Identification and analysis of cost elements of the DFX Techniques

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Abstract. *Cost is perhaps the most influential factor in the outcome of a product within many of industries today. To develop high quality products at low costs is the main challenge for the companies´ survival. Cost reduction initiatives are essential in this high competitive market place.*

DFX techniques and Design to Cost are some of these initiatives that have been successfully applied. They are processes based on cost reduction assumptions, some of them providing management with accurate cost information. While Design to Cost and DFMA explore the cost aspects in detail, most of DFX techniques address such issues indirectly. On the other hand, literature is poor in comparison between DFX techniques, focused on cost elements. This can cause problems and misunderstandings in a simultaneous DFX implementation, because some cost elements can be overwritten or forgotten by different approaches in different DFX methods.

This study aims at identifying, analyzing and classifying cost elements in DFX techniques. Final results show a matrix; linking DFX techniques with cost elements in a common basis, providing a single tool to support a truly simultaneous DFX implementation.

Keywords. DFX, cost systems, design to cost.

1.Introduction

To be successful, companies are increasingly required to improve their quality, flexibility, product variety and novelty, with consistently maintaining or reducing their costs. An efficient product development process is essential to achieve such challenges. Many different techniques and tools have been implemented to improve the efficiency, and thus to reduce costs of the product development process.

It is well known that 70-80% of a product cost is committed during the conceptual phase, as illustrated in Fig. (1). Making a wrong decision at this stage is extremely costly further down the development process. Product modifications and process alternations are more expensive the later they occur in the development cycle. (Rush & Roy, 2000; Asiedu & Gu, 1998).

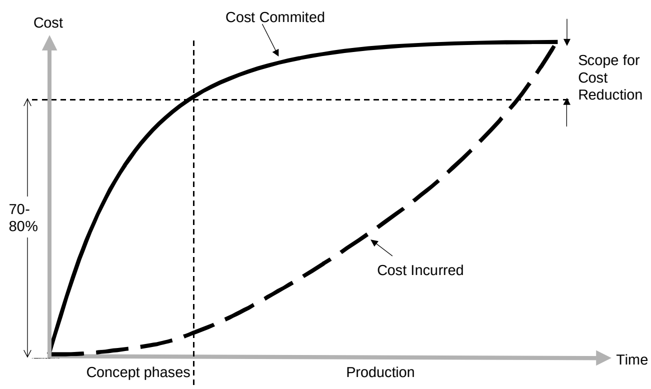

Figure 1 - Cost commitment curve (Rush & Roy, 2000).

Thus, to use cost as an evaluation criterion in the design process appears to be a potential solution for cost reduction. Design to cost is a technique that has been proven successful in this task, addressing directly cost issues. DFX techniques also have been used successfully, taking into account the life cycle of product, driven by performance, producibility, reliability, testability, maintainability, supportability, quality and environmental issues, among others, although they are not directly addressed to cost.

For this reason, the cost elements of each DFX are rarely described in the literature and case studies. Additionally, DFX techniques probably have many cost elements in common, which can cause misunderstandings when two or more techniques are applied simultaneously. The knowledge of cost elements affected by DFX techniques and its effects could increase the efficiency of such tools, increasing the cost reduction potential.

This study aims at identifying, analyzing and classifying cost elements in DFX techniques. The first section analyses the product cost issues, identifying the key cost elements. Then, the key concepts of the main DFX techniques are briefly described followed by the analysis of each technique, which is carried out for identifying the cost elements of each one. The analysis points out at the relationship between the cost elements found and the techniques studied, resulting in a common cost classification and identification for each technique. Finally, it is built a matrix that links the DFX techniques with cost elements identified, highlighting the effect of each cost element in the product life cycle cost.

2. Cost issues in design

Any engineering design process should not only transform a need into a description of a product but should ensure the design's compatibility with the physical and functional requirements. Therefore, it should take into account the life of the product as measured by its performance, effectiveness, producibility, reliability, maintainability, supportability, quality, recyclability and cost (Asiedu & Gu, 1998).

Thus, cost should be incorporated in the engineering design process as another design parameter because the design decisions affect several aspects of the product life cycle. Design to cost is a way to employ cost as evaluation criteria.

The objective of design to cost (DTC) is to make the design converge to an acceptable cost, rather than to let cost converge to design. DTC activities during the conceptual and early stages, determines the trade-offs between cost, schedule and performance for each of the concept alternatives. The general approach is to set a cost goal, then allocate the goal to the functions of the product. Designers must then confine their approaches to that set of alternatives that satisfy the cost constraint, optimizing product functionalities through introduction of new features in systems or parts. It is desirable that DTC could be assisted by cost algorithms used to determine the impact of design decisions in costs, usually provided by a tool set (Rush & Roy, 2000). Figure 3 shows the issues considered in a generic DTC algorithm.

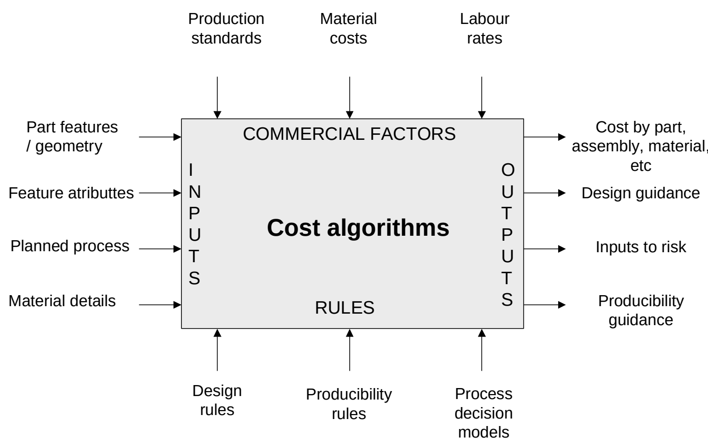

Figure 2 DTC Model (Rush & Roy, 2000).

According to Michaels & Wood (1989), DTC must ensure the integrity of functionality with affordability as program progress through development, production, and delivery of end products. Furthermore, DTC should be performed only in a design environment, which has strong control of product configurations and personnel responsibilities and actions in order to ensure an audit trail of cost experiences and a means for rewarding cost performance.

3. Product Cost Elements

Cost elements are defined in this paper as the design parameters that drive costs incurred in the entire product life cycle. Its effects on costs can be estimated at any time of the product life cycle and remain on parameters, materials, specification and process lead times, among others.

It is necessary to derive a framework to collect the cost elements in a systematic way. Life cycle cost (LCC) is the model that best fit to this need. The life cycle cost model must reflect all cost incurred at all the phases of the product life cycle. According to Asiedu & Gu (1998), the total life cycle cost can be decomposed into cost categories, known as cost breakdown structure (CBS). The level of breakdown and the cost categories considered depends on the phase to be used, the kind of information to be extracted from the model, the data available as input to the model and the product being designed/purchased.

In this paper, the purpose of the LCC model is to identify and allocate the cost elements that could represent the effect of design decisions during product development phase in all life cycle phases. Based on several life cycle cost description and models (Amhed, 1995, Kumaran et al, 2001, Rush & Roy, 2001), a specific CBS is proposed. This approach considers the life cycle composed by four phases, as follows: product development, manufacturing, operations & support, and disposal. These phases are the very cost categories. The criterion for defining cost subcategories takes into account the relationship with design, i.e., it is chosen as subcategories only the costs which incur in the life of the product as a direct result of design or those that affect design. The complete CBS is illustrated in Fig. (3) and a brief description of each category is shown below.

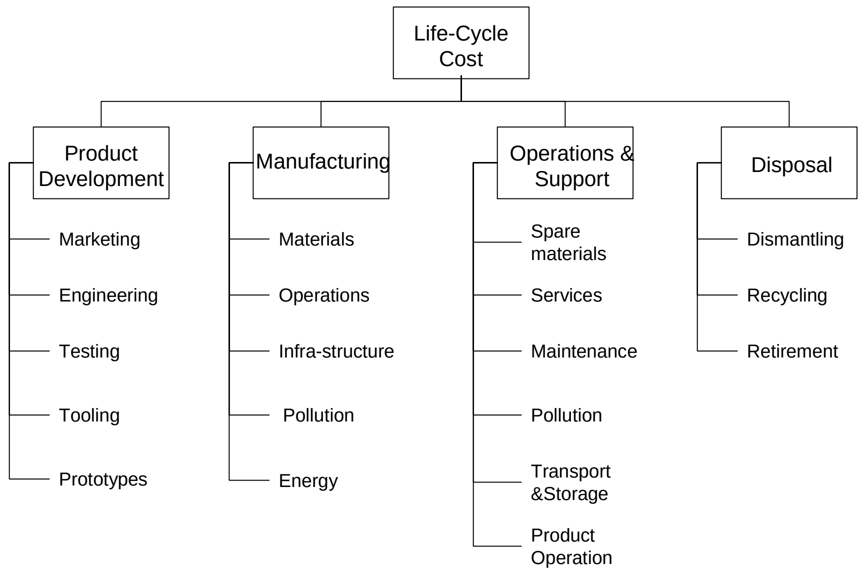

Figure 3 – Cost breakdown structure proposed.

- **Product development costs** consider all cost incurred during product development phase phase, ranging from marketing and technological research to effective design, evaluation and tests of the product and production. They usually incur in the company.
- **Manufacturing costs** consist of activities such as fabrication and assembly, production operations, quality control, facilities construction and acquisition, and pollution. These costs incur in the company, but are transferred to the customer through the price paid and to society through waste and pollution.
- **Operation & support costs** comprise the costs of product in the field that incur within the company as well as in customers and society. Costs for the company include warranty (services and spare materials), transport & storage; costs for the customer include services, spare materials, maintenance, product operation and transport & storage; costs for the society include pollution. Operation & support costs are the most significant portion of life cycle cost.
- **Disposal costs** come from product destination after its operational life. The choices in this phase might cause waste to be released into the environment. If this is not the case, cost can come from product dismantling, material recycling or product retirement. Costs from this phase can be incurred in the company, in the recycling company or directly in the society, depending on public laws and regulations.

4. DFX and Cost Elements

DFX – Design for “X” can be described as a set of techniques usually applied in the early product concept, in order to assure the complete projected product life, including product/market research, design phases, manufacturing processes, qualification, reliability issues, customer support issues and environmental issues (Keys, 1990).

The application of DFX has been pioneered with the successful application of DFM (Design for Manufacturing) and DFA (Design for Assembly) techniques in the early 60´s by General Eletric Corporation and by Boothroyd and Dewhurst, respectively. Such techniques led to enormous benefits including simplification of products, reduction of assembly and manufacturing costs, improvement of quality and reduction of time to market. This fact encouraged researchers to study the same approach applied to entire product life cycle issues, such as disassemblability, recyclability and environmental concerns. These practices might lead to optimal product designs as far as the entire life cycle of a product, from conception to disposal, is considered (Kuo et al, 2001).

In this paper, some DFX techniques have been selected, which represent the most important issues of product life cycle, according to the authors. These are: DFLC – Design for the Life Cycle, DFQ – Design for Quality, DFM – Design for Manufacture, DFA – Design for Assembly, DFS – Design for Supportability and DFE – Design for the Environment.

DFX techniques have been developed separately, with different approaches and objectives. Consequently, some overlap activities have been identified among them. This aspect has not been analyzed or explored by researches or industry, but as this paper shows, it is necessary and rather useful. Figure 4 shows a conceptual relationship of selected the DFX techniques and the areas of influence.

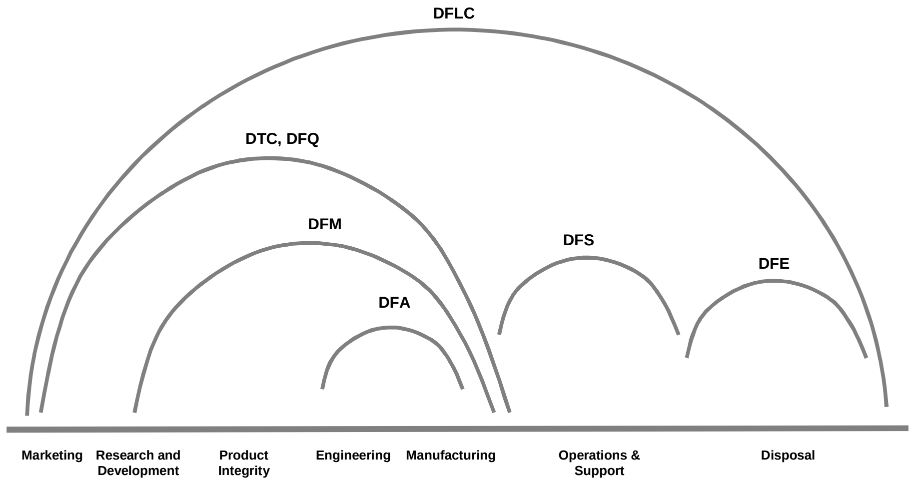

Figure 4 – DFX techniques overview and areas of influence (Adpated from Keys, 1990).

Some of the overlap activities have direct relationship with product costs, which could, by its turn, to also generate overlap of the cost elements. An identification of the common DFX cost elements can improve the cost reduction potential because it allows for the concurrent application of two or more DFX techniques, which might use the same cost and design parameters database.

The next sections explain briefly each DFX technique, and identifies the cost elements that have the strongest impact on the life cycle costs.

4.1 DFM – Design for Manufacture

Design for Manufacture (DFM) is concerned with the definition of product design alternatives, which facilitate optimization of the manufacturing system as a whole. "The overall focus of DFM are: to help identify product concepts which are ease to manufacture and assembly and to help to integrate manufacturing process design and product design to ensure the best matching of needs and requirements (Keys, 1990)".

Keys (1990) apud Stoll (1988) cited a checklist of DFM guidelines that have been empirically derived for years of design and manufacturing experiences. A sample is as follows:

1. Design with the minimum number of parts,
2. Develop a modular design,
3. Minimize part variations,
4. Design parts to be multifunctional,
5. Design parts for multiuse,
6. Design parts for ease of fabrication,
7. Avoid separate fasteners,
8. Minimize assembly directions,
9. Maximize compliance,
10. Minimize handling,
11. Evaluate assembly methods,
12. Eliminate or simplify adjustments.

4.1.1 DFA – Design for Assembly

Design for Assembly (DFA) is perhaps the most famous and most successful of the DFX methods, pioneered by Boothroyd and Dewhurst, and widely described and disseminated. Lee and Hahn (1996) defined DFA as a group of design methods used to improve a product design to enhance assembly.

Lee and Melkanoff (1991) apud Lee and Hahn divided DFA in three main approaches: design heuristics, design ratings and design revisions. Design heuristics are generalized rules sets used by designers as guidelines; design ratings are component classification schemes that help to provide assembly ratings of individual components as well the overall design and design revisions combine a component rating scheme with an assembly time and cost estimation as well as specific rules applied in an ordered assembly sequence for deciding how to revise a design.

Basic guidelines of DFA are based on to reduce the number of parts and ensure the easy of assembly. Kuo et al. (2001) apud Corbett (1987) give the follow list of DFA criteria:

1. Minimize the number of parts and fixings, design variants, assembly movements and assembly directions;

2. Provide suitable lead-in chamfers, automatic alignment, easy access for locating surfaces, symmetrical parts or exaggerate asymmetry and simple handling and transportation;
3. Avoid visual obstructions, simultaneous fitting operations, parts that will tangle or nest, adjustments which affect prior adjustments and the possibility of assembly errors.

Cost elements of DFM and DFA

DFM guidelines address several cost elements, which affect simultaneously several life cycle aspects, all of them positively, i.e., they minimize the life cycle cost. These are: minimized interfaces between systems and parts, minimum number of parts, reduced parts variation, tight tolerance, better compliance, less scraps and rework, lower process lead times, lower assembly times, better handling, optimized utilization of tools and machines, modular design and multiuse parts.

4.2 DFQ – Design for Quality

Design for Quality encompasses some tools and techniques applied during design, which are well known and documented in literature, with high acceptance and practice in industry. According to Kuo et al (2001), the objectives of DFQ are: (1) design a product to meet customer requirements; (2) design of a robust product that can counter or minimize the effects of potential variation in manufacture of the product and the product's environment; (3) continuously improve product reliability, performance, and technology to exceed customer expectations and (4) offer superior value. These objectives can be achieved though the application of QFD (Quality Function Deployment and the Taguchi method.

QFD is a systematic process that helps to identify customer desires and deploy them as the voice of customer throughout all functions and activities of the corporation. QFD ensures that customer requirements are accurately translated into relevant technical requirements through all stages of the product development process. There are four matrix that deploy, in sequence, customer requirements into product functions, then into component parameters, then into production planning and finally into the operations in the factory floor. QFD´s actions focus on decision-making interactions of the multifunctional design teams: displays visually the relevant information for ready reference and documents the design decisions in a visual corporate memory.(Clausing, 1994).

Taguchi methods assure the robustness of the product, which means small variation in performance whenever the product operates under noise conditions. A deviation in performance when the product is at the hands of the customer causes a financial loss called quality loss. Quality loss increases by the square of deviation from target value, that is determined by the performance parameter, such as tolerance, performance which will be employed in the factory or operation. Taguchi methods involve four activities to reduce total cost (quality loss plus manufacturing cost): product parameter design, tolerance design, process parameters design and on-line quality control. The first three are directly related to design: (1) product parameter design, which is the optimization of the robustness of the product design; (2) tolerance design, which is the selection of the economic precision levels around the nominal design values; (3) process parameters design, which optimizes the most important production process to produce more consistent products. (Clausing, 1994; Taguchi & Clausing, 1990).

Cost elements of DFQ

QFD drives the product development process, addressing some cost elements such as lower number of market surveys, improved teamwork, optimized interfaces between functions and systems and parts. QDF is also a proper tool to deploy the cost customer requirements. Taguchi has cost elements which increases and reduces some costs, but which decreases the total cost. The cost elements that increase prototype and testing cost are: increased number of tests and increased number of test parameter. It reduces some other cost driven by minimum tolerance deviation, improved product reliability, lower number of defects and less reworks and scraps and less service calls.

4.3 DFE – Design for the Environment

DFE is a systematic evaluation method which takes into consideration the design performance with respect to environmental, health, and safety objectives over the full product and process life cycle. It is a combination of several design related topics, including disassembly, recovery, recyclability, regulatory compliance, disposition, health and safety impact and hazardous material minimization (Mizuki et al, 1996).

According to Fiksel & Wapman (1994), the goal of DFE is to enable design teams to create eco-efficient products without compromising their cost, quality and schedule constraints. An eco-efficient product may be defined as a product, which both minimizes adverse environmental impacts, and maximizes conservation of valuable resources throughout its life cycle. They cited that a successful implementation of DFE into a new product development requires:

1. eco-efficient metrics in integrated design. Eco-metrics include energy, emissions, materials management metrics and economic metrics and should be driven by corporate goals or customer needs.
2. eco-practices in engineering design. Ernzer et al (2001) and Mizuki et al (1996) surveys showed that successful design practices incorporates DFE checklist into design phases and establishes the bases for structuring cross-functional DFE teams.

3. efficient eco-analysis methods to perform trade-offs between design alternatives. Common methods are the Life-Cycle Assessment (LCA), LCC (Life Cycle Cost) and ECO-FMEA (Environmental-Failure-Mode and Effects-Analysis). Software tools and integrated databases make feasible the use of these methods.

A tool that deserves attention is the LCA. LCA is the framework for the study of the impact that products and process have on environment. It is an environmental and energy audit that focuses on the entire life cycle of a product from raw material acquisition to final product disposal of environmental emission. However, it is important highlight that, as LCC, at present a complete model which contains all necessary parameters and relevant data does not exist. (Asiedu & Gu, 1998).

Cost elements of DFE

According to Kumaran et al (2001), initiatives such as proper materials and waste management, efficient process and product design, energy efficiency, and recycling can be both profitable and environmentally preferable. They proposed a life cycle environmental cost analysis classifying the eco costs in 8 subcategories: cost of effluent control, cost of effluent/waste treatment, cost of waste disposal, cost of implementation of environmental management systems, cost of eco-taxes, cost of rehabilitation (in case of accidents), cost of energy and cost savings of recycling and reuse strategies.

Analyzing the eco-costs, an approach to reduce it should be associated with other DFX and design techniques , although sometimes a design alternative can be expensive in terms of environmental and cheap in terms of manufacturing, for example, an eco-material can be expensive for the company. It is also important to consider that a design choice probably has several impacts on the environment. For example, reducing the mass of a product can result in reduction in energy and material usage as well as pollutant emission reduction.

Thus, cost elements of DFE are very similar to other DFX, but a cause-and-effect study must be carried out for each design alternative. DFE cost elements are: minimized interfaces between designers and DFX experts, minimum number of parts, less scraps and rework, lower process lead times, optimized utilization of tools and machines, multiuse parts, alternative materials, lower transport & storage times, improved product reliability and life-cycle, reusable parts, disassembly time.

4.4 DFS – Design for Supportability

DFS involves the evaluation of all aspects of product support at the design stage, such as DFM or DFA. Product support is the name given to the various forms of assistance that companies offer to the customers to help them gain maximum value from manufactured products. Thus, DFS includes the typical forms of support such as: installation, operational training of a product, maintenance and repair services, documentation, availability of spare parts, upgrade, customer consulting and warranty schemes. In the available literature, separate forms of DFS are found: DFMt –Design for Maintainability, DFS – Design for Serviceability and DFR –Design for Reliability.

Companies best practices usually set quantitative goals and DFS guidelines at the design stage for all aspects of support, based on life-time cost models to assure that the proper decisions are made about the trade-offs between features, manufacturability and supportability. The basic guidelines for DFS follow as (Goffin, 2000, Kuo el al, 2001):

1. Modular design for quick replacement,
2. Extensive diagnostic capabilities,
3. General design features as, possibility of damage precluded, minimum need of special tools, legibly and visible part designation, mistake proofing features, sharp edges, corners or protrusions avoidance,
4. Mounting and location of units, such as removal and replacement of LRU´s without removal of unfailed units, without interrupting critical functions, with clear access.
5. Test, checkout and calibration guidelines
6. Cables, leads, wiring and connectors with adequate viewing and hand access, cables routed, identification of cables and wires throughout their length.

Cost elements of DFS

DFS guidelines address cost elements that usually are affect by product reliability, i.e., the better is the product reliability, the smaller is the product support required. Thus, several cost elements that improve product reliability are: minimized interfaces between designers and field support team, minimum number of parts, minimum number of special tools to repair, modular design, multiuse parts, improved product reliability and life-cycle, disassembly time, mean time to repair (MTTR), mean time between failure (MTBF), diagnostic capabilities.

4.5 DFLC – Design for the Life Cycle

DFLC is also called System Engineering Life-Cycle or life-cycle design. The unique principle of DFLC is that the complete life cycle of the product is kept in consideration and treated in each phase of product development process. This means that technical and economic consideration must continually be given throughout the life-cycle development phases, comparing the cost the product design with a certain reliability level and the cost for some level of performance degradation, and providing appropriate levels of customer service support (Keys, 1990).

DFLC involves the design efforts to achieve the following goals (Keys, 1990):

1. To transform an operational need described by system performance parameters into a preferred system configuration, through the use of an iterative process of functional analysis, synthesis, optimization, definition, design, test, and evaluation,;
2. To consider related technical parameters and assure compatibility of physical, functional and program interfaces in a manner that optimizes the total system definition and design;
3. To integrate performance, producibility, reliability, maintainability, supportability, only to name a few, into the overall design process.

The main tool of DFLC is the Life-Cycle Cost Assessment (LCC). It is based on the analysis of the life-cycle costs of a product, which is, by its turn, based on product specific costs that occur within the life-cycle framework. Such costs are divided into: product development, manufacturing, operation, service, and society (waste, pollution and health damage) costs (Kuo et al, 2001). LCC models available today are database managers that have the capability, in several degrees, to import, modify, analyze, integrate and manage large amounts of data from many different sources (Sterling, 2003).

Cost elements of DFLC

Cost elements of DFLC are present in all subcategories of LCC, because it is centered in LCC analysis. LCC analysis provides the framework for specifying the estimated total incremental cost of developing, producing, using, and retiring a particular item. Through early implementation, LCC analysis can not only influence the final design by providing the relevant cost information but also contribute to cost reduction by identifying cost drivers and how changes in design parameters might affect cost. However, a complete life cycle framework has not been developed yet, because most of models developed are restricted to a specific process, simple operations, or one phase of the life cycle. (Asiedu & Gu, 1998).

In this context, DFLC yields specific cost elements depending on specific applications existent and it should be used as an analysis tool to identify cost elements. Specific applications of DFLC should be incorporated in DTC, in order to recommend optimal design solutions with life cycle aspects. It is worth noticing that when a complete DFLC works as previewed in the concept, it should be considered as a life cycle DTC.

5. Results

Tables (1) to (4) summarize all the cost elements identified, providing the effect that the cost element of a specific DFX makes in specific life cycle cost categories. Each table reflects one life cycle phase, only to improve the visibility of the results. When the cost element reduces the cost identified in the subcategory, it is marked as (R); when it increases the costs, it is marked (I), or (D) when it depends on the case. One should note that the cost elements identified by only a keyword. For example, analyzing the cost elements of DFM in product development phase, specifically in the engineering cost subcategory, is found the cost element interfaces (R). Recovering section 4.1, it is found that interfaces mean "minimized interfaces between systems and parts and the (R) indicates that is reduce the engineering cost.

Table 1 – Cost Elements of the DFX techniques of engineering design phase.

Life-cycle phase	Life-cycle costs	DFM	DFA	DFE	DFS	DFQ
Engineering design	Marketing					Nº of market surveys(R)
	Engineering	Interfaces (R)	Interfaces(R)	Interfaces(R)	Interfaces(R)	Interfaces(R)
	Prototypes	No. Parts (R),	No. Parts(R)	No. Parts(R)	No. Parts(R)	Nº of parameters tested (I),
	Tooling	Tolerance (I), Tooling material (R)				Tolerance (I)
	Testing	No. Parts (R), tolerance (R)	No. Parts(R)	No. Parts(R)	No. Parts(R), compliance(R), Diagnostic capabilities(R)	Nº of tests (I)

Table 2 Cost Elements of the DFX techniques of manufacturing phase.

Life-cycle phase	Life-cycle costs	DFM	DFA	DFE	DFS	DFQ
Manufacturing	Materials	No. Parts (R), Scraps and rework (R)	No. Parts(R)	No. Parts(R), Alternative materials (D)	No. Parts(R)	
	Energy	Process times(R), Reworks(R)	Assembly times(R)	Process times(R), Scraps and rework (R), Utilization of tools and machines(R)		Reworks and scrap(R)
	Operations	Compliance(R) Process times (R), Reworks (R),	Assembly times(R), Compliance(R)		Compliance(R)	Reworks and scraps(R), Inspection times(R), No. of defects(R)
	Infra-structure	Tools (R), Machines(R)				
	Pollution	Process times(R), Materials(R), Scraps and waste(R)	Assembly times(R), Materials(R), Scraps and waste(R)	Process times(R), Scraps and rework(R)		Reworks and scraps(R)

Table 3 Cost Elements of the DFX techniques of operations & support phase.

Life-cycle phase	Life-cycle costs	DFM	DFA	DFE	DFS	DFQ
Operations & Support	Services	Compliance(R)	Compliance(R)		Diagnostic capabilities(R), Modular design(R)	Reliability(R), No. of service calls(R)
	Spare-parts	No. parts(R), Parts variation(R)	No. parts(R)	No. Parts(R), Multiuse parts(R)	No. parts(R), Modular design(R), Multiuse parts(R)	
	Energy	No. parts(R)	No. parts(R), Material(R)		No. parts(R), Material(R)	
	Transport & Storage	No. parts(R), Modular design(R), Parts variation(R), Multiuse parts(R)	No. parts(R), Modular design(R)	Transport & storage times(R), Multiuse parts(R)	No. parts(R), modular design(R), Multiuse parts(R)	
	Maintenance	Tolerance(R), Compliance(R)	Compliance (R)	Product reliability (R)	No. of special tools to repair (R), Diagnostic capabilities (R), No. Parts (R), compliance (R), MTTR (R), MTBF (R),	Reliability (R), MTBF(R)
	Product operation			Product reliability (R)	Product reliability(R) MTTR (R), MTBF(R)	Product reliability (R), Performance deviation (R)

Table 4 Cost Elements of the DFX techniques of disposal phase.

Life-cycle phase	Life-cycle costs	DFM	DFA	DFE	DFS	DFQ	DFR
Disposal	Retirement			Alternative materials (D)			
	Recycling	Multiuse parts(R)		Alternative materials (D), Reusable parts (R)	Multiuse parts(R)		
	Dismantling	No. parts (R)	No. parts (R)	No. parts (R), Disassembly time (R)	No. parts(R), Disassembly time(R)		

An analysis of the tables (1) to (4) shows that:

1. Most of cost elements identified reduce life cycle costs, what is expected, because they are based on cost reduction assumptions of DFX;
2. Almost all of DFX have cost elements that affect all life cycle phases;
3. Some cost elements of specific DFX affect different life cycle phases; for example, minimized number of parts is a key cost element for DFA and it affects: costs of engineering design phases, reducing the cost of prototypes and testing; manufacturing costs, reducing material costs and lead times; operations & support costs, reducing the necessity of total spare parts and saving consumption energy because can reduce weight; transport & storage, reducing the total transportation needed and also the store and handling; and finally in disposal costs, where it reduces the cost of dismantling, spending less time in this task.
4. Many cost elements are present in more than one DFX; following the same example of minimized number of parts, which is present in DFM, DFA, DFE, DFE and DFS, repeated 24 times in 6 different cost subcategories in all life cycle phases;
5. Many cost elements have relationship among them, crossing phases and DFX, sometimes with contradictory effects, which demand trade-off analysis, for example, the cost element “use of alternative materials”. This element affects DFM, DFA, DFE, DFS and DFR techniques in different phases of life cycle. An alternative material such as a modified and light plastic, chosen by DFM guidelines, can reduce material costs, spare-parts costs, energy costs (saving), operations & transport cost, following simultaneously DFS and DFE guidelines; on the other hand it can cause high costs of disposal, that could require special storages or high costs of recycling.

5. Conclusion

These results let to conclude that exist a potential integration of DFX, which could increase its benefits. The identification of the DFX cost elements permit the simultaneous application of two or more DFX, through common identification and use of common cost elements among then.

Some future works must be done to make feasible such approach, as the design of integrated life cycle cost databases, which consider in fact estimated costs and real cost that could be used in any phase of life cycle phase. Based on the results, some star points can be defined, as cost of materials, cost of parts, cost of process, just to exemplify some cost element which were very common in our analysis.

An overall analysis of the DFX guidelines and characteristics and results also show that the cost elements can be considered as a design decision criteria, because they are present in all DFX crossing all life cycle phases. They should have to be common within all DFX, showing the effects for each design decision in each “X” aspect, which could support robust trade-studies. Such evaluation is feasible only if is supported by a network which considers the relationships between: (1) cost elements and cost elements, (2) life cycle cost categories and cost elements; (3) life cycle cost categories and life cycle cost categories.

Finally, result stated in tables (1) to (4) help managers to choose between DFX those which are most appropriated to the company need and characteristics, indicating how each DFX can save company costs, providing different effects that those promised by DFX authors and DFX tools vendors. It can also help managers in identify cost drivers to support cost reduction campaigns, because most of cost elements identified have cost reduction effects.

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