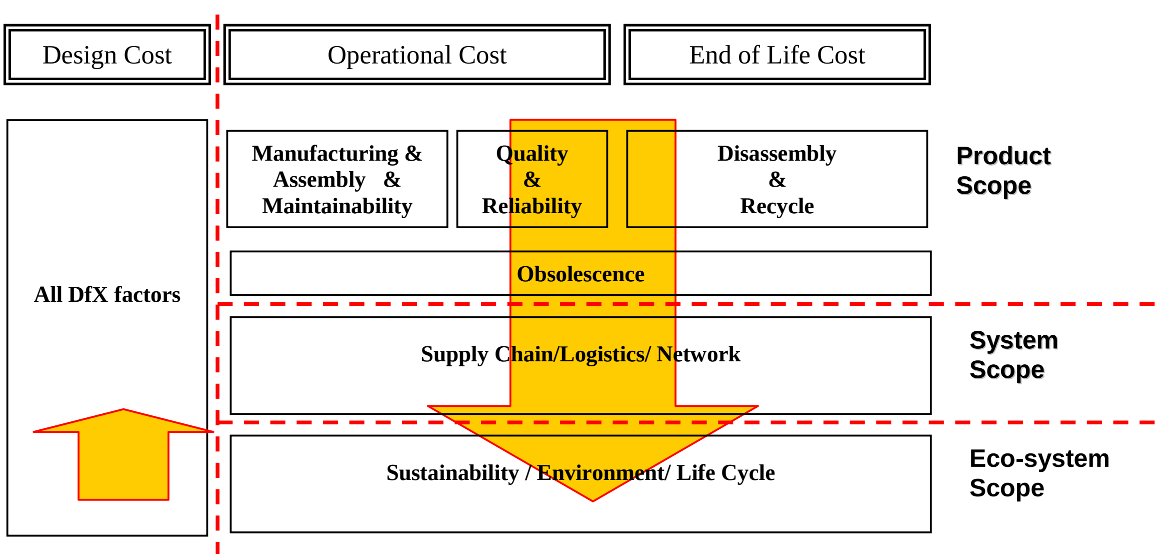


Figure 3. The benefit of DfX factors in product costs

Based on our review of the state-of-the art, and our observations, we have three assertions: (1) There is a need to integrate the existing DfX concepts into frameworks. (2) Information technology based solutions should be adopted to increase efficiencies and effectiveness in applications of DfX tools. (3) DfX tool development should carefully consider the way in which they will be used (when during the design phase, is it practical, etc.).

So far, the integration of DfX concepts has not been discussed in the literature with the exception of DfM and DfA. In real life applications, it is possible to expect synergies, and trade-offs among these concepts. For example, an advantage any one DfX concept brings to the design might also bring a drawback; hence, designers have to make decisions. At that point, an informed decision regarding the integration of various DfX tools can be very helpful. While we grouped these DfX concepts using two dimensions (scope –product, system, eco-system, and focus- efficiency and green design) in this paper, we readily acknowledge that such a structure should be validated with research and real industrial cases. We anticipate that such an integrative framework should involve design, operations and disposal of the product, etc. covering the full spectrum of the product life cycle. Indeed, recent research findings emphasize this need. The urgent requirement for reducing product life cycle cost at design stage is emerging (Herrmann *et al*, 2004; Kuo *et al*, 2001) as product design become more and more complex due to mix of materials, process and geometry.

An integrated DfX framework can also help with the communication both among and within organizations. Herrmann *et al.* (2004) suggested that designers, manufacturing engineers and marketing people should have joint responsibility for the product and cross training so as to mitigate the boundaries. However, a systematic identification and evaluation of the product life cycle requirement is prerequisite. Design alternatives such as materials and process can be specified based on the evaluation outcomes.

An important concern is regarding the efficiency and effectiveness of translating experience and information to knowledge that can be deployed within the DfX framework. Benefits from the development of information technology, knowledge sharing and the information exchange can be great as long as coherency in the framework can be achieved. In addition, several other technologies can be used in support of DfX applications. For example, artificial intelligence (AI) can support designers to clarify the blind spots during the early design stages. Steadman and Pell (1995) developed a knowledge-based expert system to aid the engineering design for injection-molded plastic parts, which provides an object-oriented, rule-based environment. Different engines such as fuzzy logic, neural networks, genetic algorithms, or case-based reasoning can be applied to support design teams in the early design stages (Kuo *et al.*, 2001).

Finally, we assert that neither integration nor tool development activities can be fruitful unless a careful consideration for how, when and by whom the developed outcomes (e.g., framework, guidelines, software tools, etc.) will be used. Accordingly, we expect the research in this area to proceed with collaboration from industry.

4. CONCLUSIONS & RECOMMENDATIONS FOR FUTURE WORK

This paper summarizes our finding based on our comprehensive literature review of DfX concepts and related tools. Our overall goal with the paper is to aid design practitioners and researchers in the area. Our recommendations for future research flow from our assertions in Section 3. Future research and development efforts should be invested towards integration of DfX concepts into a framework with a broad scope (product, system, eco-system), and related tools that are comprehensively developed for practical applications with ease and efficiency.

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