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Towards an integrated approach to "Design for X": an agenda for decision-based DFX research

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Abstract Concurrent engineering encourages holistic product development, considering all aspects of the product in design decisions. "Design for X" (DFX) techniques are popular for doing this, yet each focuses on just one aspect of the product (manufacture, cost, etc.). To provide the holistic approach required by concurrent engineering, these techniques must be brought together, but this has received little attention in the literature. This paper argues for "top down" development of DFX, starting from the needs of design decision-making, to balance the current "bottom-up" approach. Existing DFX techniques are compared to see how they can be used together. The importance of relating DFX techniques to the overall purpose of a product, not just other DFX, is highlighted, along with some of the challenges in making trade-offs. The paper concludes by highlighting relevant lessons from decision research and four themes for future research necessary to develop the proposed "top down" approach.

Keywords Design for X · Decision analysis · Concurrent engineering

1 Introduction

Increasing global competition and fast-moving markets are forcing manufacturers to find ways of improving flexibility and cutting time-to-market, without compromising the cost or quality of the goods they make. This places greater responsibility on designers to think beyond form and function, and consider the implications of their choices for all stages of product development: an approach known as "concurrent engineering". This, in turn, increases the complexity of the decisions they have to make and demands methods that can help designers structure and manage the competing needs of a product across its lifecycle. Among these methods are *Design for X* (DFX) techniques, where X stands for a particular lifephase (e.g. manufacture, assembly) or a virtue that the product should possess (e.g. quality, environmental impact). Each technique provides guidelines and/or metrics to help designers develop products that are better from the given point of view. However, concurrent engineering requires a holistic view of the product, so DFX techniques must be integrated with broader product development, and not applied in isolation. As yet, the relationships between DFX techniques, and their links to the design process as a whole, have not received attention in the literature.

This paper explores the similarities and differences between DFX techniques and highlights the challenges in relating them to other aspects of the design, including other DFX. The paper reviews a range of DFX techniques, looking at the similarities and differences in their stated purpose, the type of support they provide and how they fit into the design process. The difficulties in applying multiple DFX are then discussed, before looking more specifically at the problem of trade-offs, including the need for preference information and lessons from the field of decision research. The paper concludes by arguing for a "top–down" approach to DFX development, to balance the "bottom-up" approach currently used, and highlights four areas for future research to do this.

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2 Review of design for X techniques

DFX developed from the recognition that design decisions affects every subsequent stage of the product lifecycle, through development and beyond. As product development progresses, the cost and effort of changing a design increase, so it is best to catch potential problems as early as possible. DFX techniques come in a variety of forms, from general guidelines to detailed software tools, and each addresses a different aspect of the product's lifecycle or performance. This section will review a range of DFX techniques described in the literature, beginning with design for manufacture and assembly, then design for environment before moving on to look at less well-established techniques.

2.1 Design for manufacture and assembly

Design for manufacture (DFM) and design for assembly (DFA) developed from the recognition that the cost of producing a product is largely determined by its design. Failing to consider manufacture and assembly in design can result in products that are either fundamentally impossible to make, or more expensive (and hence less profitable) than they could be. The focus of these techniques is therefore on reducing the cost of product development, either by minimising manufacture and assembly costs, or by avoiding needless design iteration.

DFM support comes in a variety of forms. The simplest are general guidelines for features to include or avoid, such as "Avoid the use of undercuts where possible" (Edwards 2002). However, different processes have different capabilities: a feature that may be easy for one manufacturing process may be expensive or impossible to produce by another. Therefore, support is often provided in the form of handbooks that provide specific guidelines for each manufacturing process: Process Information Maps (Swift and Booker 2003), for example, or the Design for Manufacturability Handbook (Bralla 1999). Given that "cost is the most complete measure of manufacturability" (Bralla 1999, p. 181), methodologies have also been developed to help designers estimate the costs of their designs, providing a metric for evaluating the effects of any changes (e.g. Swift and Booker 2003; Boothroyd et al. 2002). Support software for DFM is also available, which helps to estimate manufacturing costs (La Trobe-Bateman and Wild 2003), or knowledge-based systems that highlight manufacturing constraints while a product is being designed on a CAD system (Abdalla 1998).

Whereas DFM is concerned with the component level of a design, DFA is also concerned with product structure, and therefore provides a different type of support. General guidelines are again available, highlighting desirable features in assembly [e.g. "minimise number of parts", "Make parts symmetrical where possible", (Edwards 2002)]. However, unlike DFM, DFA has a number of general methodologies, which are not tied to specific processes. The best known of these are the Boothroyd–Dewhurst System (Boothroyd et al. 2002), the Lucas DFA Methodology (Lucas Engineering Systems Ltd. 1993) and the Hitachi Assemblability Evaluation Method (Miyakawa and Ohashi 1986). All three include procedures for identifying parts that can be eliminated or combined, and for estimating assembly times and costs based on component characteristics. Computer-based support is also available, generating feasible assembly sequences, and estimating their associated costs while a product is being designed in a CAD system (Barnes et al. 2004).

The guidance from DFM and DFA can conflict: for example, DFM's emphasis on simplifying components often contradicts DFA's emphasis on combining parts to simplify product structure. Applying either one by itself can lead to false economies—a small reduction in manufacturing cost being offset by huge increases in assembly costs, for example. Therefore, it has become increasingly common for methodologies to apply both, under the heading design for manufacture and assembly (DFMA) (e.g. Swift and Booker 2003; Boothroyd et al. 2002). As both focus on reducing costs, DFM and DFA methodologies that provide cost estimates are easy to combine—trade-offs are made on the basis of finding the lowest overall cost. However, this presents a problem for qualitative guidelines, which provide no way of evaluating trade-offs between manufacture and assembly.

Regardless of the technique adopted, DFMA always serves the same purpose: identifying infeasible or costly designs as soon as possible, to minimise redesign and reduce the overall cost of making the product. Not all DFX share this purpose: some seek to address less commercial aspects of the product, and this is especially true of design for environment (DFE) techniques.

2.2 Design for environment

Growing concern about damage to the environment has lead to a variety of research to develop more environmentally friendly products. Like cost, the environmental impact of a product across its lifecycle is determined largely by the decisions taken in its design, leading to a variety of design for environment (DFE) tools. Unlike DFM and DFA, which are concerned with cost, there is no single measure for environmental impact, with many stages of a product's life affecting the environment in different ways. DFE is therefore part of a family of environmentally conscious design techniques with several branches: Design for disassembly, design for recycling, design for end-of-life, lifecycle costing and sustainable design.

DFE tools, as opposed to their more specific relatives mentioned earlier, aim to reduce the overall environmental impact of a product. Therefore, they often provide metrics that help to quantify the different environmental impacts of a product, so that trade-offs between them can be made. Examples of such metrics, or methodologies for deriving them, are given by Veroutis and Fava (1996), O'Shea (2004) and by Lifecycle Costing Methodologies (Woodward 1997). There are also general guidelines for developing environmentally friendly products, such as the "Ten Golden Rules" (Luttrop and Lagerstadt 2006). Other DFX concerned with the environment addresses more specific areas.

Design for disassembly (DFD) is similar to DFA, in that, it establishes and evaluates feasible disassembly sequences for a product. Evaluation is sometimes based on the time/cost of disassembly: the easier a product is to disassemble, the greater the chance that its parts will be reused or recycled (Desai and Mital 2003). Unlike DFA, DFD does not just focus on reducing costs: some methods evaluate alternative disassembly paths based on recovering parts with the most reuse or recycling value first (Knight and Curtis 2002).

The most significant work to date on design for end-of-life (DFEOL) is Stanford University's End-of-Life Advisor (Rose et al. 2000). This evaluates five possible end-of-life strategies [reuse, service, remanufacture, recycle (without shredding) and recycle (shred first)] based on a product's characteristics, to identify which is most environmentally friendly.

Design for recycling (DFR) is closely related to DFD and DFEOL. After all, assemblies whose parts are difficult to separate are much more difficult to recycle, and recycling is not always the most environmentally friendly option. DFR research has developed a number of qualitative guidelines (Masanet et al. 2002), such as the need to label components so that their materials can be identified, rather than metrics or methodologies. Quantitative methods related to DFR have tended to focus on ease of disassembly (e.g. Kroll and Hanft 1998), although efforts have been made to develop quantitative metrics for rating the recyclability of a design (Huisman et al. 2003; Ardente et al. 2003).

More recently, the issue of sustainable design has arisen. Instead of looking merely at the economic impact of a product, sustainable design recognises that products must be sustainable environmentally, economically and socially. This is known as the "triple bottom-line" (Elkington 1997) and emphasises the need to balance all three, though how such trade-offs should be made remains an open question (Ljungberg 2007).

These various DFX related to the environment do two things: they help to establish feasible lifecycle choices (mainly at the end of the product's life) and provide metrics and criteria for evaluating the environmental performance of the product.

2.3 Other DFX

Although DFMA and the various branches of environmentally conscious design are the DFX which receive the most attention in the literature, tools supporting other DFX do exist. Quality, ease of maintenance, reliability and cost are all important selling points in a product that are determined largely by design decisions.

Design for quality (DFQ) is concerned with developing a product that is fit for purpose. This means making sure that the underlying design of the product meets or exceeds the customers' requirements and that the product is robust to variations in manufacture (Kuo et al. 2001). For the former, Quality Function Deployment (Ako 1990) is a commonly used tool, relating customer requirements to specific parameters of the design, ensuring that all requirements are reflected in the finished product. For the latter, Taguchi loss functions (Taguchi 1986) are used as a way of quantifying the cost of deviating from an idealised parameter value, providing a metric that can be optimised. Benchmarking (Zairi 1992) is also used, as a way of measuring how well a product performs its main functions compared to its competitors. In all cases, these tools provide a way of measuring how well a product satisfies the requirements of its customers, and they are therefore similar to metrics.

Ease of maintenance is a selling point for any product and is becoming more important with the trend for long term service agreements, particularly in the aerospace industry. For example, Rolls Royce has moved from selling engines, to selling "power by the hour" where they take responsibility for maintaining and servicing their engines (Kumar and Crocker 2003). Design for maintainability (DFMt) tools is available to help designers assesses how easy their designs will be to maintain. These are usually in the form of guidelines (Kuo et al. 2001, p. 251), or tools for predicting maintenance cost (Slavila et al. 2004).

Related to maintenance is reliability: the ability of a product to perform its function over a period of time without failing (Kuo et al. 2001). Like maintenance, reliability is important in terms of both repeat purchases and where the manufacturer is responsible for maintaining the product. It is also important where warranties are set. General design guidelines are available for design for reliability (Ireson and Coombes 1988). More specific tools are also available, providing a metric for reliability which is used to allocate target reliability values to the parts within a system. Simulation software can be used to estimate the reliability of different components within a product (e.g. Minehane et al. 2000).

Given the financial pressures on any design project, two important DFX related to cost have developed: Design for cost (minimising the cost of a product) and design to cost (keeping the cost within a specified constraint). The main tools in this area deal with cost estimation, based on the information available at the given stage of design (Koonce et al. 2003; Roy 2003). These provide a metric—estimated cost of the product—in the same way as DFMA and DFMt tools, but this time based on *all* the costs incurred by the manufacturer over the product lifecycle (e.g. material costs, supply chain costs, quality inspection costs).

Although the DFX methods discussed in this section cover a wide range of issues, all help to measure a particular characteristic of the product: its quality, ease of maintenance, reliability and cost. While some guidelines are provided, the methodologies and techniques used focus on providing metrics—ways of measuring the desired characteristic in a proposed design.

2.4 Future DFX

DFX is not a static field: while the DFX techniques discussed so far are well established, new DFX methods continue to be developed in response to changing market pressures. This section will discuss three new DFX areas that are not yet as well developed as those discussed so far.

Design for supply chain is sometimes called 3D concurrent engineering (Fine et al. 2005) to distinguish it from 2D concurrent engineering (which deals with only product and process design—not product, process and supply chain). Companies have become increasingly concerned with supply chain management, and how they can improve efficiency there. As with other DFX, however, design provides a limiting factor on how efficient a supply chain can be, and therefore designers need to consider the implications of their decisions for the supply chain. Tools in this area are fairly limited, but generally focus on establishing and evaluating feasible supply chains (in the same way that DFM establishes and evaluates feasible process chains and DFA feasible assembly sequences) (e.g. Li et al. 2001). Cost is an important metric, but supply chains can also be evaluated based upon product quality, lead time, level of partnership with suppliers and the associated risk (Fine et al. 2005).

Another area that is becoming increasingly important is the affective properties of products (Jordan 2000), known as affective design. Although the name does not fit the DFX pattern, the principles behind affective design are exactly the same as other DFX. Increasingly, issues such as brand identity, and having the right look and feel are becoming more important, particularly for mass-market consumer goods, which must stand out in a crowded market. Tools are being developed to provide metrics that quantify emotional responses to a given design [e.g. backwards kansei (Matsubara and Nagamachi 1997), the affective engineering toolkit (Henson et al. 2006)].

Another area of growing interest is inclusive design. Designers often inadvertently exclude a portion of the population from using their designs, as they do not consider users with physical or cognitive impairments. Inclusive design is a field concerned with developing tools to help designers understand the needs and capabilities of a diverse user base, so that they can include as much of the population as possible in their designs. Tools in this area include kits for physically simulating impairments (Dong and Clarkson 2005), simulating the capabilities of different users in a CAD system (Porter et al. 2004) and measuring “Design Exclusion” (the proportion of the target population excluded by a design), so that this can be minimised (Clarkson and Keates 2003). There are also general guidelines available—for example, the Seven Principles of Universal Design (Coleman et al. 2003).

Tools in all three areas—supply chains, affective design and inclusive design—are still relatively new, but will continue to develop. As before, there is an emphasis on developing metrics to measure desirable characteristics (desired emotions, level of inclusion) and to establish and evaluate feasible options for the product lifecycle (possible supply chains).

3 Discussion

Whereas concurrent engineering encourages a holistic approach to product development, DFX are themselves reductionist, each technique focussing on a specific virtue or lifephase to the exclusion of others. In considering how these different DFX techniques can be used together, it is important to look at their similarities and differences. DFX tools are developed by different groups with different purposes in mind and can therefore have different structures, even when they fall under the same DFX heading. Nevertheless, similarities do exist. This section compares the DFX techniques that have been reviewed, based on their purpose, the type of support that they provide and how they fit into the design process. It then goes on to discuss the challenges these present for applying multiple DFX.

3.1 Purpose of DFX techniques

Each DFX cited in Sect. 2 has its own specific purpose, as summarised in Table 1, but all follow a similar pattern. Every DFX technique seeks to improve a particular aspect of the product being designed, such as cost or environmental impact, by helping designers consider that aspect as early as possible. In effect, they highlight areas that designers should consider and provide information to guide design decisions in areas where designers may not have expertise.

Table 1 Purposes of DFX tools

Design for…	Purpose
Manufacture and assembly	Reduced production costs
Environment	Reduced environmental impact
End-of-life	Reduced environmental impact
Disassembly	Reduced disassembly cost/time (leading to reduced environmental impact)
Recycling	Greater recycling (leading to reduced environmental impact)
Quality	Greater user satisfaction
Maintainability	Reduced maintenance cost
Reliability	Reduced failure rate
Cost	Reduced cost
Affective design	Greater emotional satisfaction
Supply chain	Reduced supply chain costs
Inclusive design	Reduced design exclusion

Design, by definition, is purposeful: it is always undertaken for a reason, with a goal in mind. Designed objects therefore have both a *physical* nature and an *intentional* nature (Kroes 2002), and design is a process of generating a physical form to satisfy a given intent. These are not necessarily well defined, and different individuals may have different views on them, which can be source of conflict and miscommunication in design (Bucciarelli 1994). Traditionally, the *physical nature* of a product is taken to be its shape and substance, while its *intentional nature* is defined by the functions it performs. Concurrent engineering stems from the recognition that the physical and intentional natures of a product actually go beyond this.

Companies do not normally develop products to provide functions—rather, their goal is to make profit. This is influenced by much more than function, so the *intentional nature* of products increasingly includes aspects such as comfort, aesthetic appeal, cost and sustainability: all important selling points that designers need to be aware of. Similarly, there is a growing recognition that the *physical nature* of a product needs to account for all the impacts it has across its lifecycle, and not just its shape and form: manufacture, distribution, use and disposal must also be considered. Concurrent engineering requires that designers take a holistic view of the product, integrating *all* important phases of the product lifecycle, and *all* intentions for the product, to ensure that the information used in design decisions is as complete and as correct as possible. DFX techniques support this by highlighting virtues and lifephases whose implications designers should consider, and providing tools for doing so.

DFX techniques can be divided into two groups: those that optimise a product with respect to a particular virtue (cost, quality, usability, etc.), and those that optimise a product with respect to a particular phase of its lifecycle (manufacture, assembly, disposal, etc.) (Van Hemel and Keldmann 1996). These can be labelled DFX_{virtue} and $DFX_{lifephase}$, respectively: Table 2 summarises how the methods reviewed in Sect. 2 divide under these headings. Each group of DFX techniques serves a different purpose, provide different types of support and have a different relationship to the trade-offs needed in using multiple DFX techniques, as will be shown in the following sections.

Table 2 Examples of DFX_{virtue} and $DFX_{lifephase}$ techniques

DFX_{virtue}	$DFX_{lifephase}$
Design for environment	Design for manufacture and assembly
Design for quality	Design for end-of-life
Design for maintainability	Design for disassembly
Design for reliability	Design for recycling
Design for cost	Design for supply chain
Affective design	
Inclusive design	

DFX_{virtue} techniques do not dictate which virtues a product should possess, but provide ways of checking how well a design satisfies the given virtue. They help designers extend the product's intentional nature *beyond* functionality, to other issues important to consumers (comfort, cost, appearance, environmental friendliness etc.) and the needs of other stakeholders in the product.

$DFX_{lifephase}$ techniques help to ensure that the influence of the whole product lifecycle on the product's performance is considered for all the product's requirements. They help designers to extend their understanding of the product's *physical* nature beyond its shape and material, to thinking about every stage of its life. Designers need to understand the implications of their choices across the product lifecycle in two ways: firstly, how they will influence the choices made in subsequent lifephases; and secondly, how these subsequent choices will impact the performance of the product.

DFX techniques improve a design from their given point of view in two ways. The first is simple awareness raising: making designers aware of important virtues or lifephases that they may need to consider and might otherwise have been unaware of. However, the main assistance offered by DFX techniques is decision support: they provide designers with tools to help evaluate their designs from the given perspective. DFX_{virtue} and $DFX_{lifephase}$ techniques provide this support in different ways.

3.2 Type of support provided

The support provided by DFX techniques can be divided into four types: qualitative guidelines, metrics, feasibility

Table 3 Examples of support provided by different classes of DFX

Design for…	Support provided
Manufacture and assembly	Guidelines
	Feasibility check: manufacturing processes
	Feasibility check: assembly sequences
	Metrics: manufacturing and assembly costs
Environment	Guidelines
	Metric: environmental impact across lifecycle
End-of-life	Feasibility check: end-of-life options
	Metric: environmental impact of product end-of-life
Disassembly	Feasibility check: disassembly sequences
	Metric
	Disassembly cost/time
	Recovery value
Recycling	Guidelines
	Metrics: recyclability rating
Quality	Metric
	Priorities for engineering requirements based on customer requirements.
	Cost due to quality loss
	Benchmarking
Maintainability	Guidelines
	Metric: maintenance costs
Reliability	Guidelines
	Metric: estimated reliability
Cost	Metric: estimated cost
Affective design	Metric: affective responses
Supply chain	Feasibility check: supply chains
	Metrics: supply chain cost, quality, level of partnership, risk
Inclusive design	Guidelines
	Metric: design exclusion

checks and software that apply metrics or feasibility checks. Table 3 summarises the type of support provided by the DFX reviewed in Sect. 2.

Guidelines are qualitative, open to interpretation and often generic, but extremely flexible. Guidelines can be found for almost any virtue or lifephase and can be applied at any stage of the design process—although specific guidelines may only be useful at certain stages of design. Guidelines are able to support the generation of new designs by calling attention to features and properties that designers should be trying to include or avoid in their designs. They can also support evaluation by helping designers to identify pros and cons in their designs. However, the lack of a systematic method means that they have to be applied ad hoc and may be interpreted in different ways by different individuals. Equally, where guidelines conflict, there is no way of resolving trade-offs between them. For example, where DFM guidelines suggest a larger number of simpler components, and DFA suggests a smaller number of more complex components, the problem can only be resolved by estimating the cost of each approach. To make comparisons, it is necessary to have some way of measuring performance; hence the need for metrics.

Metrics are often associated with DFX techniques. For DFX_{virtue} techniques, they provide ways of measuring a design's performance against the given virtue. So, DFC tools provide cost estimates; DFE tools provide ways of estimating environmental impact; DFRel tools measure the likelihood of failure; DFMt tools estimate the cost of maintenance. Precise metrics may vary and different metrics may be applicable at different stages of the design process. In particular, it is very difficult to achieve an accurate estimate of performance when a design is only at its earliest stages. For this reason, metrics are often relative, rather than absolute—they provide a target to minimise, or a way of distinguishing the performance of two designs, or whether a given change is an "improvement".

While measuring performance is the heart of DFX_{virtue}, dealing with lifephases means estimating what is likely to happen at the given lifephase *as well* as measuring how this affects the performance of the design. This means working out what choices are feasible for the design at the given lifephase, and which is the most likely to occur (or the most desirable). Therefore, $DFX_{lifephase}$ techniques do two things. Firstly, they make the designers aware of, and encourage them to consider, the options available at the given lifephase. For example, in DFMA, feasible manufacturing processes and assembly sequences are identified; in design for end-of-life, the range of end-of-life options available is highlighted. This makes designers aware of the constraints their decisions place on later actors in the product lifecycle, so they can be aware of taking subsequent decisions by default. They also provide metrics for evaluating how desirable different outcomes are, normally by selecting a single virtue (for example, production cost in DFMA, environmental impact in DFEOL). In this way, they help designers to evaluate whether their designs are feasible (and acceptable) given their impact on the given lifephase. This allows an element of concurrency in product development, as it is possible to begin "locking in" later lifephase choices during the design process, and use these as constraints on subsequent design decisions.

Both DFX_{virtue} and $DFX_{lifephase}$ techniques can be supported by software, although this is often a way of automating the metrics and feasibility checks described earlier. Examples of this include cost estimation tools such as FIPER (Koonce et al. 2003), automatic assembly sequence generation and evaluation (Barnes et al. 2004) and the application of manufacturing constraints while generating a design in a CAD system (Abdalla 1998). This substantially reduces the effort involved in applying these techniques. Alternatively, software may also be used for simulation purposes, to establish reliability (Minehane et al. 2000), for example, or to validate manufacturing feasibility or identify potential manufacturing defects (Galantucci and Spina 2003).

DFX techniques, therefore, provide three types of support—qualitative guidelines, metrics and feasibility checks—which can be implemented through software. The next section will consider how this support fits into the design process.

3.3 Fit with the design process

To generate better designs, one must improve the two main activities that make up the design process: *definition* (generating ideas) and *evaluation* (determining which designs are acceptable, and/or most promising) (Sim and Duffy 2003). Design tools tend to fall into three categories: those that try to generate better ideas, those that try to provide more accurate evaluations and those that try to use feedback from evaluation to generate better ideas.

Supporting definition is a proactive use of DFX, as it takes place before designs are evaluated. However, few DfX methods provide formal support for the synthesis of designs: after all, there are few formal methods for generating designs in the first place. The most common way of supporting definition is to provide qualitative guidelines, specifying properties to be sought or avoided when defining designs. Some computer-aided systems use knowledge about these features to generate designs that conform to a brand identity (Chau 2002) or provide a particular emotional response (Nagamachi 2002). Of course, if the implications of the lifephase or virtue in question are not reflected in evaluation, then the improved design may not be recognised as such. For example, a more expensive yet more aesthetically pleasing design may be rejected if its evaluation considers cost, but not aesthetic appeal. Equally, where the recommendations of different DFX conflict, there is no way of deciding which should take precedence, without evaluating the proposed changes, to see which offers the greater benefit. Therefore, even where a DFX technique is used to improve the definition of a design, it is still important to think about its evaluation.

Most DFX techniques are reactive, reviewing and critiquing an existing design, and therefore supporting *evaluation* activities in the design process. To evaluate a design, it is necessary to make judgements in terms of *fact* (what is the case, and how the world behaves) and *value* (what is desirable or undesirable) (Vickers 1965; cited in Checkland and Casar 1986). To support evaluation, one must improve the accuracy of these judgements. DFX techniques do this by helping designers to determine the expected behaviour of their designs and to relate this behaviour to a particular performance characteristic. However, evaluation is limited to identifying the best of the available designs—no amount of evaluation will improve a bad design, without using the feedback to change its definition.

Many DFX techniques that support definition use the results of evaluation to explore alterations and improvements to designs *before* making any decisions about which to pursue. This creates a cycle of definition, evaluation and redefinition. The Lucas DFA approach (Lucas Engineering Systems Ltd. 1993), for example, uses nine questions to analyse a design and suggesting ways of reducing its number of parts by eliminating or combining components. Some computer-aided systems take a similar approach, analysing the design and flagging up problems while designers are generating it on a CAD System (Abdalla 1998; Brissaud and Tichkiewitch 2000; Barnes et al. 2004). This helps to improve the overall quality of designs and provides a level of structure that is not normally possible when generating designs with more qualitative support. As with methods that only support definition, it is necessary to reflect the relevant lifephases and virtues in downstream evaluation, to ensure that revised designs are not rejected later on.

Each of the DFX techniques described in Sect. 2 have been developed individually, the developers' goal being to develop a technique that can analyse the particular design from the specific point of view. This decomposition into separate viewpoints is necessary in developing these techniques: each DFX has its own complexities and requires substantial research as an underpinning. To develop a single technique that analysed a design from every possible point of view would be cumbersome to develop and extremely complex to apply. However, to apply DFX techniques in practice, their findings must be related to other analyses—including other DFX—to give a holistic view of a product's performance.

3.4 Applying multiple DFX

As each DFX technique evaluates and improves a design from just one perspective, applying one in isolation works *counter* to the purpose of concurrent engineering. With no reference to the wider purpose of the product being designed, each DFX tool restricts the designers' view to a single aspect of the product's intentional and physical nature. This makes their view of the product being designed *less*, rather than more, holistic and raises the possibility of false economies being made. A product optimised to be cheap for manufacture is useless if it no longer appeals to its target customers: the results of applying a DFX tool must be considered against the purpose of the product as a whole. This section examines the issue of applying multiple DFX and linking them to the intentional nature of the product being designed.

Developers of DFX techniques recognise that their tools should not be applied in isolation: the links between DFX techniques simply fall outside the scope of their work. DFX techniques are developed using a reductionist, bottom-up approach, starting with the needs of the specific virtue or lifephase, and working out how these can be addressed in the design process. Efforts at developing an integrated approach for applying multiple DFX techniques have been limited. Huang (1996) suggests restricting attention to between 5 and 9 of the most important DFX for the particular project. This limits the complexity of the problem, but does not discuss how the DFX can be linked. Watson et al. (1996) propose a system for ranking DFX guidelines using a House of Quality style matrix, weighting each guidelines according to its importance and how it contradicts or supports other important guidelines. These approaches are also bottom-up, starting from the DFX techniques, and trying to link them to each other and the design process. They do not address the larger problem of relating choices to the intentional nature of the product as a whole.

All design decisions should be value-focussed (Keeney 1992): driven by the intentions that initiated the project. While DFX_{virtue} helps to expand designers' view of the intentional nature beyond function, not every aspect of the intentional nature necessarily has a DFX technique to represent it. Just as applying one DFX in isolation goes against the purpose of concurrent engineering, so does restricting attention to *only* those virtues and lifephases that have associated DFX techniques. Also, whether the changes suggested by even a single DFX represent an actual improvement will depend upon the overall intentional nature of the design. This is true regardless of how many, or how few, DFX techniques are applied: even down to a single guideline. The problem is not how multiple DFX can be used together—but how DFX techniques can be related to the intentional nature of the product. This requires a top–down approach: starting from the needs of design decision-making, and identifying how DFX techniques can support this.

Furthermore, different techniques provide different types of support: in Sect. 3.2, it was identified that DFX provide guidelines, feasibility checks and metrics, and sometimes embody these as software. The challenge in linking multiple DFX to each other and to the intentional nature of a product is how these different types of support can be compared. For feasibility checks, there is no problem: they indicate what is possible, and the choices necessary at subsequent lifephases if the design as currently envisaged is to be used. They say nothing about how well a design performs. Metrics and guidelines, however, have an element of performance measurement; directly, in the case of metrics, and implicitly in the case of guidelines, which suggest improvements. While designs can be compared based on a single metric or guideline, the difficulty is in comparing them against *multiple* metrics or guidelines: how does one decide the net benefit of a given score on a metric, or implementing a given guideline? Also, where different DFX use metrics to compare the same attribute (cost, for example), are these estimates actually comparable? Can costs estimated from Swift and Booker's Design Costing Methodology (Swift and Booker 2003) be compared with estimates from Fiper (Koonce et al. 2003)? In order to relate the metrics and guidelines supplied by different DFX techniques to the product's intentional nature, some way of evaluating trade-offs between them must be found.

4 Trade-offs in DFX

This section examines the importance of trade-offs in DFX and the difficulties in making them. The first part discusses the need for trade-offs in DFX and the differences between $DFX_{lifephase}$ and DFX_{virtue} techniques when it comes to making trade-offs. The second discusses the issue of preferences, which are necessary to make trade-offs, but not easily obtained in engineering design. Trade-offs are the domain of decision research, and the section closes by discussing lessons from that field for the development and application of DFX techniques.

4.1 The importance of trade-offs in DFX

Trade-offs are an inherent part of engineering: real products can rarely achieve the ideal goals of their developers, and compromise is often necessary. To make an object stronger may mean increasing its weight, using more expensive materials, or both. Extra functions may make a product more expensive and harder to maintain. Without the need for trade-offs, each DFX technique could be applied in isolation, safe in the knowledge that it would improve the design without reducing its performance in other areas. In practice, as concurrent engineering aims to provide a more complete view of the physical and intentional natures of the products being developed, it increases the number of competing goals to be considered. This then increases the number and complexity of the trade-offs that need to be made. Because each DFX technique is independent, applying one in isolation can lead to false economies, but *how* these different DFX should be related is still an open research issue (Horváth 2004). This raises the difficult questions of how trade-offs should be evaluated, and what makes a design “better”.

DFX_{virtue} and $DFX_{lifephase}$ techniques have different relationships with the trade-offs that need to be made in design. By definition, trade-offs can only occur between virtues: a trade-off exists because one benefit must be given up to achieve another. Trade-offs between the virtues measured by DFX_{virtue} techniques can be made directly: the difficulty is in determining how much of each virtue is equivalent. Conversely, trade-offs cannot be made between lifephases directly: one does not give up a certain amount of manufacturing to gain a certain amount of assembly. Trade-offs can only be made between lifephases when they have different effects on a given virtue. For example, one may increase manufacturing costs to reduce assembly costs by a greater amount—a net reduction in cost. Such trade-offs are trivial: one simply selects the option that offers the greatest benefit over all the relevant lifephases. The difficulty is in ensuring that estimates of the same virtue from different $DFX_{lifephase}$ techniques are comparable.

To be a complete picture of the intentional and physical natures, however, virtues must be assessed across the whole product lifecycle, and lifephases against every important virtue for the product, as illustrated in Fig. 1. In principle, this means that evaluation should encompass all lifephases and virtues that are relevant to the product: not just those for which DFX are available. In practice, resources for evaluation are limited, and there needs to be some way of determining which will be prioritised.

This also raises the problem of different lifephases having different effects on competing virtues—for example, where more environmentally friendly disposal means increasing the cost of manufacture. As long as the effect of each lifephase on each virtue can be estimated, this reduces to the problem of making trade-offs between virtues.

Evaluating trade-offs is critical to the holistic view required by concurrent engineering: raising designers' awareness of the trade-offs they are making, and determining what is best for the product as a whole. This makes evaluating trade-offs the key to linking DFX to the wider problem of the intentional nature, regardless of whether

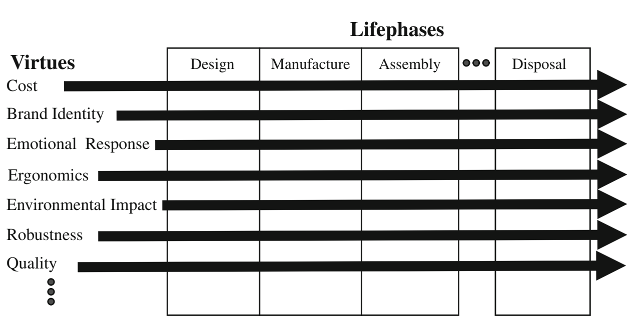

Fig. 1 Virtues must be assessed across all product lifephases

one or many are applied. Trade-offs imply decision-making—trading off the benefits of one option against another. Both are integral to the design process, whether deciding which ideas to pursue, or deciding whether the cost of revising a design is worth the potential benefits. Relating DFX to a product's intentional nature means linking them to the general issue of design decision-making, using them to inform and expand design decisions, rather than treating them separately. This means exploring the relationship between DFX and an area inherent to decision-making, but not normally considered in this context: preferences.

4.2 Preferences in DFX

Any decision has three elements: *options* to choose from, *expectations* about the outcomes of choosing each option, and *preferences* indicating what is desirable or undesirable in the decision's outcome. Both $DFX_{lifephase}$ and DFX_{virtue} techniques help to provide complete and correct expectations—identifying how design decisions affect those made downstream and estimating performance against relevant virtues. However, they do not say anything about preference, which is necessary if trade-offs are to be evaluated.

In design, preferences would indicate which virtues are desirable in the product: which properties should be present or absent, and which are most or least important. They also indicate equivalence: how much gain against one virtue is necessary to compensate for a given loss against another. Without preferences, evaluation is unnecessary: all options are equally good, and decisions become trivial. This section considers the problem of preferences in engineering design, and their importance for DFX and design evaluation.

If design is to be value-focused, then the only basis for preference should be the intentional nature of the product: the purpose that initiated product development. It is therefore important that the tools used in design do not impose preferences on the designer artificially. For example, a tool that guides a designer to choose the cheapest design will lead to false economies if this means compromising critical functions of the design. Equally, the intentional nature of the product should define which virtues are considered: it is important that DFX techniques are not imposed, but applied because they are relevant. This is true for any design tool which, if followed without due care, can impose its own preference structure on the user (Olewnik and Lewis 2005).

However, establishing preferences in design is not trivial, and presents a number of difficulties. Firstly, preferences are normally personal and subjective, individual value judgements that cannot be empirically verified. Secondly, design is driven not by the personal preferences of the designers (although these may play a role in practice), but by company strategy, needs and values. Most design projects have many stakeholders, whose preferences may conflict and may be difficult to elicit, so whose views take precedence? Even with a single, clearly defined customer driving the design process, their intentions and preferences may not be well formulated, well communicated, or easy to express. The problem of capturing and communicating intent and preference is inherent to design as a whole, and not specific to DFX. As a result, the intentional nature of a product is often drawn up as a formal requirements' specification, and requirements' management practices have developed (McKay et al. 2000) to help trace and communicate requirements throughout product development.

Requirement's specifications state which virtues are important, provide target values, and may indicate which are mandatory and which are desirable, but not essential. They provide imposed or agreed structures to guide design decisions, but do not capture other elements of preference, such as the relative priorities of different virtues and equivalences between them, which are necessary to evaluate trade-offs. This is the domain of decision theory, an area which has been explored in design, but not in the context of design for X techniques.

4.3 Decision research and DFX

The importance of trade-offs in decision-making means that they have received considerable attention in the literature, and a range of methods for evaluating options against conflicting preferences has been developed. These are normally termed multi-criteria decision-making (MCDM) techniques, and range from complex mathematical processes such as multi-attribute utility theory (MAUT) (Keeney and Raiffa 1976), to simpler quantitative approaches such as the analytic hierarchy process (Saaty 1980) or SMART (Edwards 1977), to extremely simple "fast and frugal" approaches (Gigerenzer et al. 1999). Simple variants of these methods have long been advocated by design methodologists (Pahl and Beitz 1996; Pugh 1990), and attention has also been given to the use of more complex techniques such as MAUT in design (Hazelrigg 1998; Thurston 2001; Fernández et al. 2005). There is no consensus on which method is "best". MAUT is generally accepted as the normative "gold standard" in MCDM, but is often regarded as too complex to be of value in practical decision-making (Edwards 1992).

Edwards and von Winterfeldt (1986) argue that the question is irrelevant, because of the *principle of the flat maximum*. This states that there is a limit to how precise any MCDM algorithm can be, especially given the difficulty in verifying that the data fed into them are correct. Instead, they argue that alternatives are either so similar in performance that it doesn't matter which is chosen, or so different that even a simple technique can separate them. All decision makers are subject to *bounded rationality* (Simon 1957): there is a limit to how much information can actually be gathered and considered, so any technique will end up working with incomplete information, regardless of its mathematical rigour. The real benefit comes from the systematic approach that these techniques provide to compare alternatives against criteria, which help avoid errors or oversights.

A particular difficulty in evaluating preferences and trade-offs mathematically is Arrow's impossibility theorem (AIT) (Arrow 1973), which demonstrates that there is no rational way of equitably combining the preferences of multiple individuals. This has serious implications for design, particularly in concurrent engineering, where the preferences of many stakeholders need to be considered. Hazelrigg (1996) identifies this as the source of all sub-optimal design, and a serious problem for any technique that tries to aggregate the preferences of multiple stakeholders. Conversely, Scott and Antonsson (1999) argue that AIT does not apply to design, where equity is irrelevant, because designers work to an imposed requirement specification. However, as noted in Sect. 4.2, it is rare for requirements' specifications to provide the detailed preference information needed by decision algorithms. Franssen (2005) goes further, using AIT to demonstrate that there is no general mathematical solution to multi-criteria decision-making. Every MCDM technique has its limitations—all designers can do is be aware of these limitations, and select the algorithm best suited to their situation. Philips (Phillips 1984) argues that MCDM is not about uncovering the finely tuned preferences of decision makers but that it should be used to build a shared preference model that all stakeholders are willing to subscribe to. Whether the model is a "true" reflection of preference or not is irrelevant, as long as the stakeholders agree that it is acceptable.

For these reasons, the best decision-making is generally adaptive (Payne et al. 1993), matching the technique chosen to the resources available, and the level of risk in the given decision. How one determines the best algorithm for a given decision is still an open question. In practice, design decision-making is often complicated by practicalities, including time pressure, uncertain information and distributed decision-making that complicate the issue of gathering preferences, regardless of the mathematical technique adopted. In contrast to the prescriptive research on design decisions (Thurston 2001; Fernández et al. 2005), there has been little descriptive research on design decision-making processes. The approaches actually adopted by designers, the limitations on their time and the methods they feel most comfortable with, need to be investigated to provide a practical balance to the mathematical theory.

The mathematics of trade-offs is only part of MCDM: these methods also provide benefits by encouraging a systematic approach to evaluation, making sure that decision makers have considered all the important issues. Indeed, some methods—such as ProACT (Hammond et al. 1999)—remove the mathematical component entirely and focus just on the structure. It is the insights, rather than the numbers generated from the analysis that are most beneficial (Phillips 1984; Edwards and Von Winterfeldt 1986). Regardless of which algorithm—if any—is selected, this structured process itself could provide a basis for systematically linking DFX to the intentional nature of the product. This could be done in two ways. Firstly, where a change is proposed by a DFX technique that supports definition (see Sect. 3.3), this change could be evaluated using an MCDM technique against all the relevant virtues for the product, to see if it provided an overall benefit. Alternatively, the outputs of DFX techniques supporting evaluation (again, see Sect. 3.3) could be linked to the design evaluation process, where a selection of designs is evaluated using MCDM techniques. In this case, the output of the DFX techniques would help to ensure that the relevant virtues and lifephases were reflected in the evaluation. To adopt these approaches, there is a need to look at the structure of MCDM and DFX techniques to see if, and how, they can be used together.

5 An agenda for decision-based DFX research

This paper has applied the holistic view of product development encouraged by concurrent engineering to DFX techniques. Most DFX literature is inherently reductionistic as shown in Sect. 2, picking out a single virtue or lifephase of a product and addressing it in detail. If DFX techniques are to support concurrent engineering, then they must be integrated into the holistic view it encourages. This paper has used the dual nature of technical artefacts (Kroes 2002) to explore this holistic view, and highlighted the importance of evaluation, trade-offs and decision-making in relating it to DFX techniques. This leads to a number of important conclusions highlighting the importance of decision-making to DFX and concurrent engineering and suggests a number of new avenues for future research.

5.1 Conclusions: the need for decision-based DFX research

Concurrent engineering is, by definition, a holistic approach to product development. It goes beyond merely overlapping stages of product development, encouraging consideration of all important aspects of a design throughout its development. Although DFX techniques are intended to support concurrent engineering, each focuses on an individual aspect of the product, and there has been little work on how the two actually link together. This paper has applied the holistic perspective of concurrent engineering to DFX techniques, and this leads to five important conclusions:

1. *The goal of concurrent engineering is to take as complete a view of a product's physical and intentional natures as possible when making decisions.* It follows from this that all design decisions should be based on the *intentional nature* of the product, and the implications of all lifephases for this intent should be considered. Of course, in practice, *bounded rationality* applies: resources are limited, and some limits must be placed on the level of detail in analysis.
2. *Applying any DFX technique in isolation goes against the concurrent engineering philosophy that they are intended to support.* This means more than just finding ways of relating different DFX to each other. To be consistent with the concurrent engineering philosophy, they must be linked to the physical and intentional natures as a whole, including to virtues and lifephases that are not represented by DFX.
3. *To properly evaluate trade-offs, the intentional nature must include preference information, which is not normally captured in the design process.* Requirements' specifications capture some, but not all, of this information. Preferences should not be imposed by the design tools chosen, and this includes DFX techniques—rather, the overall preferences, encapsulated as the intentional nature of the product, should drive the choice of DFX techniques.
4. *Different DFX provide different types of support and apply at different stages of the design process, complicating the process of relating them.* In particular, $\text{DFX}_{\text{virtue}}$ and $\text{DFX}_{\text{lifephase}}$ techniques relate to the issue of preferences and trade-offs in different ways.
5. *Relevant virtues and lifephases must be reflected in every relevant design decision, not treated as a separate stage of the design process.* The benefits achievable through DFX are limited if they are only applied at one stage of design: ideally, all relevant virtues and lifephases would be reflected throughout product development.

These points highlight the importance of design decisions in concurrent engineering and, as tools supporting this approach, DFX techniques must be linked to broader design decision-making. However, current DFX techniques provide information to guide decisions, a process known as decision support, but do not say *how* that information should be used in a wider decision-making context. If DFX techniques are to reflect the holistic nature of concurrent engineering, then future research must address their links with design decision-making, a topic that has yet to be explored.

5.2 New directions for future DFX research

There are many lessons from decision research that can be applied to DFX, and this suggests an agenda for future decision-based DFX research. Future research will need to cover both normative issues, concerned with the theoretical logic of decision-making, and descriptive issues, concerned with its practicalities. If DFX techniques are to conform to concurrent engineering's holistic view of product development, then four areas need to be addressed:

1. *Logical coherence between DFX and MCDM*: The cornerstone of formal decision-making is coherence, being consistent with a set of principles: even simple MCDM algorithms have a set of underpinning assumptions. It is important that design tools do not introduce logical inconsistencies into design decisions (Olewnik and Lewis 2005). There is therefore a need to investigate the relationship between the support provided by DFX techniques and MCDM algorithms, to see if they can be used together coherently. As different DFX techniques provide different types of support and different MCDM algorithms have different underlying axioms, it may be due to that some combinations are coherent, while others are not.
2. *Capture and representation of preference information*: Preference information is essential to evaluating tradeoffs and capturing the intentional nature: but this is not normally represented by current requirements' management practices. There is a need for research to address how preferences in design can be represented and amalgamated. Whose views count, and how should differences of opinion or conflicting stakeholder needs be reconciled? Arrow's impossibility theorem has already been addressed in engineering design literature, but how suitable are methods that circumvent this, such as game theory (Vincent 1983) or decision conferencing (Phillips 1984)?
3. *Decision-making practice*: As yet, descriptive literature on design decision-making has been less abundant than literature on normative aspects, such as the mathematics of decision algorithms. However, if decision-making is to be adaptive, then there is a need to look at how designers make decisions in practice, and the practical constraints on their evaluations. What decisions are taken, and who is responsible? What resources are available, and what strategies do designers use for making choices? How much does this vary within and between organisations? Is there an underlying taxonomy of design decisions, or are they unique to a given design process, or even a given individual? Which MCDM techniques are most appropriate at different stages of design? Are formal decision algorithms compatible with current design practices?
4. *Prioritising DFX and other sources of decision-support*: Given the limitations on resources for evaluation in practice, it is important to look at how designers can prioritise which virtues and lifephases they will consider in a given decision. Are some virtues and lifephases more affected by certain stages of product development? Does linking more virtues and lifephases into the decision-making process simply create information overload? Can automation of DFX analyses, such as software implementations, ease the burden? Or does it reduce designers' confidence in the information they receive?

Applying the holistic view of concurrent engineering to DFX techniques has highlighted their relationship to the decision-making process, which suggests a new way of looking at these techniques. Traditionally, they have been developed using a bottom-up process, starting from the needs of the specific virtue or lifephase that they address, and presenting this information to the designer. This paper advocates a top–down approach: considering the needs of design decision-making in concurrent engineering, and looking at how DFX techniques can provide this information. The research agenda set out earlier provides a basis for developing this approach and a new generation of DFX techniques that integrates coherently to support the holistic view encouraged by concurrent engineering.

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