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Evolution of Design for X Tools Applicable to Design Stages: A Literature Review

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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 product cost and development lead time. Design for manufacture, assembly, quality, maintenance, environment, obsolescence and recyclability, etc. are among these. Despite the availability of these numerous concepts/methods, a "big picture" to illustrate the relations and the interactions among these X factors remains absent. In the paper, we attempt to provide our version of this "big picture" along with maturity and trajectory of these factors as identified from the published literature.

Keywords: *Design for X, Engineering Design Process*

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 the product life cycle cost [1, 19, 57, 106]. Accordingly, how to well-utilize this prime time to create a successful product has been widely discussed. 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. Our main 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: (1) A mapping of the DfX concepts/methods on the design process phases, (2) a schematic, which describes the relationships of the DfX concepts/methods among each other, and (3) 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 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 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 practicing engineering with the inclusion of natural system as a fundamental consideration [77]. 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.

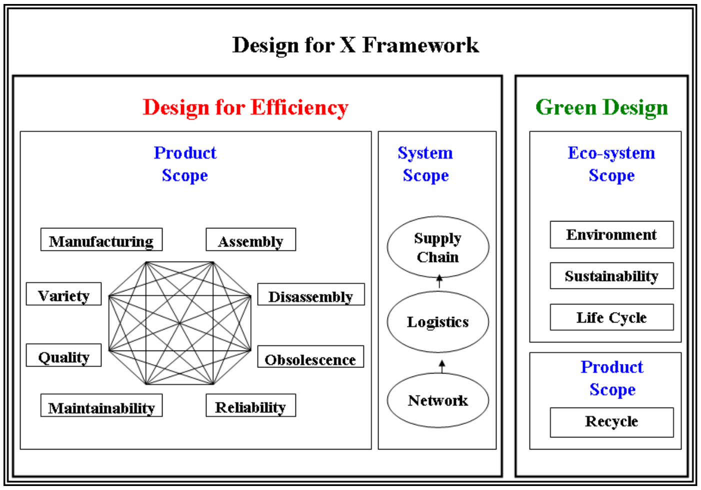

Figure 1. Framework for Design for X Perspectives.

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. Fabricius [23] proposed a set of guidelines "Seven step procedure for design for manufacture" to enhance the linkage between design and manufacturing using a model with three-dimensions. Different from guidelines proposed by Fabricius [23], which are metric-based, Stoll [92] 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 [100] 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. There are other methods, however, that are component-based rather than systematic top-down reviews. For example, Boothroyd and Alting [4] pointed out that the Assembly Evaluation Method (AEM) developed by Hitachi follows the "one motion for one part" principle. The three techniques summarized above (guidelines by Stoll [92], AOPD and AEM) are all applied in the preliminary and detail design phases.

Boothroyd [5] proposed a design for manufacture and assembly (DfMA) method. This method can be applied during preliminary design and detail design phases. La Trobe-Bateman and Wild [63] 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; and 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. van Vliet and van Luttervelt [96] presented a DfM methodology which includes design coordination and continuous design evaluation. This method can be used during the detail design phase. Xiao *et al.* [102] 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 design for manufacturing (DfM). This method is appropriate for the preliminary design phase.

Goncalves-Coelho and Mourao [33] applied the Axiomatic Design (AD) method for DfM. AD has four design domains: 1) customer, 2) functional, 3) physical, and 4) process domains, with corresponding customer needs, functional requirements, design parameters and process variables. It is a top down method, which begins at the system level and decomposes the system into smaller design objects until all design objects are clearly represented. This method can be implemented at the conceptual design phase. Zha *et al.* [103] proposed a rule based expert system, which concurrently considers product design and process planning. There are six functions in this system: knowledge based conceptual design (CD); computer-aided design (CAD); design for manufacture (DfM; design for assembly (DfA); assembly system design (ASD; and assembly planning (AP). The implementation of this method starts in the preliminary design phase.

Lin *et al.* [66] presented a contact relation matrix (CRM) approach to generate an assembly sequence for product design. This method is suited to the detail design phase. Despite availability of 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.* [14]. They proposed an assembly sequence analysis (ASA) method, which tackles complex assemblies in two steps. 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 [72] developed a Design for Variety (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 standardization and product offerings. This method is applicable at the preliminary design phase. Martin and Ishii [73-74] 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. This method can be useful in the problem definition phase of design. However, 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 [38]. 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 customization. While we recognize 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.*[31], Simpson [87], Jiao *et al.* [48], and Fixson [27].

Fujita *et al.* [28] developed an integer programming (IP) model that considers customer needs, functions, manufacturing modules and the hierarchical representation of the system. The objective is to minimize the cost. Simulated annealing (SA) algorithm is employed to find the optimal solution. This method is applicable in the preliminary design phase. Fujita [29] also applied IP to simultaneously optimize both module attributes and module combinations. Liu and Hsiao [67] incorporated analytic network process (ANP) and goal programming (GP) approach to select variant components with budget limits. This method is suited to the problem definition and conceptual design phases. Sireli *et al.* [89] integrated QFD and Kano's model for simultaneous design of multiple products. This method can be helpful at the problem definition phase.

With regard to Design for obsolescence (DfO), various researchers (e.g., [83,88]) observed the sharp increase of maintenance costs 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. In addition, software obsolescence has been addressed by considering mitigation, redevelopment, rehosting, media management and case resolution [107]. This method is appropriate at the detail design phase.

Desai and Mital [17] 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. The overall purpose of DfMa is to have designers consider maintainability during the preliminary design phase in order to reduce the maintenance time and frequency at the shop floor.

The design for quality (DfQ) is generally deployed in the preliminary design phase when the first prototype is available. Das *et al.* [13] developed a Design for Quality Manufacturability (DfQM) method to classify the defects and map them to design parameters. Failure Mode Effects Analysis (FMEA) is applied to identify the root cause of the failure and certify the quality of the product in the detail design phase [41, 92]. Gironimo *et al.* [32] developed the Erto-Vanacore method (EVA) in virtual reality environment. This method aims at design for quality (DfQ). This method relies highly on expert customers since it is applied in the absence of a physical prototype. It might be appropriate for the conceptualization phase. Suh [93] proposed the axiomatic design (AD) method as a set of guidelines, which are applicable at the problem definition phase. Among other tools to ensure design for quality, designers can use Quality Function Deployment (QFD), and FMEA. QFD is used during the problem definition phase to translate the customer requirements to product functions [41, 61, 69, 75]. Vairaktarakis [95] incorporated QFD with a LP model to satisfy the performance expectations of customers within the budget limit. This method is suited to the conceptualization 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 [61]. Efforts regarding design for reliability (DfR) are by Ireson [47] and Kuo *et al.* [61]. Ireson [47] provided reliability guidelines. Kuo *et al.* [61] 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 Design for Quality (DfQ). Koch *et al.* [55] proposed a mathematical model to improve the structural reliability and robust design of the product. This method may fit well in the preliminary design phase. Savage [84] adapted probability constrained optimization (PCO) function as a tool for Design for Six Sigma (DfSS) with three stages. This method can be implemented in the preliminary design phase. Kaymaz and McMahon [51] 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, Lee *et al.* [65] 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 optimization formulation. These guidelines are useful in the detail design phase.

Design for disassembly (DfD) is an important consideration for repair, cannibalization, or refurbish during a product's operational phase, and end-of-life situations such as reuse, remanufacturing, and recycle. Boothroyd and Alting [4] provided various DfD guidelines, which address product structure, design of functional units, material selection, minimizing waste and harmful contaminating materials and recycling principles and requirements. Harjula *et al.* [40] 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. This method is recommended for the detail design phase.

Zhang and Kuo [104] developed a graph-based heuristic approach to generate a disassembly tree. The approach has three steps, which use the graph representation. Due to the nature of graph representations, quantitative analysis is possible. Based on the graph-based heuristic approach, Kuo [59] presented a disassembly sequence and cost analysis method that classifies disassembly cost into three parts: target disassembly, full disassembly and optimal disassembly. Two methods presented above are generally used in the preliminary and detail design phases. Desai and Mital [15-16] proposed a design for disassembly 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. This method is suited for the detail design phase. Finally, Güngör [37] indicated the importance of connectors in Design for Disassembly (DfD), and evaluated the connectors with analytic network process (ANP) method. This method is applicable in the detail design phase.

Design for recycle (DfRe) intends to utilize 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.* [105] presented a DfRe method that can assess the future value of a product in its "End-of-Life" phase both in revenue and cost. This method may fit well in the detail design phase. For destructive recycling material plays a critical role. Pento [79] presented that a decrease of non-recyclable ingredients of a product can increase the recyclability. Knight and Sodhi [53] summarized 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.* [58] 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 [64] 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. Lee and Sasser [64] constructed a mathematical model to support various decision making situations for the supply chain (e.g., inventory levels, trans-shipments and product postponement). Garg [30] developed a Supply Chain Modeling 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 decentralized supply chain. This method can be helpful in the preliminary design phase. One other work relating to DfSC is by Appelqvist *et al.* [1]. They built a framework for supply chain decision making, and guidelines for designers to create the supply chain in the detail design phase. Fixson [26] 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. This framework can identify the linkages among functions and interfaces, hence support trade-off analyses in product, process and supply chain design. This method is applicable in the detail design phase. Blackhurst *et al.* [3] presented the Product Chain Decision Model (PCDM) as a tool to tackle the problems of product design, process design and supply chain design using Integer Programming. This method is suited to the detail design phase. Sharifi *et al.* [82] presented a framework that considers both product development and agile supply chain design. This set of guidelines is applicable at the preliminary design phase.

Lamothe *et al.* [62] 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. This method is applicable at the preliminary design phase. Johansson and Johansson [49] 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. These guidelines can be used in the detail design phase. Wang and Shu [99] developed a mathematic model, which employs the fuzzy sets and genetic algorithms in new product supply chain design. This model is suitable for the detail design phase. Graves and Willems [34] constructed a multi-echelon dynamic programming model to represent the configurations of new product supply chain based on: 1) cost of sold goods, 2) holding cost for safety stock, and 3) 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 minimize the total supply chain cost. This method is applicable in the detail design phase. 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 [71] provided two DfL guidelines for logistically effective designs to be applied during the detail design phase. Dowlatshahi [19] 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 [19] provided guidelines to accomplish this.

Design for network (DfN) is proposed as an extension for the DfM. Maltzman *et al.* [70] 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.

2.2 Green Design

Green design is practicing engineering with the inclusion of natural system as a fundamental consideration [77]. 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.

Ijomah *et al.* [46] provided Design for Remanufacturing (DfRM) guidelines for sustainable development, which involve material, assembly technique and product structure aspects. These guideline are applicable at the detail design phase. Howarth and Hadfield [42] developed "Bournemouth University model" for designers to review the sustainability of a product in the detail design phase.

Ljungberg [68] summarized the guidelines for sustainable products which includes reduction of materials and energy use during its lifetime while increasing the usage of recyclable materials and renewable energy. Ljungberg [68] 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 and disadvantages with regards to sustainability are also discussed.

Chen [8] proposed the Quality-Based Model, which simultaneously evaluates customer preferences, producer's product strategy and environmental standards and their interactions among them from demand, supply, and policy views. This mathematical model may be helpful in the problem definition phase. Korpalski [56] proposed DfE guidelines as well as product assessment and product stewardship metrics to aid computer part manufacturing at Hewlett-Packard. To a similar end, Herrmann *et al.* [41] also indicated that there is a balance point where both design for efficiency and green design goals would improve. Likewise, Feldmann *et al.* [24] developed a metrics-based software: "Green Design Advisor" (GDA). This method can point out the weak points as a DfE factor for users to improve designs. This method is applicable during the preliminary design phase.

Design for life cycle (DfLC) is another important factor in green design. Keoleian [52] recommended that the life cycle consideration should be undertaken in the needs assessment phase. Life cycle assessment (LCA) method has been widely discussed [11, 21, 36, 52, 61, 68]. As for practical applications, Vezzoli and Sciama [97] translated the general LCA rules into guidelines and checklists and customized them for vending machine industry. Park and Seo [78] 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 [54] developed a life cycle planning (LCP) methodology that considers multi-generational product planning at product/component level from quality, cost and environmental viewpoints. This method is well-suited for the conceptualization phase. Similarly, Sakao [81] employed three tools: LCA, Quality Function Deployment for Environment (QFDE) and TRIZ. LCA provides material, energy guidelines on design for environment (DfE), QFDE points out improvement direction for design parameters, and TRIZ generates solutions for the new product design. This set of guidelines is applicable in the conceptualization phase.

Newcomb *et al.* [76] 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 the product into modules. These metrics can be integrated to the preliminary design phase. Umeda *et al.* [94] also pointed out that modularity is an important technique in product life cycle design with implications for maintainability, upgradeability, reusability and recyclability. Self-organizing maps (SOM) technique is recommended for evaluating geometric feasibility of the modular structure. SOM is applicable at the preliminary design phase.

A related concept, design for recycle (DfRe), focuses on maximizing the reuse of parts and minimizing the amount of landfill waste. Wittenburg [101] 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 [43] presented a knowledge modeling method that supports decision making in product recyclability. This method can be used in the preliminary design phase. Fitch and Cooper [25] proposed a "life cycle modeling for design method" that incorporates LCA with probabilistic design methods to predict attributes of possible final designs with limited information. This method is appropriate for the preliminary design phase.

Kasarda *et al.* [50] presented a new concept of Design of adaptability (DfAD). This method can be appropriate at the conceptualization phase. Gu *et al.* [35] developed an adaptability design (AD) method that benefits both profitability and environmental considerations for a supply chain. This method is suitable for applications during the design conceptualization phase. Waage [98] presented a four phase process for achieving sustainable designs. The resultant guidelines can be used during design conceptualization. One other approach in achieving sustainable designs is the Design for Sustainability Matrix (DFSM), which analyzes the functional and environmental profile of a product [85]. This metric is applicable at the preliminary design stage. Donnelly *et al.* [18] developed a product-based environment system (PBEMS) for wireless hardware products. This method is appropriate for the problem definition phase.

3. DISCUSSION

3.1 DfX tools in four design phases

Based on our review of DfX tools, we have compiled information responding to two questions for each DfX concept: (1) At what design phase the DfX tool 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 1. 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 two is classified into five categories based on the nature of the DfX tools (concepts) published. These categories are: 1) guidelines, 2) checklists, 3) metrics, 4) mathematical models, and 5) methods. Guidelines provide the direction and ideas needed to be followed during the design phases. 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 quantitative terms. Mathematic models involve equations and formulas that are validated. Finally, a method has a systematic structure and procedures for users to verify design content. In Table 1, we represent different categories in different colors.

Upon review, it is observed that fewer 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. On the other hand, 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 (e.g., Korpalski [56]; Vezzoli and Sciama [92]) 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 toward 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 left part of Table 2, 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 globalization. In Table 2, we provide the distribution of DfX tool categories. As seen in the table, for Design for Manufacturing, Assembly, Quality and Variety methods have been proposed while for design for Sustainability and Supply Chain, currently there are only guidelines and mathematical models. This might indicate that there is room for further research in these areas.

In order to draw a clearer view of maturity, we analyzed the number of the tools recommended for each of the four design phases as provided in Table 3. We provide a weighted version of the information here. 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: 1) Tool complexity, 2) Comprehensiveness (i.e., step by step instructions or overall directions); and 3) Result generation (i.e., tangible evaluations). An increase in the weight indicates an increase across these criteria. Tables 3 indicates that Design for Manufacturing, Assembly, Disassembly/Recyclability, Quality, Variety and Environment have achieved higher levels of maturity in comparison to Supply chain and Sustainability. A higher maturity (as indicated with the values in the total columns of Table 3), might mean an increased level of preparedness of these DfX tools for industrial deployment.

3.3 Benefit of DfX factors in product costs

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. Boothroyd and Dewhurst [6] announced that DfMA saved 42% of labor cost, 54% of part cost, 60% assembly time, 45% product development time and 50% of total cost for their customers. Daabub and Abdalla [12] 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% to 50% reduction in engineering changes, 35% to 50% shorter design cycles, 20% to 60% lower startup costs and 20% to 50% fewer warranty claims [2]. Martin and Ishii [74] 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 can not be precisely measured because of the variety of the product types and required manufacturing systems. Moreover, an increase in cost at the design phase should be expected. Figure 2 shows this overall expected reduction in cost schematically. In the figure, the direction of arrows represents the cost change, where pointing upwards meaning an increase and downwards a decrease. Moreover, the size of the arrow represents the amount of monetary savings.

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, computer-aided design (CAD) software (e.g., Inventor, Solidworks, Unigraphics, etc.) and Computer-Aided Manufacturing (CAM) software (e.g., Master-CAM, PowerCAM) are widely used 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.* [90] 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.* [39] 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 [22] applied Cambridge Engineering Selector (CES) [7] 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 [45] 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 [86] 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.

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 a framework. 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.

The integration of DfX concepts, in general, 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 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 [41, 61] as product designs become more and more complex due to mix of materials, processes and geometry.

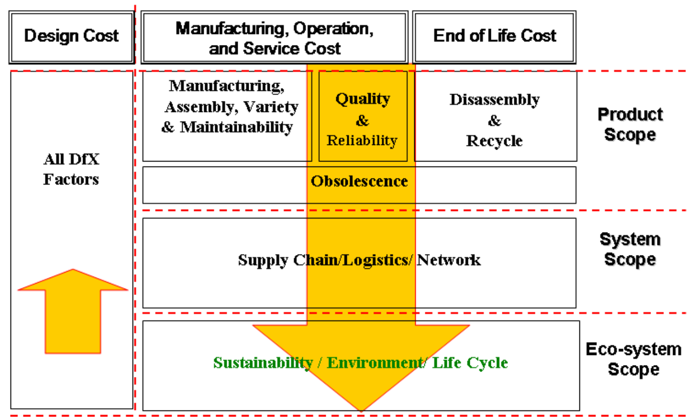

Figure 2. The benefit of DfX factors in product costs

An integrated DfX framework can also help with the communication both among and within organizations. Prasad [80] extended QFD as Concurrent function deployment (CFD) to simultaneously consider X-factors. Durai Prabhakaran *et al.* [20] applied the graph theory in conceptual design phase with DfX factors as vertices and their interdependencies as edges which form a directed graph. Herrmann *et al.* [41] observed the difficulty of breaking organizational 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 [44] combined Boothroyd's [5] DfMA method with internet to create a collaborative development platform. Coma *et al.* [10] incorporated fuzzy theory with Boothroyd and Alting's [4] DfA method to deal with the uncertainty in product design. Choi *et al.* [9] developed virtual tools based on Boothroyd and Alting's [4]DfA method to give geometry and visual aids. Steadman and Pell [91] 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 [61].

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 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 summarizes our findings based on our literature review of DfX concepts and related tools. Our overall goal with the paper is to aid design practitioners and researchers in the area. Thanks to the contributions from prior studies [1-107], the significance of the design stage is reaffirmed. Further, based on the reviewed studies, we expect the design for efficiency and green design applications to be compatible with win-win solutions by adopting modular design, recyclable materials, renewable energy and carefully process selection. 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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Table 1. The DfX tools/concepts applied in the four design phases

Phases / Factors	Needs Assessment/ Problem definition	Conceptualization	Preliminary Design	Detail Design
Manufacturing (1988)	V*23(Seven steps procedures for DFM(a)), V*33(AD(e)),	V*23(Seven steps procedures for DFM(a)), V*5(DFMA(e)), V*33(AD(e)),	V*23(Seven steps procedures for DFM(a)), V*92(DFM guidelines(a)), V*5(DFMA(e)), V*101(CMDM(e)),V*33(AD(e)), V*63(Spreadsheet(c)), V*44 (Internet DfMA(e)),	V*23(Seven steps procedures for DFM(a)), V*92(DFM guidelines(a)), , V*5(DFMA(e)), V*96(DFM(e)), V*101(CMDM(e)), V*33(AD(e)), V*63(Spreadsheet(c)), V*44 (Internet DfMA(e)),
Assembly (1988)		V*5(DFMA(e))	V*100(AOPD(e)),V*4(AEM(c)), V*5(DFMA(e)), V*102 (CDAPFAES(e)), V*10 (Fuzzy DfA(e)), V*9 (Virtual DfA(e)), V*44 (Internet DfMA(e)),	V*100(AOPD(e)),V*4(AEM(c)), V*5(DFMA(e)),V*102(CDAPFAES(e)), V*66(CRM(e)), V*10 (Fuzzy DfA(e)), V*9 (Virtual DfA(e)), V*44(Internet DfMA(e)), V*14(ASA(e)),
Disassembly & Recyclability (1992)			V*60,103(graph based heuristic approach(e)), V*61(Recycling path(a)), V*4,40(DfD(a)), V*59(Disassembly sequence and cost analysis(e)), V*43(Knowledge modeling(e))	V*60,103(graph based heuristic approach(e)), V*61(Recycling path(a)), V*4,40(DfD(a)), V*59(Disassembly sequence and cost analysis(e)), V*15,16 (DfD(e)), V*37(ANP(e)), V*43(Knowledge modeling(e)), V*104 (DfRe(e)), V*58 (DfRe(a)), V*53 (Material Separation(d))
Logistics (1992)				V*19(CE guidelines(a)), V*71(DFL guidelines(a))
Life Cycle (1993)	V*61,36,52,21(.LC Assessment(a)),	V*97(Guidelines and checklist for LC design(c)), V*21,36,52,61(LC Assess-ment (a), V*54(LCP(e))	V*97(Guidelines and checklist for LC design(c)), V*21,36,52, 61,78 (LC Assessment(a), V*25 (LCMD (e)),V*54(LCP(e)), V*26(Modularity Metrics(c)), V*94(SOM(c))	V*97(Guidelines and checklist for LC design(c)), V*21,36,52,61,78(LC Assessment(a), V*25(LCMD(e)), V*54(LCP(e)), V*26(Modularity Metrics(c)), V*94(SOM(c))
Quality(1995)	V*93(AD(a))	V*41,61,69,75(QFD(c)), V*32 (EVA(e)), V*95 (QFD + LP(e)), V*93(AD(a))	V*13(DFQM(d)), V*84 (PCO(d)), V*55(Six Sigma(d)), V*32 (EVA(e)), V*95 (QFD + LP(e)),V*93(AD(a))	V*13(DFQM(e))V*41,92(FEMA(e)), V*84 (PCO(d)), V*55(Six Sigma(d)), V*32 (EVA(e)), V*95 (QFD + LP(e)), V*93(AD(a))
Reliability (1995)				V*61(Reliability allocation(d)), V*47(Reliability guidelines(a)), V*65 (RBRDO(d)), V*51(RSF(d))
Supply chain (1995)			V*82(SCD & DfSC(a)), V*62(MILP(d)), V*30(SCMAT(d))	V*64(Rainbow Model(d)), V*1(DSC guideline(a)), V*26(3D-CE(e)), V*3 (PCDM(d)), V*82(SCD & DfSC(a)), V*34(DfSC(d)), V*62(MILP(d)), V*49(PDM(a)), V*99 (Fuzzy SC Model(d)), V*30(SCMAT(d))
Variety (1996)	V*73,74(DfV+ plat-form (e)), V*89(QFD +Kano (e)), V*67 (ANP-GP(e)), V*38 (DfA +DfV(e))	V*73,74(DfV+platform(e)), V*89(QFD+Kano(e)), V*67(ANP-GP(e)), V*38(DfA+DfV(e))	V*73,74(DfV+ platform(e)), V*89(QFD+Kano(e)), V*72 (DfV(e)), V*28,29 (IP(d)), V*67 (ANP-GP(e)), V*38 (DfA+DfV(e))	V*73,74(DfV+ platform(e)), V*89(QFD+Kano(e)), V*72 (DfV(e)), V*28,29 (IP(d)), V*67(ANP-GP(e)), V*38(DfA+DfV(e))
Environment (1996)	V*56(DFE guidelines (a), product assess-ment (b), product stewardship metrics (c)), V*18 (PBEMS (e)), V*8 (Quality Based Model(d))	V*56(DFE guidelines(a), product assessment(b), product stewardship metrics(c)), V*81 (LCA +QFD+TRIZ(e)) , V*18 (PBEMS(e))	V*56(DFE guidelines(a), product assessment(b), product stewardship metrics(c)), V*81(LCA+QFD+TRIZ(e)), V*18 (PBEMS(e)), V*24(GDA(e))	V*56(DFE guidelines(a), product assessment(b), product stewardship metrics(c)),V*81(LCA+QFD+TRIZ(e)), V*18 (PBEMS(e)), V*24(GDA(e))

Table 1 (cont). The DfX tools/concepts applied in the four design phases

Factors / Phases	Needs Assessment/ Problem definition	Conceptualization	Preliminary Design	Detail Design
Sustainability (2004)	V*68 (1. **guidelines for sustainable product design(a)**, 2.**sustain-ability strategies for design(a)**)	V*68 (1. **guidelines for sustainable product design(a)**, 2.**sustain-ability strategies for de-sign(a)**), V*50(**DfAD(a)**), V*98(**Road-map(a)**), V*35(**DfAD(e)**),	V*68 (1. **guidelines for sustain-able product design(a)**, 2.**sus-tainability strategies for de-sign(a)**), V*42 .(**Bourne-mouth University model(e)**), V*98 (**DfAD(a)**), V*50(**Road-map(a)**), V*35(**DfAD(e)**), V*85(**DFSM(c)**)	V*68 (1. **guidelines for sustainable product design(a)**, 2.**sustainability strategies for design(a)**), V*42 .(**Bournemouth University model(e)**), V*50(**DfAD(a)**), V*98(**Road-map(a)**), V*35(**DfAD(e)**), V*45(**DfRem(a)**), V*85(**DFSM(c)**)
Network (2005)	V*70 (**Process mngt architecture(e)**)	V*70 (**Process mngt architecture(e)**)	V*70 (**Process mngt architecture(e)**)	V*70 (**Process mngt architecture(e)**)
Maintainability (2006)			V *17(**Structure design review procedure(b)**)	V *17(**Structure design review procedure(b)**)
Obsolescence (2006)				V*83,88(**MOCA methods(e)**)

a. Guidelines **b.Check list** **c. Metrics** **d. Math Model** **e. Method**

Table 2. Distribution of the DfX tools proposed over the years (left) and their types (right)

Factor / Phase	Before 1990	1991~ 1995	1996~ 2000	2001~ 2005	After 2005	Total	Guide-line	Check-list	Metrics	Math Model	Method	Total
Manufacturing	1	2 1 2			2 8		2	0	1	0	5	8
Assembly 1		2	3	2 1		9		0	1	0	8	9
Disassembly & Recyclability		2	6	3 2		13	4	0	0	1	8	13
Logistics		1	1			2	2	0	0	0		2
Life Cycle		1	1	2	3	7 2		0	3	0	2	7
Quality		1 2 2			2 7			0	1	2	4	7
Reliability		1 0 2			1 4		1	0	0	3	0 4	
Supply chain		1	1	5	3 10		3	0	0	6	1 10	
Variety			3	2	3	8 0		0	0	2	6	8
Environment			2	1	2	5	0	0	1	1	3	5
Sustainability				2	5	7	4	0 1		0	2	7
Network				1		1					1	1
Maintainability					1	1		1				1
Obsolescence					1	1					1 1	
Total						83						83

Table 3. Number of the DfX tools (Left) and weighted total of the DfX tools proposed across four design phases (right)

Factor / Phase	Needs Assess-ment	Concep-tualization	Preli-minary Design	Detail Design	Maturity Index	Problem definition	Concep-tualization	Preliminary Design	Detail Design	Weighted Maturity Index
Manufacturing 2		3	7	8	20	10 19		29	38	96
Assembly		1	7	9	17		9	59	77	145
Disassembly& Recyclability			5	10	15			29	64	93
Logistics				2	2				2	2
Life Cycle	1	3	6	6	16	1 15		34	34	84
Quality 1		4	6	7	18	9 32		50	51	142
Reliability				4	4				22	22
Supply chain			3	10	13			15	54	69
Variety 4		4	6	6	20	36 36		52	52	176
Environment 3		3	4	4	14	21 23		32	32	108
Sustainability 1		3	6	7	17	1 3		26	27	57
Network 1		1	1	1	4	9 9		9	9	36
Maintainability			1	1	2			3	3	6
Obsolescence				1	1				9	9
Total	13	22	52	75	163	87 146		338	474	1045

Weighted scores a. Guideline(1) b. Checklist(3) c. Metrics(5) d. Math Model(7) e. Method(9)