Investigation of the applicability of Design for X tools during design concept evolution: a literature review

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Abstract: Despite the availability of numerous "Design for X (DfX)" concepts/methods, their application is challenging for two reasons:

- because methods have been developed with different foci (e.g., manufacturing vs. quality), it is difficult to know how different methods complement each other
- in what sequence and where at the design stage they should be applied.

We address this challenge with a review of DfX methods with recommended design stages for their use from the published literature. We also provide a thematic clustering for their application along with a maturity index for each DfX concept.

Keywords: design for X; engineering design process; DFX structure; design for efficiency; green design; DfX maturity index.

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1 Introduction

Many studies 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 (e.g., Keys, 1990; Fabrycky and Blanchard, 1991; Dowlatshahi, 1996; Appelqvist et al., 2004). Accordingly, how to well utilise 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) also 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

Choice	*Responsible department*		
	Mfg.	*Design*	*Sales*
Reduce P time	X	X	
Extend D time			X
Standardise 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

P: Total lead time.

D: Customer lead time.

Source: Adapted from Dowlatshahi (1996)

In this paper, we review the DfX concepts and methods with potential applications at different design phases. Overall, design stage activities can be divided into four phases:

- problem definition and customer needs analysis
- conceptual design (CD)

- preliminary design
- detail design.

In the first phase, Customer Requirements (CRs) 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 prototypes are developed. 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 for providing cheaper products with high quality in shorter lead times. Accordingly, based on our review, we provide the following:

- a mapping of the DfX concepts/methods on the design process phases
- a schematic, which describes the relationships of the DfX concepts/methods among each other
- a maturity index for each DfX concept to guide/aid practitioners in selecting tools and methods for implementation.

In the following sections, we first provide brief descriptions of DfX concepts, and outline their relationships and recommended design phase for their implementation. Then, we provide a maturity index along with the insights we have gained based on our review.

2 DfX applications

In the paper, we present the DfX methods using two organising themes (design for efficiency and green design) to show their complementary nature. In addition, we categorise the DfX methods using three ranges of perception:

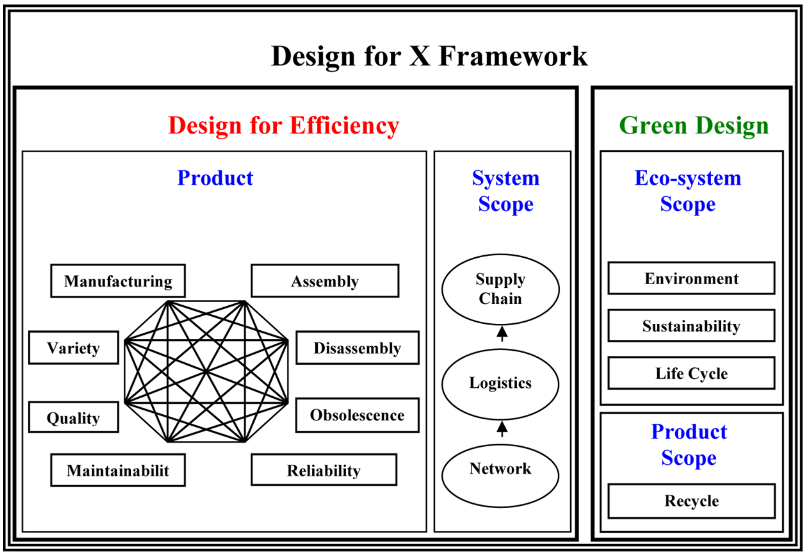
- product scope
- system scope
- eco-system scope.

In this context, we define efficiency as the ratio of the effective or useful design process output (e.g., designed artefact and the process itself) to the total input to the design process and the designed artefact (e.g., information, materials). We review the DfX concepts relating to efficiency in two ranges of perception: product scope and system scope. On the basis of our review, we group Design for Manufacturing (DfM), Design for Assembly (DfA), Design for Variety (DfV), 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 practising 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. On the basis of 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 categorise 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 categorisation.

Figure 1 Structure of the DfX concept categorisation (see online version for colours)



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 is 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 DfA of a product, quality and reliability issues might affect the material and process choices. Likewise, DfM might be impacted by DfMa.

Among the design for efficiency concepts, assembly and manufacturing are the earliest discussed topics. According to Das et al. (2000, p.457) DfM 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-dimensional model. The first dimension consists of the design phases. The second includes the seven universal virtues, which are production costs, quality, flexibility, risk, lead time, efficiency and environment impact. The third dimension covers the activity levels. In this context, activity levels start from the component level, then proceed 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:

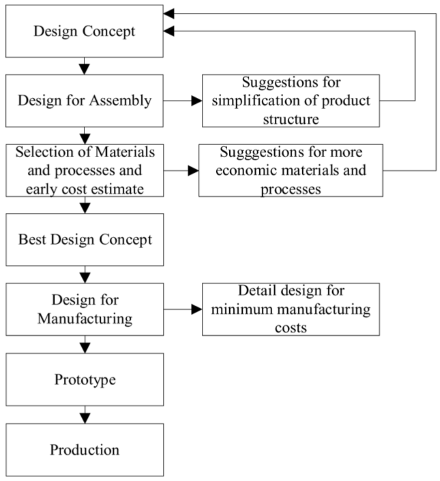
- modular design
- multi-use parts with standardisation
- ease of assembly to increase the manufacturability.

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 systematic top-down 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. In AEM, two indices, evaluation score (E) and assembly cost ratio (K), are used. The evaluation score (E) examines the difficulty of assembly and cost ratio (K) projects the assembly costs based on the current product structure. These two indices support the analysis of the current assembly method and provide suggestions for the new product design. The three techniques summarised earlier (guidelines by Stoll (1988), AOPD and AEM) are all applied in the preliminary and detail design phases.

Boothroyd (1994) claimed that product Design for Manufacture and Assembly (DfMA) can be the key to high productivity in all manufacturing industries comparing it with automation. He proposed a DfMA method for a motor-drive assembly as example, which is illustrated in Figure 2, to shorten the time to bring a product to market. In his method, the concept of DfA was first indicated in the CD phase to ensure the best design concept for materials and processes. Then, the concept was evaluated to minimise the manufacturing costs. In his example, the number of motor screws was two before evaluation. It is reduced to zero after implementing the DfMA method. A total of three parts are eliminated from the original seven parts, which provides a 42% parts reduction with respective assembly time. Although DfMA will slightly increase the time in CD phase, considerable time savings would be achieved during preliminary design and detail design phases.

La Trobe-Bateman and Wild (2003) developed a spreadsheet model, which simultaneously considers product design, manufacturing and marketing as a whole. The input information contains three aspects: product design, process design and manufacturing and operations; the output information consists of unit cost, inventory level and response time. This model serves as a metric to support decision-making, and is suitable for the preliminary design phase.

Figure 2 Typical steps of DfMA method (on left) and the result of DfMA analysis for redesign of motor-drive assembly as an example (on right)



Item	**Current Number**	**Theoretical Part Count**	**Assembly Time (sec)**	**Assembly Cost (¢)**
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**

Source: Adapted from Boothroyd (1994)

van Vliet and van Luttervelt (2004) presented a DfM methodology, which includes design coordination and continuous design evaluation. The design coordination focuses on the best combination of materials, geometry, process, manufacturing method, tools, machines and tolerance for all parts of the product while fulfilling the Functional Requirements (FRs). A product information model is generated to maintain the manufacturability of the product. Then, continuous evaluation verifies and quantifies the manufacturability of the product based on the DfM rules throughout the entire design process. The evaluation process is a knowledge-based system, which provides the user a manufacturability score according to the violations of DfM rules. This method can be used during the detail design phase.

Xiao et al. (2007) perceived three design challenges: exchange of information, accommodating interactions between activities, and maintaining feasible and satisfactory overall designs. Accordingly, they proposed a Collaborative Multidisciplinary Decision-Making (CMDM) methodology with three steps for DfM. Step 1 constructs a multi-objective decision model, which will generate a compromise solution to reduce the iterations caused by information exchange and communication; next, a set of game-theoretic principles is presented to eliminate iterations caused by interdisciplinary interactions. In step 3, design capacity indices are incorporated with the mathematical model in step 1 to reduce costly iterations caused by unexpected downstream requirements and constraints. This method is appropriate for the preliminary design phase.

Goncalves-Coelho and Mourao (2007) applied the Axiomatic Design (AD) method for DfM. AD has four design domains:

- customer
- functional
- physical
- process domains.

With corresponding customer needs, FRs, design parameters and process variables. It is a top-down method, which begins at the system level and decomposes into smaller design objects until all design objects are clearly represented. Two major axioms of AD are independence axiom and information axiom. The independence axiom maintains the independence of the FRs where each FR is satisfied without affecting the other FRs. The information axiom aims to minimise the information content of the design. The design that satisfies both independence and information axioms will be the optimal concept. Independence axiom first screens out the solutions that are 'not good'. Then, the information axiom will analyse the remaining solutions to pick the best one. This method can be implemented at the CD phase.

Zha et al. (1999) proposed a rule-based expert system, which concurrently considers product design and process planning. There are six functions in this system: CD, which is a knowledge-based system for material and fabrication; CAD, which is an interface for AutoCAD software; Design for Manufacture (DfM), which evaluates the concept with established rules and manufacturing analysis; DfA, which evaluates the concept with established rules and assemblability analysis; Assembly System Design (ASD), which includes equipment selection, layout, task assignment and line balancing; Assembly Planning (AP) that generates assembly operation process chart, knowledge-based Petri net modelling and simulation. The implementation of this method starts in the preliminary design phase.

Lin et al. (2007) presented a Contact Relation Matrix (CRM) approach to generate an assembly sequence for product design. This approach first identifies the independence of all design parameters and suggests that assembly sequence of independent components should be first. The assembly sequence for interdependent components is regulated using an assigned integer value between 1 and 4, where the lower the assigned value is the earlier the recommended order in the sequence becomes. After pairwise comparison of all components/parts, the total value of each part is displayed on a matrix, and the assembly starts from the minimum value and ends at the part with the highest value. This method is suited to the detail design phase.

Despite the availability of the above-mentioned methods, prior research on complex assemblies with high part-counts such as aircrafts and sea-crafts is limited. One exception in this regard is the work by De Fazio et al. (1999). They proposed an Assembly Sequence Analysis (ASA) method, which tackles complex assemblies in two steps. The first step uses the precedence relations to identify opportunities to relax assembly constraints to ease assembly. The second step measures assembly move difficulty to generate alternative design details, subassembly partitioning and assembly sequence. Then, a criterion-based search is executed to find the favourable design and assembly details. This method is suitable for the detail design phase.

Customer Requirements became diverse and variant in recent years. Responding to this challenge, Martin and Ishii (1996) developed a DfV method. DfV refers to product and process designs that meet the market demand for product variety with the most appropriate balance of design modularity, component standardisation and product offerings. DfV method leads to a wide coverage of customer preferences while reducing the manufacturing cost, shortening the production cycle and enhancing product line flexibility. The key strategy in DfV is to identify the 'standard' model and utilise the methodology to design the products and processes that lead to short in-process time, low inventory and low logistics costs. Martin and Ishii (1996) also proposed three indices: commonality index, differentiation index and set-up cost index to measure the cost of providing variety, representation of variety and measure the importance of variety. Their research showed that cost of providing variety could be reduced by

- differentiating as late as possible
- shortening the time between processes
- reducing set-up costs
- delaying the addition of value to the product to later in the process flow.

This method is applicable at the preliminary design phase.

Martin and Ishii (2000, 2002) extended the product variety to spatial and generational variety. Spatial variety refers to variety with the current product line while generational variety tackles the variety across future generations of the product. Two indices are proposed in this paper:

- Generational Variety Index (GVI), which is an indicator of the expected amount of redesign required for a component to meet the future market requirements
- Coupling Index (CI), which indicates the strength of coupling between components in a product.

There are four steps in the DfV method:

- generate GVI and CI
- order the components
- determine where to focus efforts – where to standardise or modularise
- develop the product platform architecture.

In addition, this paper provided two approaches to reduce GVI and CI while ensuring standardisation and modularisation. This method can be useful in the problem definition phase of design.

Fujita et al. (1999) developed an Integer Programming (IP) model that considers customer needs, functions, manufacturing modules and the hierarchical representation of the system. The objective is to minimise the cost. Simulated Annealing (SA) algorithm is employed to find the optimal solution. This method is applicable in the preliminary design phase. Fujita (2002) also applied IP to three classes of optimisation problems: Class I – to optimise module attributes under fixed module combinations; Class II – to optimise module combinations under predefined module candidates; Class III – to simultaneously optimise both module attributes and module combinations.

Liu and Hsiao (2006) incorporated Analytic Network Process (ANP) and Goal Programming (GP) approach to select variant components with budget limits. Four phases of this approach are:

1. market planning to collect CR, and determine product markets and desired features
2. ANP approach, which calculates relative importance and interdependencies of CRs, deploys CRs to physical components and prioritises components for product variety

3 GP approach identifies the components that need to be redesigned according to non-recurring expenses

4 identification of the internal and external drivers of component variation and establishment of the product family architecture.

This method is suited to the problem definition and CD phases.

Sireli et al. (2007) integrated QFD and Kano's model for simultaneous design of multiple products. The voice of customer is first translated into design requirements using QFD. Kano's model classifies (using survey data) the design requirements into:

- must-be requirements
- one-dimension requirements
- attractive requirements
- indifferent requirements
- reverse requirements
- questionable requirements.

The ranking of these classifications is confirmed by testing statistical significance. On the basis of these rankings, four different categories of products are proposed: Basic product, entry-level product, advanced product and high-end product. This method can be helpful at the problem definition phase.

DfV methods for small and medium enterprises that can only attack one target at a time remain limited. One exception in this area is recent work by Gupta and Okudan (2008). They applied modularity, DfA index and DfV index simultaneously using a pre-populated design repository for design concept selection. This method is suitable for the preliminary design phase. It should also be mentioned that there is an extensive body of research discussing product platform, modularity and mass customisation. While we recognise the relation of these topics to DfX concepts in general, we deem them beyond the scope of this paper. Readers who are interested in these topics should refer to papers by Gershenson et al. (2004), Simpson (2004), Jiao et al. (2007) and Fixson (2007).

With regard to DfO, Singh and Sandborn (2006) and Sandborn (2008) observed the sharp increase in 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 for 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 minimise the life-cycle sustainment cost of a product under the uncertainties of cost analysis and time 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 provides guidelines for how systems should be 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 propagated 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.

This method is appropriate at the detail design phase. The problem of software obsolescence has been addressed in Sandborn (2007) by considering mitigation, downgrade, redevelopment, requalifying, rehosting, media management and case resolution when the software is not capable with the complex system.

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, which are listed here, to account for DfMa at the design stage:

- *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.
- *Modularity*: Modularity requires grouping functionally similar parts into subassemblies, which then can be put together to form the product. Effective modularisation can be achieved only if interfaces are standard.
- *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.
- *Standardisation*: Standardisation 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.
- *Foolproofing*: Precautions should be devised to prevent fitting to the wrong assembly.
- *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 DfMa. The overall purpose of DfMa is to have designers consider maintainability during the preliminary design phase to reduce the maintenance time and frequency at the shop floor.

The 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 design parameters. This method first analyses 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, enabling users to foresee the possible defects and correct them at the design stage. Failure Mode Effects Analysis (FMEA) is a tool to identify the root cause of the failure and certify the quality of the product in the detail design phase (Stoll, 1988; Herrmann et al., 2004). Gironimo et al. (2006) developed the Erto-Vanacore method (EVA) in virtual reality environment. This method aims at DfQ and contains five phases. Quality elements are identified in phase 1. Phase 2 classifies these elements into three categories:

- all must be (have) quality elements
- one-dimensional quality elements
- at least one attractive element.

Phase 3 is product concept generation, and phase 4 evaluates these concepts with quality elements. On the basis of phase 4 results, the final phase determines the optimal concept. This method relies highly on expert customers since it is applied in the absence of a physical prototype. It might be appropriate for the conceptualisation phase.

According to AD method, Suh (1995) proposed six criteria for a quality product:

- equal number of FRs, DPs and PVs
- robust design
- redundant design
- source of variance and errors
- control sequence in decoupled designs
- non-linear design.

This set of guidelines is applicable at the problem definition phase. Among other tools to ensure DfQ, designers can use Quality Function Deployment (QFD) and FMEA. QFD is used during the problem definition phase to translate the CRs to product functions (Lockamy and Khurana, 1995; Moskowitz and Kim, 1997; Kuo et al., 2001; Herrmann et al., 2004). Vairaktarakis (1999) incorporated QFD with an LP model to satisfy the performance expectations of customers within the budget limit. This method is suited to the conceptualisation phase.

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 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. The above-mentioned methods are advisable for the detail design phase.

Six sigma is an important concept in DfQ. Koch et al. (2004) proposed a mathematical model to improve the structural reliability and robust design of the product. This model can maintain performance variation within acceptable limits or constraints and reduce performance variation. This method may fit well in the preliminary design phase. Savage (2007) adapted Probability Constrained Optimisation (PCO) function as a tool for Design for Six Sigma (DfSS) with three stages. Stage 1 determines Most-Likely Failure Point (MLFP); stage 2 finds a feasible design solution; stage 3 seeks the optimal solution where objective function is to minimise the cost and the defect rate is the major constraint. This method can be implemented in the preliminary design phase. Kaymaz and McMahon (2004) applied Response Surface Method (RSM), which replaced probabilistic constraints with response functions to save time in structural reliability analysis. This mathematical model is suitable for application in the detail design phase.

The accuracy of computation dictates the tolerance value in DfQ. Aware of the importance of this accuracy, Lee et al. (2008) compared three statistical moment calculation methods: the univariate Dimension Reduction Method (DRM), Performance Moment Integration (PMI) method and Percentile Difference Method (PDM) in reliability-based robust design optimisation formulation. The experimental results suggest users to apply different methods under different distributions and number of variables. These guidelines are useful in the detail design phase.

Design for Disassembly (DfD) is an important consideration for repair, cannibalisation, or refurbishment during a product's operational phase, and end-of-life situations such as reuse, remanufacturing and recycle. Boothroyd and Alting (1992) provided various DfD guidelines, which address product structure, design of functional units, material selection, minimising waste and harmful contaminating materials and recycling principles and requirements. Harjula et al. (1996) pointed out that DfA method might be compatible with DfD after addition of environmental criteria such as ease of removal and selection of recyclable materials. However, in applications, minimisation of environmental impact should be taken into account along with maximisation of financial benefits. This method is recommended for the detail design phase.

Zhang and Kuo (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 components such as weight, volume and recycling methods. The last step relates to recycling cost minimisation, which determines the disassembly strategy and the ultimate recycling cost. Owing to the nature of graph representations, quantitative analysis is possible. On the basis of the graph-based heuristic approach, Kuo (2000) presented a disassembly sequence and cost analysis method that classifies 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 application of the method was also shown for electromechanical products (Kuo et al., 2000). The two methods, presented earlier, are generally used in the preliminary and detail design phases.

Desai and Mital (2003, 2005) proposed a DfD methodology, which not only focuses on product itself but also incorporates ergonomics considerations. It first determines end-of-life option for each component (by choosing from reuse, remanufacturing or recycling), and then, evaluates its disassemblability indices including:

- degree of accessibility of components and fasteners
- amount of force required for disengaging components
- positioning
- need for tools
- design factors such as weight, shape and size of components being disassembled.

The overall score of these indices generates a DfD diagnostic report indicating the direction for alternative design configurations. This method is suited for the detail design phase. Finally, Güngör (2006) indicated the importance of connectors in DfD, and evaluated the connectors with ANP method. Three main criteria for selection of connectors are assembly complexity, in-use period and disassembly complexity. This method is applicable in the detail design phase.

Design for Recycle (DfRe) intends to utilise the value of product in the end-of-life phase using either non-destructive, or destructive recycling techniques. DfD-related methods can be used for non-destructive recycling purposes. Zussman et al. (1994) presented a DfRe method that can assess the future value of a product in its 'End-of-Life' phase both in revenue and in cost. Different possible values of cost and revenue of a product are considered as scenarios, and a recovery graph is represented for all technically feasible possibilities for disassembly. The optimal recycling strategy is the scenario with the maximum profit. This method may fit well in the detail design phase. For destructive recycling, material plays a critical role. Pento (1999) presented that a decrease in non-recyclable ingredients of a product can increase the recyclability. A printed paper example was presented that showed that with less mineral content in a paper over 800,000 tonnes of waste can be saved in one year. Knight and Sodhi (2000) summarised bulk recycling separation processes: size reduction (shredding), magnetic separation, eddy/current separation, air classification, density separation and others. A mathematical model is constructed to determine optimal separation sequence for the maximum revenue based on the material information of the product. This model can be applied in the detail design phase.

In general, DfRe should involve product, process and logistics considerations. Indeed, Kriwet et al. (1995) suggested that the designer, consumers, recyclers and suppliers should cooperate as a recycling network. A set of guidelines was provided, which involves five aspects: components, product, assembly operations, disassembly operations and logistics. These guidelines are applicable in the detail design phase.

2.1.2 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 utilises product line structure, bill of materials and customisation processes of a product to optimise the logistics costs and customer service performance. Garg (1999) developed a Supply Chain Modelling and Analysis Tool (SCMAT) (a mathematical model), which can help the decision-maker to find the optimal cost while designing products and processes for a decentralised supply chain. This method can be helpful in the preliminary design phase.

Lee and Sasser (1995) constructed a mathematical model to support various decision-making situations for the supply chain (e.g., inventory levels, transhipments and product postponement). One other work related 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.

Fixson (2005) developed a three-dimensional concurrent engineering (3D-CE) framework that integrates product, process and supply chain design measures with the backbone of a product architecture. Three dimensions are:

- function-component allocation scheme
- interface characteristics
- product architecture maps.

Function-component allocation scheme illustrates the product functions and their corresponding components. A matrix is generated to present their relationship.

The interface roles are classified in three categories: product function (type); making, changing and unmaking of the product (reversibility); substitutes (standardisation). The last dimension pulls the first two dimensions together and presents as a figure, where the functions are on the horizontal axis and the interface characteristics are on the vertical axis. This allows quick visual references of similarities and differences of analysed product architectures. This framework can identify the linkages among functions and interfaces, and hence support trade-off analyses in product, process and supply chain design. This method is applicable in the detail design phase.

Blackhurst et al. (2005) presented the Product Chain Decision Model (PCDM) as a tool to tackle the problems of product design, process design and supply chain design using IP. The model first constructs the supply chain as a network, and finds the optimal inventory level. Then, the component with longest lead time is screened out. The supply chain performance is improved when an alternative component with a shorter lead time is implemented. In the same manner, the process design could be improved. This method is suited to the detail design phase.

Sharifi et al. (2006) presented a framework that considers both product development and agile supply chain design. The guidelines are as follows. First of all, extraction and classification of product features are done. These features are further assessed in terms of how they are aligned to one or more possible strategic product differentiators. Then, business environment, company capability and supply chain are assessed to carry out the feature clustering and alignment. On the basis of the results, a company can select product features that can rapidly meet market demand and meanwhile determine a potential growth strategy. This set of guidelines is applicable at the preliminary design phase.

Lamothe et al. (2006) proposed a Mixed Integer Linear Programming Model (MILP) that can help designers of a product family in making design choices and evaluating the consequences of their choices on the layout of the supply chain that will deliver products. It contains two iterative processes. First, bills of materials of the new product family are generated according to design principles and product architectures. The product variants are the key parameters in this step. The next step is to optimise the overall cost simultaneously for the selection of supply chain and product variant of the product family. This method is applicable at the preliminary design phase.

Johansson and Johansson (2004) pointed out that closing the information gap between design engineering and supply chain and information quality of product data can improve the supply chain design with the support of a Product Data Management (PDM) system. PDM provides accessibility, ease of operation, timeliness, understandability, interpretability, relevancy and completeness of performance measures, which help evaluate product design and supply chain design decisions, and enhance information quality. These guidelines can be used in the detail design phase.

Wang and Shu (2007) developed a mathematic model, which employs fuzzy sets and genetic algorithms in new product supply chain design. The goal of this model is to minimise the total supply chain cost while maximising the possibility of fulfilling the target service level. Fuzzy logic deals with the uncertainty, which might be due to unreliable or unavailable data in the supply chain environment. Genetic algorithm determines the supply chain configuration and inventory policies to find the optimal solution. This model is suitable for the detail design phase.

Graves and Willems (2005) constructed a multi-echelon dynamic programming model to represent the configurations of new product supply chain based on:

- cost of sold goods
- holding cost for safety stock
- holding cost for the pipeline stock.

Users can decide the options of different service levels and cost. The objective function of this model is to minimise the total supply chain cost. This method is applicable in the detail design phase. Overall, five observations were provided by Graves and Willems (2005):

- in the optimal supply chain configuration, downstream stages are more likely to use high-cost options and upstream stages are more likely to use low-cost options and hold safety stock
- the benefits of supply chain configuration increase as the importance of inventory cost increases relative to the total supply chain costs
- the benefits of supply chain configuration increase as the relative demand variability increases
- the benefits of supply chain configuration increase with longer lead times at downstream stages
- more echelons increase the benefits of the supply chain configuration.

Supply chain management focuses on service level and products in the production cycle while logistics concentrates on the materials-related issues such as acquisition, storage, transportation and delivery. Mather (1992, p.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 (1996) 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 (1996) provided guidelines to accomplish this.

Design for Network (DfN) is proposed as an extension for the DfM when the final product is a customised complex system. It was first highlighted in the telecommunication industry. Maltzman et al. (2005) described that the goal of DfN is 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) hence the product considerations and network considerations are synchronically addressed. 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 practising engineering with the inclusion of natural system as a fundamental consideration (Ogot and Kremer, 2004). On the basis of our review, we group Design for Sustainability (DfS), 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.

Indeed, however, the original definition of sustainability refers to keeping an existing system operational, and maintaining field versions of the system such that the original requirements are satisfied (Sandborn and Myers, 2008). Three types of sustainability are:

- environmental sustainability, which aims to increase energy and material efficiencies, preserve ecosystem integrity, and promote human health and happiness
- business or corporate sustainability, which increases productivity or reduction of consumed resources without compromising product or service quality
- technology sustainment that keeps an existing system operational with respect to its technology (Sandborn and Myers, 2008).

In the last two decades, most recent academic publications and other written material connected the sustainability concept to 'green design' and 'sustainability of (and on) earth' due to the effort of governments and international organisations. For example, World Commission on Environment and Development (WCED) of UN (WCED, 1987) defines sustainable development as "*meet[ing] present needs without compromising the ability of future generations to meet their needs*". In addition, US Environmental Protection Agency (EPA) describes sustainability as

> "the satisfaction of basic economic, social, and security needs now and in the future without undermining the natural resource base and environmental quality on which life depends." (EPA, 2009)

Therefore, DfS is classified in the area of Green Design.

Ijomah et al. (2007) provided Design for Remanufacturing (DfRM) guidelines for sustainable development, which involve material, assembly technique and product structure aspects. These guidelines are applicable at the detail design phase. 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 step of the life cycle (raw materials, manufacturing, 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 pertaining to the product, the company and the site. Users input the impact scores in the worksheets and the worksheets will illustrate a graph with economic, environmental and social risks.

Ljungberg (2007) summarised the guidelines for sustainable products as follows:

- reduce the materials and the use of energy for a product including services during its lifetime
- reduce the emissions, dispersion and creation of toxic elements during its lifetime

- increase the amount of recyclable materials
- maximise the sustainable use of renewable resources
- minimise the service intensity for products and services
- extend the useful life for a product
- assess and minimise the environmental impact over the product lifetime
- having a 'functional economy' by which company earns revenue by long-term service instead of selling product only once
- use 'reverse logistics', which means that all efforts should be used to reuse products and materials
- increase the efficiency of a product in the use phase.

Ljungberg (2007) observed that there are six groups of materials, which cover approximately more than 99% of the materials used in mechanical, civil and electrical engineering fields. These are metals, ceramics, synthetic polymers, natural organic materials, natural inorganic materials and composites. Their advantages, disadvantages and classification of their sustainability are summarised by Ljungberg (2007). Table 2 provides a small section of this summary. Ljungberg (2007) further suggested a comprehensive and yet generic set of sustainability strategies (guidelines), which can be used during all design phases. We provide them here.

- Eco-design, which is known as Design for the Environment (DfE).
- Modular design. Easy repair and change of components are important (e.g., copier or computer parts).
- Design for material substitution. Substitution of materials of high environmental impact with superior materials in terms of sustainability.
- Waste source reduction by design. Reduce the amount of materials that go into the product or its packaging.
- Design for Disassembly (DfDA). A product should be easy to disassemble to recycle its materials (e.g., usage of snap fits, mechanical locks, etc.).
- 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; different parts should be labelled for easy separation of materials.
- Design for disposability. Assures that non-recyclable parts or materials can be disposed in an ecological way.
- Design for reusability. Focuses on possible reuse of different components in a product. The reused parts could be freshened up and reused.
- Design for Service (DfS). The design of a product should enable easy service from the outer regions of the product.
- Design for substance reduction. Undesirable substances, which are used during a product's life cycle, should be minimised.

- Design for energy recovery. The design uses materials suitable for burning with a minimum of toxic or harmful emissions.
- Design for life extension. Reduced waste through prolonged life for components or products is the aim of this strategy.

Table 2 A sample of materials for sustainable design

Material group	*Examples of 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)
	Aluminium	Often plastically formable	Mostly corrosion sensitive	
	Bronze	Often cheap		
Ceramics	Porcelain (clay)	Non-toxic	Brittle	Easy to deposit

Source: Adapted from Ljungberg (2007)

Chen (2001) proposed the Quality-Based Model to simultaneously evaluate customer preferences, producer's product strategy and environmental standards and their interactions among them from demand, supply and policy views. Two sets of attributes: traditional attributes and environmental attributes are modelled as parameters. The value of each attribute is indicated as either high or low. When suppliers differentiate product variants for non-green design friendly segments of the market, and the potential decrease in greenness of product portfolio will limit the benefits of the green products. Accordingly, the model will suggest that green product development and stricter environmental standards might not necessarily benefit the environment. This mathematical model may be helpful in the problem definition phase.

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 environmental 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 up to which both design for efficiency and green design goals would improve. Likewise, Feldmann et al. (2000) developed a 'Green Design Advisor' (GDA) that contains eight metrics: the number of materials, recycled material content, recyclability, toxicity, energy use, time for disassembly and dismantling cost at end-of-life. This method can point out the weak points in a design relevant to DfE to subsequently improve the design. This method is applicable during the preliminary design phase.

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; Consoli et al., 1993; EPA, 1994; Kuo et al., 2001; Guinée, 2002; Ljungberg, 2007). As for practical applications, Vezzoli and Sciama (2006) translated the general LCA rules into guidelines and checklists and customised them for vending machine industry. Park and Seo (2006) developed a Knowledge-based Approximate Life-Cycle Assessment System (KALCAS) for designers to predict the LCA result of their new product design in the preliminary design phase.

Kobayashi (2005) developed a Life-Cycle Planning (LCP) methodology that considers multi-generational product planning at product/component level from quality, cost and environmental viewpoints. QFD and LCA are employed to set up target values for quality and environmental characteristics. The target price, cost values and life cycle of the product are estimated according to company's strategy and methods. New concepts are generated based on these constraints. These concepts are then evaluated with cost-importance analysis, value degradation analysis, upgradability analysis, reusability analysis and recyclability analysis. The final concept minimises the product development cost while fulfilling customer needs. This method is well suited for the conceptualisation phase. For similar purposes, Sakao (2007) employed three tools: LCA, Quality Function Deployment for Environment (QFDE) and TRIZ. LCA provides material, energy guidelines on DfE, QFDE points out improvement direction for design parameters, and TRIZ generates solutions for new product design. This set of guidelines is applicable in the conceptualisation phase.

Newcomb et al. (1998) indicated that a product's architecture plays a large role in determining its life-cycle characteristics. To improve DfLC, first they recommend the application of the decomposition algorithm to partition product into modules. Then, two metrics are evaluated:

- correspondence ratio, which measures modules from different viewpoints such as functions and recyclability
- cluster independence, which measures coupling between modules.

These metrics can be integrated to the preliminary design phase. Umeda et al. (2008) also pointed out that modularity is an important technique in product life-cycle design with implications for maintainability, upgradeability, reusability and recyclability. Self-Organising Maps (SOMs) technique is recommended for evaluating geometric feasibility of the modular structure. SOM is applicable at the preliminary design phase.

A related concept, DfRe, focuses on maximising the reuse of parts and minimising 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. Houe and Grabot (2007) presented a knowledge modelling method that supports decision-making in product recyclability. The method involves a software solution with three main functions:

- integrating CAD–Computer-Aided Manufacturing (CAM) tools
- selecting standard or eco-label database
- assessing product design according to the selected standard.

This method can be used in the preliminary design phase.

Fitch and Cooper (2005) proposed "life cycle modelling for design method" that incorporates LCA with probabilistic design methods to predict attributes of possible final designs with limited information. There are three phases in this method:

1 goal and scope definition
2 performance metric assessment
3 scenario analysis and interpretation.

In the first phase, baseline design is characterised and alternative design concepts for different materials are generated. Then, a set of modelling equations evaluates all design concepts. Finally, scenario analysis and interpretation provide optimal analysis or preference analysis in cost, mass and energy. This method is appropriate for the preliminary design phase.

Kasarda et al. (2007) presented a new concept of Design of Adaptability (DfAD), which uses classical control theory. The principal idea of this concept is that the product can be designed as a dynamic adaptable system where control and feedback can be used to modify/improve system performance. Three different DfAD adaptation strategies that are based on biological, cultural and engineered systems are presented. In biological adaptation, genetic variations, fitness and natural selection are three dynamic interactions where natural selection serves as the control algorithm. Cultural history presents numerous case studies of successful/unsuccessful product designs, which can provide insights. The characteristics of engineered systems with longevity and adaptation can indicate the general guidelines for DfAD. This method can be appropriate at the conceptualisation phase.

Gu et al. (2004) developed an Adaptable Design (AD) method that benefits both profitability and environmental considerations for a supply chain. Two types of adaptability are considered:

- product adaptability
- design adaptability.

Design adaptability refers to adaptability in the design of a product, which yields design variants. The same design is reused to create different products with modifications. Product adaptability focuses on the ability of a product to various usages or capabilities. AD has four degrees of adaptability:

- upgrades
- customisation
- variety
- versatility of a product.

There are three steps in AD: design process for product adaptability, design process for design adaptability, and functional and physical independence. This method is suitable for applications during the design conceptualisation phase.

Waage (2007) presented a four-phase process for achieving sustainable designs. These phases comprise:

1 establishing the sustainability context
2 defining the sustainability issues
3 assessing and acting
4 receiving feedback.

The resultant guidelines can be used during design conceptualisation. One other approach in achieving sustainable designs is the Design for Sustainability Matrix (DFSM), which analyses the functional and environmental profile of a product (Short and

Lynch, 2004). To facilitate team-level decision-making, sticky-notes are used during communications within the design group to achieve a consensus on alternative solutions. This metric is applicable at the preliminary design stage.

Donnelly et al. (2006) developed a Product-Based Environment System (PBEMS) for wireless hardware products. This method takes eco-concepts into account in four design steps. In the problem definition (step 1), it incorporates an eco-road map, which considers short-term and long-term environmental drivers such as environmental legislations and policies. In the conceptualisation phase (step 2), it takes eco-environmental requirements into consideration. DfE guidelines are further reviewed in preliminary design (step 3). Finally, LCA guidelines are evaluated in the detail design phase (step 4). This method also includes a Plan-Do-Check-Action (PDCA) loop, which continuously improves product design. This method is appropriate starting with the problem definition phase.

3 Discussion

3.1 DfX tools in four design phases

On the basis of our extensive review of DfX tools, we have compiled information responding to two questions stated earlier:

- At what design phase the DfX tool should/could be used?
- What does the DfX tool provide for application (derived from the published research)?

The information collected as a response to question 1 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 number listed under the references section.

The information collected as a response for question 2 is classified into five categories based on the nature of the DfX tools (concepts) published. These categories are:

- guidelines
- checklists
- metrics
- mathematical models
- methods.

Guidelines provide the direction and ideas needed to be followed during the design phases (e.g., guidelines of Ljungberg (2007) for sustainable design can be found in Section 2.2). Checklists give a list of items that require a ‘Yes’, ‘No’ response, judgements, and brief calculations to verify designs. Metrics might involve both guidelines and checklists; however, they are generally presented in quantitative terms. Mathematic models involve equations and formulas that are validated. Finally, a method has a systematic structure and procedures for users to verify the design content (e.g., DfMA method (Boothroyd, 1994) in Section 2.1.1). In Table 3, we represent different categories in different colours.

Table 3 The DfX tools/concepts applied in the four design phases (see online version for colours)

Factor / *Phase*	*Needs assessment/problem definition*	*Conceptualisation*	*Preliminary design*	*Detail design*
Manufacturing (1988)	Seven steps procedures for DFM(a), Fabricius, 1994; AD(e), Goncalves-Coelho and Mourao, 2007	Seven steps procedures for DFM(a), Fabricius, 1994; DFMA(e), Boothroyd, 1994; AD(e), Goncalves-Coelho and Mourao, 2007	DFM guidelines(a), Stoll,1988; CMDM(e), Wittenburg, 1992; DFMA(e), Boothroyd, 1994; Seven steps procedures for DFM(a), Fabricius, 1994; Internet DfMA(e), Huang and Mak, 1999. Spreadsheet(c), La Trobe-Bateman and Wild, 2003 AD(e), Goncalves-Coelho and Mourao, 2007	DFM guidelines(a), Stoll,1988; Seven steps procedures for DFM(a), Fabricius, 1994; CMDM(e), Wittenburg, 1992; DFMA(e), Boothroyd, 1994; Internet DfMA(e), Huang and Mak, 1999. Spreadsheet(c), La Trobe-Bateman and Wild, 2003; DFM(e),van Vliet and van Luttervelt, 2004; AD(e), Goncalves-Coelho and Mourao, 2007
Assembly (1988)		DFMA(e), Boothroyd, 1994	AOPD(e),Warnecke, and Babler, 1988; AEM(c), Boothroyd and Alting, 1992; DFMA(e), Boothroyd, 1994; Internet DfMA(e), Huang and Mak, 1999; Virtual DfA(e), Choi et al., 2002; Fuzzy DfA(e), Coma et al., 2004; CDAPFAES(e), Xiao et al., 2007	AOPD(e), Warnecke, and Babler, 1988; AEM(c), Boothroyd and Alting, 1992; DFMA(e),Boothroyd, 1994; Internet DfMA(e), Huang and Mak, 1999. ASA(e), De Fazio et al, 1999; Virtual DfA(e), Choi et al., 2002; Fuzzy DfA(e), Coma et al., 2004; CDAPFAES(e), Xiao et al., 2007; CRM(e), Lin et al., 2007
Disassembly and Recyclability (1992)			DfD(a), Boothroyd and Alting, 1992; Harjula et al., 1996; Graph based heuristic approach(e), Zhang and Kuo, 1996; Kuo et al., 2000; Disassembly sequence and cost analysis(e), Kuo, 2000; Recycling path(a), Kuo et al., 2001; Knowledge modeling(e), Houe and Grabot, 2007	DfD(a), Boothroyd and Alting, 1992; Harjula et al.,1996; DfRe(a), Kriwet et al.,1995; Graph based heuristic approach(e), Zhang and Kuo, 1996; Kuo et al., 2000; Material Separation(d), Knight and Sodhi, 2000; Recycling path(a), Kuo et al., 2001; Disassembly sequence and cost analysis(e), Kuo, 2000; ANP(e), Güngör, 2006; Knowledge modeling(e), Houe and Grabot, 2007
Logistics (1992)				V*71(DFL guidelines(a)), Mather, 1992; V*19(CE guidelines(a)), Dowlatshahi, 1996
Life Cycle (1993)	LC Assessment(a), Keoleian, 1993; EPA, 1994; Kuo et al., 2001; Guinée, 2002;	LC Assessment(a), Keoleian, 1993; EPA, 1994; Kuo et al., 2001; Guinée, 2002; LCP(e), Kobayashi, 2005; Guidelines and checklist for LC design(c), Vezzoli,and Sciama, 2006	LC Assessment(a), Keoleian, 1993; EPA, 1994; Kuo et al., 2001; Guinée, 2002; Park and Seo, 2006; LCMD(e), Fitch and Cooper, 2005; LCP(e), Kobayashi, 2005; Modularity Metrics(c), Fixson, 2005; Guidelines and checklist for LC design(c), Vezzoli, and Sciama, 2006; SOM(c), Umeda et al., 2008	LC Assessment(a), Keoleian, 1993; EPA, 1994; Kuo et al., 2001; Guinée, 2002; Park and Seo, 2006; LCMD(e), Fitch and Cooper, 2005; LCP(e), Kobayashi, 2005; Modularity Metrics(c), Fixson, 2005; Guidelines and checklist for LC design(c), Vezzoli and Sciama, 2006; SOM(c), Umeda et al., 2008

Table 3 The DfX tools/concepts applied in the four design phases(see online version for colours) (continued)

Factor / *Phase*	*Needs assessment/problem definition*	*Conceptualisation*	*Preliminary design*	*Detail design*
Quality (1995)	AD(a), Suh, 1995	AD(a), Suh, 1995; QFD(c), Lockamy and Khurana, 1995; Moskowitz and Kim, 1997; Kuo et al., 2001; Herrmann et al., 2004; QFD + LP(e), Vairaktarakis, 1999; EVA(e), Gironimo et al., 2006	AD(a), Suh, 1995; QFD + LP(e), Vairaktarakis, 1999; DFQM(d), Das et al., 2000 Six Sigma(d), Koch et al., 2004; EVA(e), Gironimo et al., 2006; PCO(d), Savage, 2007	AD(a), Suh, 1995; QFD + LP(e),Vairaktarakis, 1999; DFQM(e), Das et al., 2000; FEMA(e), Stoll, 1988; Herrmann et al., 2004; Six Sigma(d), Koch et al., 2004; EVA(e), Gironimo et al.,2006; PCO(d), Savage, 2007
Reliability (1995)				Reliability guidelines(a), Ireson, 1995; Reliability allocation(d), Kuo et al., 2000; RSF(d), Kaymaz and McMahon, 2004; RBRDO(d), Lee et al., 2008
Supply chain (1995)			SCMAT(d), Garg, 1999; MILP(d), Lamothe et al., 2006; SCD & DfSC(a), Sharifi et al., 2006	Rainbow Model(d), Lee and Sasser, 1995; SCMAT(d), Garg, 1999; DSC guideline(a), Appelqvist et al., 2004; PDM(a), Johansson and Johansson, 2004; PCDM(d), Blackhurst et al., 2005; 3D-CE(e), Fixson, 2005; DfSC(d), Graves and Willems, 2005; MILP(d), Lamothe et al., 2006; SCD & DfSC(a), Sharifi et al., 2006; Fuzzy SC Model(d), Wang and Shu, 2007
Variety (1996)	DfV+ platform(e), Martin and Ishii, 2000; Martin and Ishii, 2002; ANP-GP(e), Liu and Hsiao, 2006; QFD+Kano(e), Sireli et al., 2007; DfA+DfV(e), Gupta and Okudan, 2008	DfV+ platform(e), Martin and Ishii, 2000; Martin and Ishii, 2002; ANP-GP(e), Liu and Hsiao, 2006; QFD+Kano(e), Sireli et al., 2007; DfA+DfV(e), Gupta and Okudan, 2008	DfV(e), Martin and Ishii, 1996; IP(d), Fujita et al., 1999; Fujita, 2002; DfV+ platform(e), Martin and Ishii, 2000; Martin and Ishii, 2002; ANP-GP(e), Liu and Hsiao, 2006; QFD+Kano(e), Sireli et al., 2007; DfA+DfV(e), Gupta and Okudan, 2008	DfV(e), Martin and Ishii, 1996; IP(d), Fujita et al., 1999; Fujita, 2002; DfV+ platform(e), Martin and Ishii, 2000; Martin and Ishii, 2002; ANP-GP(e), Liu and Hsiao, 2006; QFD+Kano(e), Sireli et al., 2007; DfA+DfV(e), Gupta and Okudan, 2008;
Environment (1996)	DFE guidelines(a), product assessment(b), product stewardship metrics(c), Korpalski, 1996; Quality Based Model(d), Chen, 2001; PBEMS(e), Donnelly et al., 2006	DFE guidelines(a), product assessment(b), product stewardship metrics(c), Korpalski, 1996 PBEMS(e), Donnelly et al., 2006 LCA+QFD+TRIZ(e), Sakao, 2007	DFE guidelines(a), product assessment(b), product stewardship metrics(c), Korpalski, 1996; GDA(e), Feldmann et al., 2000; PBEMS(e), Donnelly et al., 2006; LCA+QFD+TRIZ(e), Sakao, 2007	DFE guidelines(a), product assessment(b), product stewardship metrics(c), Korpalski, 1996; GDA(e), Feldmann et al., 2000; PBEMS(e), Donnelly et al., 2006; LCA+QFD+TRIZ(e), Sakao, 2007

Table 3 The DfX tools/concepts applied in the four design phases (see online version for colours) (continued)

Factor / *Phase*	*Needs assessment/problem definition*	*Conceptualisation*	*Preliminary design*	*Detail design*
Sustainability (2004)	Guidelines for sustainable product design(a), and Sustainability strategies for design(a), Ljungberg, 2007	DfAD(e), Gu et al., 2004; DfAD(a), Kasarda et al., 2007; Guidelines for sustainable product design(a), and Sustainability strategies for design(a), Ljungberg, 2007; Road-map(a), Waage, 2007;	DfAD(e), Gu et al., 2004; DFSM(c), Short and Lynch, 2004; Bournemouth University model(e), Howarth and Hadfield, 2006; DfAD(a), Kasarda et al., 2007; Guidelines for sustainable product design(a) and Sustainability strategies for design(a), Ljungberg, 2007; Road-map(a), Waage, 2007	DfAD(e), Gu et al., 2004; DFSM(c), Short and Lynch, 2004; Bournemouth University model(e), Howarth and Hadfield, 2006; DfRem(a), Ijomah et al., 2007; DfAD(a), Kasarda et al., 2007; Guidelines for sustainable product design(a) and Sustainability strategies for design(a), Ljungberg, 2007; Road-map(a), Waage, 2007
Network (2005)	Process mngt architecture(e), Maltzman et al., 2005	Process mngt architecture(e), Maltzman et al., 2005	Process mngt architecture(e), Maltzman et al., 2005	Process mngt architecture(e), Maltzman et al., 2005
Maintainability (2006)			Structure design review procedure(b), Desai and Mital, 2006	Structure design review procedure(b), Desai and Mital, 2006
Obsolescence (2006)				MOCA methods(e), Singh and Sandborn, 2006; Sandborn, 2008;

a: Guideline; b: checklist; c: Metrics; d: Math model; e: Method.

Upon review of Table 3, it is observed that fewer tools have been developed for the early stages in design (the needs analysis and CD phases) in comparison with 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 underdefined. On the other hand, most of the product-scope-related DfX concepts are emphasised in the preliminary design and detail design phases, whereas system-scope-related concepts concentrate in the detail design. During detail design phase, the variables become fixed. Eco-system-scope-related concepts are applicable for all four design phases. Studies (e.g., Korpalski, 1996; Vezzoli and Sciama, 2006) mentioned that some products are redesigned because of environmental considerations. In other words, the environmental factor itself becomes 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.

3.2 Maturity measure of DfX factors

As part of our review, we also propose a 'maturity index', which can provide an indication for the amount of effort spent by the research community on each DfX concept. The maturity index is impacted by the longevity of the attention towards the DfX tool (i.e., the interval that spans the publication years for each DfX concept), and complexity of the tools proposed (i.e., starting from guidelines to methods). In Table 4, we tabulate the number of papers published for each DfX concept in 5-year increments. When the resultant table is reviewed, it is seen that the interest peaks for Assembly and Disassembly/Recyclability in the 1996–2000 time period. Then, Supply Chain emerges as an important DfX concern for the 2001–2005 interval. After 2005, Sustainability and Variety receive attention. Further, the concentration of research work shifts from product scope to system and to eco-system scope after 1990s. This might reflect the development of international enterprises and the increased awareness of globalisation.

Table 4 Distribution of the DfX tools proposed over the years (see online version for colours)

	Before 1990	*1991~1995*	*1996~2000*	*2001~2005*	*After 2005*	*Total*
Manufacturing	1	2	1	2	2	8
Assembly	1	2	3	2	1	9
Disassembly and recyclability		2	6	3	2	13
Logistics		1	1			2
Life cycle		1	1	2	3	7
Quality		1	2	2	2	7
Reliability		1	0	2	1	4
Supply chain		1	1	5	3	10
Variety			3	2	3	8
Environment			2	1	2	5
Sustainability				2	5	7
						83

In Table 5, we provide the distribution of the published DfX tools across categorisation levels (i.e., simple guidelines to comprehensive methods). For example, for Design for Manufacturing, Assembly, Quality and Variety there exist a higher number of tools (4–8) under the 'method' category, whereas for Design for Sustainability and Supply Chain there are fewer 'methods' (1–2), and the proposed tools concentrate under the 'guidelines' and mathematical 'model' categories. This observation might be interpreted as that there is room for further research in these areas.

Table 5 Type distribution of the DfX tools proposed

	Guidelines	*Checklist*	*Metrics*	*Math model*	*Method*	*Total*
Manufacturing	2	0	1	0	5	8
Assembly		0	1	0	8	9
Disassembly and recyclability	4	0	0	1	8	13
Logistics	2	0	0	0		2
Life cycle	2	0	3	0	2	7
Quality		0	1	2	4	7
Reliability	1	0	0	3	0	4
Supply chain	3	0	0	6	1	10
Variety	0	0	0	2	6	8
Environment	0	0	1	1	3	5
Sustainability	4	0	1	0	2	7
Network					1	1
Maintainability		1				1
Obsolescence					1	1
						83

To draw a clearer view of the DfX concept maturity, we analysed the number of tools recommended for each of the four design phases as provided in Table 6. In Table 7, we provide a weighted version of the information given in Table 6. The following weights were used for guidelines, checklists, metrics, mathematical models and methods, respectively: 1, 3, 5, 7 and 9. Assignment of these weights consider three criteria:

- tool complexity
- comprehensiveness (i.e., step-by-step instructions or overall directions)
- result generation (i.e., tangible evaluations).

An increase in the weight indicates an increase across these criteria. Tables 6 and 7 indicate that Design for Manufacturing, Assembly, Disassembly/Recyclability, Quality, Variety and Environment have achieved higher levels of maturity in comparison with Reliability and Obsolescence, for example. A higher maturity (as indicated with the values in the last columns of Tables 6 and 7) might mean an increased level of preparedness of these DfX tools for industrial deployment.

Table 6 Number of the DfX tools proposed for four design phases

Factor \ *Phase*	*Needs assessment*	*Conceptualisation*	*Preliminary design*	*Detail design*	*Maturity index*
Manufacturing	2	3	7	8	20
Assembly		1	7	9	17
Disassembly and recyclability			5	10	15
Logistics				2	2
Life cycle	1	3	6	6	16
Quality	1	4	6	7	18
Reliability				4	4
Supply chain			3	10	13
Variety	4	4	6	6	20
Environment	3	3	4	4	14
Sustainability	1	3	6	7	17
Network	1	1	1	1	4
Maintainability			1	1	2
Obsolescence				1	1
Total	*13*	*22*	*52*	*75*	*163*

Table 7 Weighted total of the DfX tools proposed across four design phases (see online version for colours)

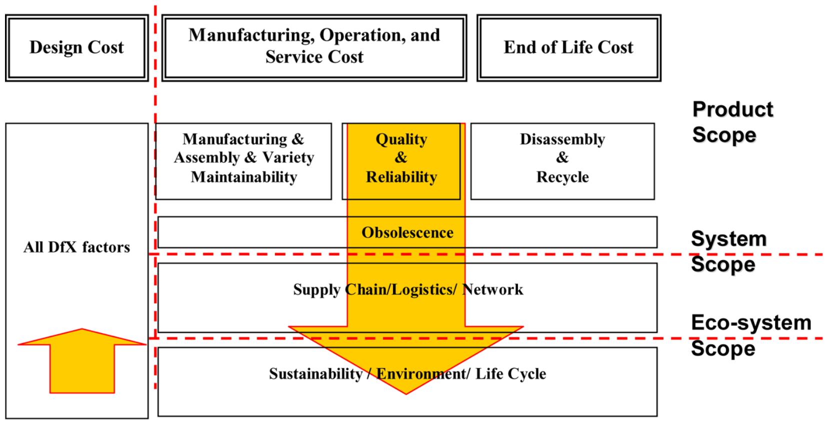
Factor \ *Phase*	*Problem definition*	*Conceptualisation*	*Preliminary design*	*Detail design*	*Maturity index (weighted)*
Manufacturing	10	19	29	38	96
Assembly		9	59	77	145
Disassembly and recyclability			29	64	93
Logistics				2	2
Life cycle	1	15	34	34	84
Quality	9	32	50	51	142
Reliability				22	22
Supply chain			15	54	69
Variety	36	36	52	52	176
Environment	21	23	32	32	108
Sustainability	1	3	26	27	57
Network	9	9	9	9	36
Maintainability			3	3	6
Obsolescence				9	9
Total	*87*	*146*	*338*	*474*	*1045*

Weighted scores: a: Guidelines (1); b: Checklist (3); c: Metrics (5); d: Math model (7) and e: Method (9).

3.3 Potential benefits of DfX factors in product costs

From a cost point of view, starting with the operational cost and ending with end-of-life cost, the DfX concepts and methods might benefit (reduce) the overall cost. Boothroyd and Dewhurst Inc. (2009) stated that DfMA saved 42% of labour cost, 54% of part cost, 60% assembly time, 45% product development time and 50% of total cost for their customers. Daabub and Abdalla (1999) found that the expert system they developed based on the DfA method reduced 34.5% overall product manufacturing cost in their case study. QFD can bring 35–50% reduction in engineering changes, 35–50% shorter design cycles, 20–60% lower start-up costs and 20–50% fewer warranty claims (Bicknell and Bicknell, 1995). Martin and Ishii (2002) estimated that total redesign cost will drop from 98% to 6% by saving in components reuse, tool and jig cost, etc. Despite these estimates, however, the actual percentage savings due to each DfX concept cannot be precisely measured because of the variety of the product types and required manufacturing systems. Moreover, an increase in cost of the design phase should be expected. Figure 3 shows this expected reduction in overall cost schematically. In the figure, the direction of arrows represents the cost change, where pointing upwards means an increase and downwards a decrease. Moreover, the size of the arrow represents the amount of monetary savings.

Figure 3 Potential cost benefits of DfX factor implementation (see online version for colours)



3.4 Other software tools in product design

In addition to the DfX tools/concepts presented in Table 3, there are software tools that aid design and design for manufacturing. For example, CAD software (e.g., Inventor, Solidworks, Unigraphics, etc.) and CAM software (e.g., MasterCAM, PowerCAM) are widely used during design phases. In general, CAD software provides parametric modelling 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 process-based LCA software package, which follows ISO 14040. It provides modelling functions and scenario analysis such as complex waste treatment and recycling scenarios.

On the basis of our review of the state-of-the-art and our observations, we have three assertions:

- there is a need to integrate the existing DfX concepts into a framework
- information-technology-based solutions should be adopted to increase efficiencies and effectiveness in applications of DfX tools
- DfX tool development should carefully consider the way in which they will be used (when during the design phase should they be used? and is their use 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 trade-off 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 emphasise 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 designs become more and more complex due to mix of materials, processes and geometry.

An integrated DfX framework can also help with the communication both among and within organisations. Prasad (2000) extended QFD as Concurrent Function Deployment (CFD) to simultaneously consider X-factors. Durai Prabhakaran et al. (2006) applied the graph theory in CD phase with DfX factors as vertices and their interdependencies as edges, which form a directed graph. Herrmann et al. (2004) observed the difficulty of breaking organisational barriers and suggested that designers, manufacturing engineers and marketing people should have joint responsibility for the product and cross-training 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. Huang and Mak (1999) combined Boothroyd's (1994) DfMA method with internet to create a collaborative development platform. Coma et al. (2004) incorporated fuzzy theory with Boothroyd and Alting's (1992) DfA method to deal with the uncertainty in product design. Choi et al. (2002) developed virtual tools based on Boothroyd and Alting's (1992) DfA method to give geometry and visual aids. Steadman and Pell (1995) developed a knowledge-based expert system to aid the engineering design for injection-moulded 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 and recommendations for future work

This paper summarises our findings 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. In Section 2, a framework housing all published DfX factors was presented. Section 3 first discussed the applicability of the DfX methodologies across four design phases. In addition, the maturity indices pointed out that the evolution of the concepts indicates a natural progression from the product scope to system and eco-system scopes. The potential benefit of DfX factors in product costs is also described. Finally, the software tools that can aid designers in implementing DfX factors are reported. Future research and development efforts should be invested towards validating the integration of DfX concepts into a framework (e.g., product, system, eco-system).

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