Integrating Product and Process Design through Decision Analysis

by
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The candidate confirms that the work submitted is his/her own and that appropriate credit has been given where reference has been made to the work of others.

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Abstract

With fast moving markets and increasingly global competition, companies now recognise that every aspect of a product, through its development and beyond, must be considered when making design decisions. Design for X tools are a popular way of doing this, providing information on how design choices affect subsequent lifephases or important virtues of the product. However, each DfX tool imposes a preference structure on the designers by giving precedence to a single virtue or lifephase, and offering no way of reconciling trade-offs with others. This thesis demonstrates that decision analysis – a technique for evaluating alternatives against conflicting objectives – can resolve this problem by incorporating DfX information in design decisions without imposing a preference structure.

As many DfX techniques are available, attention is restricted to the context of integrated product and process design, where design decisions include the implications of manufacturing. Eight characteristics are proposed, taken from concurrent engineering principles and decision analysis, for successful integrated product and process design decisions. A relationship is shown to exist between DfX and decision analysis, and this relationship is embodied as a methodology for decision-making in integrated product and process design. Three Design Experiments and two Case Studies demonstrate that this methodology is feasible, and exhibits the desired characteristics in practice.

Further work is necessary to determine whether these findings generalise to other DfX and whether this is an appropriate method of combination. Then future DfX tools could be developed based on decision analysis principles that can analyse designs systematically against multiple virtues and lifephases. By demonstrating the relationship between Design for X and decision analysis, and showing that it can be used in practice, this thesis provides the first step along this path.

Abbreviations

A number of abbreviations and acronyms are used throughout this thesis. Although they are introduced the first time they are used in the text, for ease of reference, their meanings are given here:

AHP	The Analytic Hierarchy Process
AIT	Arrow's Impossibility Theorem
DfA	Design for Assembly
DfM	Design for Manufacture
DfMA	Design for Manufacture and Assembly
DfX	Design for X
$DfX_{lifephase}$	Design for Lifephase
DfX_{virtue}	Design for Virtue
ELECTRE	Elimination Et Choix Traduisant la Réalité
IPPD	Integrated product and process design.
M	Mandatory
MCDM	Multi-Criteria Decision-Making
PD	Process Dependent
PI	Process Independent
PRIMA	Process Information Map
QFD	Quality Function Deployment
SMART	Simple Multi-Attribute Ratıng Technique
vN-M	von Neumann-Morgenstern

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Chapter 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 tools that can help them systematically structure and manage the competing needs of a product across its lifecycle. This thesis argues that the field of "decision analysis" provides a set of tools that meet this need and deserve a place in the body of concurrent engineering techniques. This thesis specifically addresses a subset of concurrent engineering known as "integrated product and process design" (IPPD) – considering the implications of choices for manufacture when making design decisions. However, it will also be shown that the principles set out here could be extended to the other aspects of product development considered by concurrent engineering.

This chapter is a map of the thesis. The first half defines where the research begins, by positioning it relative to current work in the field. **Section 1.1** examines the meaning of concurrent engineering, the business drivers behind it and techniques for its implementation. **Section 1.2** highlights the importance of decision-making in design, its relevance to concurrent engineering in particular, and the application of decision analysis techniques to design problems. The second half of the chapter defines where the research goes, the contribution it makes to the field of concurrent engineering, and the steps required to get there. **Section 1.3** sets out the focus and scope of this thesis, and the research question it answers. **Section 1.4** provides an overview of the remaining chapters, and their relevance to the question posed. This chapter introduces the shape and purpose of the thesis, setting the scene for the work that follows.

1.1 Concurrent Engineering

Research never takes place in a vacuum, and it is important to understand how this thesis fits in with existing work on concurrent engineering. The term "concurrent engineering" itself is often used in different ways in different contexts, making it even more important to be clear on how it is being used here. This section

is divided into two halves. The first defines what concurrent engineering means in this thesis, and the reasons for carrying out research in this area. The second discusses the tools currently available for putting the concurrent engineering philosophy into practice.

1.1.1 The Concurrent Engineering Philosophy

Manufacturers across the world have to adapt to the increase in global competition – particularly from countries such as China and India. There is the constant threat of low-cost competition, forcing companies to keep their costs down without compromising quality (Rajagopal, 2003). Successful companies are those most able to move quickly into new product areas, and react quickly to market changes (Bentley, 2003), driving companies to shorten their product development time. Methods that were once a source of competitive advantage are becoming necessary for survival. Concurrent engineering is one response to the growing need for more efficient development, though its roots go back to the earliest stages of mass production.

The philosophy behind concurrent engineering has been used by successful designers and engineers for more than a century. The Second World War gave the first instances of industries deliberately adopting a concurrent approach (Ziemke and Spann, 1998), but the principles were also evident in the early work of Ford (Jo *et al.*, 1993), and Eli Whitney (Bralla, 1999). As organisations grew, they tended to divide into specialised departments, each responsible for one aspect of product development, passing work "over the wall" to one another without much additional communication. Designers – responsible for the shape and substance of a design – might not worry about manufacturing cost, but the choices they make constrain what production engineers can do. In fact, although design only accounts for a fraction of the money spent in product development, its choices commit most of the overall cost (Miles and Swift, 1997), as illustrated in Figure 1. Feedback from later stages is not received until the design has been completed and handed on, so designs are sometimes handed back and changed several times before being accepted. Such late changes are expensive, and often lead to huge delays, accounting for as much as 50% of development time (Ford and Sterman, 2003; Miles and Swift, 1997). The goal of concurrent engineering is to identify downstream problems during design, so they can be corrected when change is more straightforward, and less work needs to be repeated.

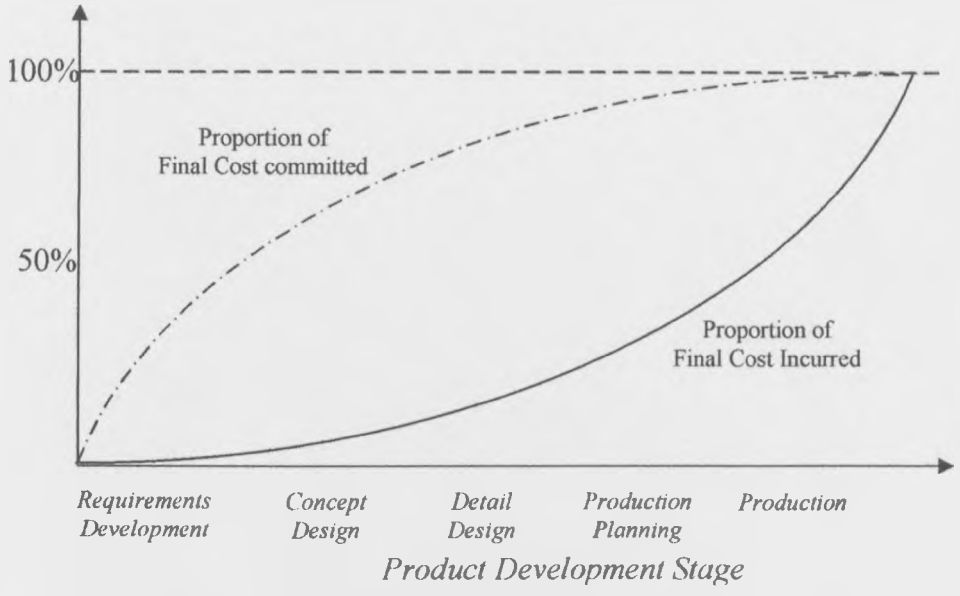

Figure 1: Costs incurred and committed as product development progresses

The term concurrent engineering is not well-defined, and is used in slightly different ways by different people. The terms lifecycle engineering, simultaneous engineering, collaborative engineering, and integrated product and process design are sometimes used interchangeably with concurrent engineering, and are sometimes given a different meaning. For the purpose of this thesis, the definition cited by Carter and Stillwell-Baker from the USA's Institute for Defense Analysis will be accepted:

> "Concurrent Engineering is a systematic approach to the integrated, concurrent design of products and their related processes, including manufacture and support. This approach is intended to cause the developers, from the outset, to consider all elements of the product life cycle from concept through disposal, including quality, cost, schedule and user requirements" (Carter and Stillwell-Baker, 1992)

By contrast, integrated product and process design will be taken to mean considering the implications of manufacturing during product design. Concurrent engineering describes an approach to product development rather than a technique in its own right. This approach has three elements (Koufteros *et al.*, 2001):

- **Concurrent Workflow:** Overlapping the stages of product development, to reduce the overall time needed to bring a product to market (see Figure 2);
- **Cross-functional product development teams:** Bringing together experts from all stages of product development to take design decisions, enhancing communication between development stages; and
- **Early involvement of constituents:** Considering every phase of the product lifecycle from the earliest stages of design.

This increases the time and effort required in design, but pays off by reducing the number of difficult and more time-consuming changes later in the project.

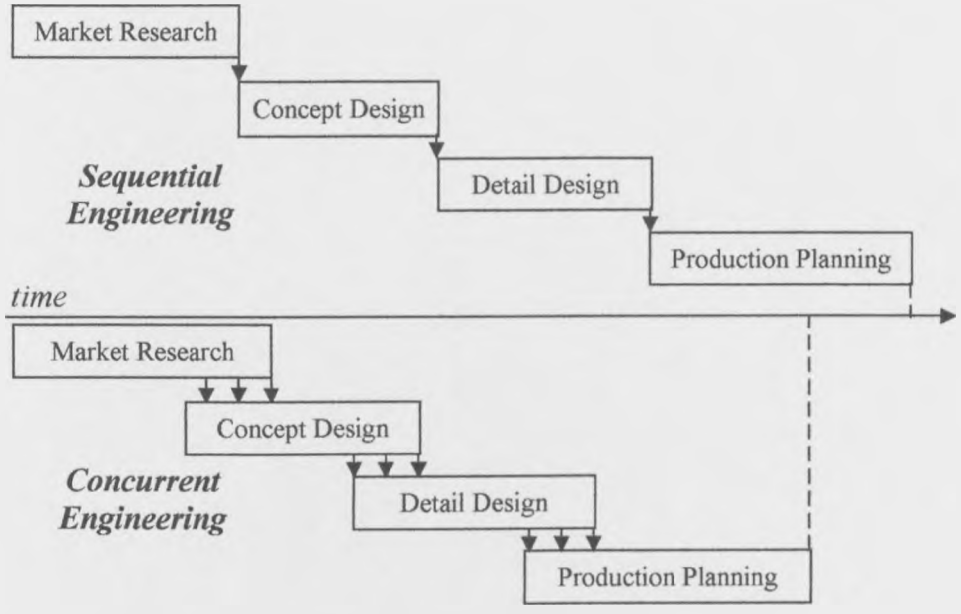

Figure 2: Contrast between concurrent and sequential engineering

There are many industrial examples of the benefits concurrent engineering can offer. Cincinnati Milacron UK, for example, reported a 75% reduction in product development time, and a 55% increase in margins, despite a 40-60% reduction in selling price after introducing concurrent engineering (Scarlett, 1996). Applications of formal Design for Manufacture and Assembly (DfMA) methods have lead to assembly cost savings of 43-48% across a number of sectors (Swift and Brown, 2003). Concurrent engineering has also been linked with high levels of product innovation, leading to improved quality and premium pricing (Koufteros *et al.* 2001). Despite these positive results, concurrent engineering is no panacea.

Concurrent engineering carries risks if not implemented properly. Concurrent workflows increase the danger of basing decisions on immature information which is *more* likely to change, and increase the amount of work needed if late changes do occur (Handfield, 1994; Shalia *et al* 1995; Krishnan, 1996; Ford and Sterman, 2003). There is evidence that just overlapping stages of development rarely offers significant benefits, as it does not prevent poor choices being made in the first place (Verganti, 1998). The consideration of all lifephases from the start of product development increases the complexity of the decisions to be taken, increasing the time and effort needed for analysis. Care must be taken to match the methods and tools used to implement concurrent engineering to the business environment where it takes place.

Methods for implementing concurrent engineering can be divided into three levels (Brookes and Backhouse, 1997). At the *objectives* level, the fundamental

goals and structure of an organisation are addressed – implementing concurrent engineering through business process reengineering, for example. At the *strategic* level, the arrangement of activities in the development of a particular product are considered – overlapping development stages, for example, or handing information over earlier. At the *tactical* level, specific tools for carrying out tasks are considered – DfMA, cross-functional development teams, Quality Function Deployment, and so forth. Although all three levels are important in implementing concurrent engineering, this thesis focuses exclusively on the tactical level and specific implementation tools.

1.1.2 Tactics for Concurrent Engineering

A huge number of techniques are available for implementing concurrent engineering, addressing different aspects of the product development process. Some are on the border between the tactical and strategic levels, providing tools for arranging and co-ordinating product development activities to minimise the risk of redesign while maximising concurrent workflow (Ainscough *et al.*, 2003; Ostrosi *et al.*, 2003; Poveda *et al.* 2003). Cross-functional development teams are a popular way of implementing concurrent engineering, and methods are available for determining their composition and responsibilities (Kusar *et al.*, 2004; Dong *et al.*, 2004; Starbek and Grum, 2002). The global nature of many organisations means that product development is geographically distributed, making it difficult for such teams to meet. To overcome this, a variety of computer-based tools that allow collaboration over the internet (Li *et al.*, 2004; Nahm and Ishikawa, 2004; Sun and Gramoll, 2002) or dynamic data sharing between distributed engineers (Noel and Brissaud, 2003; Bai *et al.* 2004) have been proposed. These techniques address the first two elements of concurrent engineering: concurrent workflow and cross-functional development teams. This thesis, however, will concentrate on techniques that help designers address the third element – considering the whole product lifecycle from the earliest stages of design.

These are typically referred to as Design for X techniques, where 'X' denotes a particular issue that the method will help to address in the design phase. These can be divided into *virtues* – desirable characteristics that the product should exhibit – and *lifephases* that should be considered (van Hemel and Keldmann, 1996). The earliest of these were Design for Manufacture and Assembly, but the field has since expanded to include issues such as disassembly, environmental impact and quality (Kuo *et al.*, 2001). Recent pressures have also led to the consideration of brand identity (Chau, 2002), and even the emotional responses of consumers (Jordan, 2000). Table 1 summarises some of the important virtues and lifephases that need to

be considered in design. Of course, the exact virtues and lifephases that are relevant will vary from one product to another.

Table 1: Virtues and lifephases to be considered in design

Virtues	Lifephases
Brand Identity (Chau, 2002)	Manufacture (Bralla, 1999)
Cost (Roy, 2003)	Assembly (Boothroyd *et al.* 2002)
Emotional Response (Jordan, 2000)	Supply Chain (Rungtusanatham and Forza, 2005)
Environmental Impact (Veroutis & Fava, 1996)	
Ergonomics (Bubb, 2003)	Maintenance (Slavila *et al.* 2004)
Reliability (Edson & Tian, 2004)	Disassembly (Desai & Mital, 2002)
Universal Design (Beecher & Paquet, 2005)	Disposal/Recycling (Rose *et al.* 2002)

DfX techniques provide designers with information about factors affecting the relevant virtue or lifephase. One of the most basic ways of doing this is through a set of guidelines for "good practice" from the given perspective. Table 2 gives examples from the literature.

Table 2: Sample Design for X guidelines

Design for...	Sample Guidelines	Source
Assembly	• Design symmetrical components wherever possible. • If symmetry cannot be achieved, make sure marked asymmetry is present, artificially if necessary. • Provide location features on parts to facilitate assembly.	Miles and Swift (1997)
Manufacturing	• Avoid the use of undercuts where possible. • Use the widest possible tolerances and finishes on components. • Fillets should be used at corners wherever possible. • Develop the design to contain as many identical components as possible	Edwards (2002)
Maintenance	• Minimise the need for special tools. • Part reference designations shall be located next to each part legibly and permanently. • Mount heavy units as low as possible. • Provide clearance around connectors to provide adequate viewing and hand access.	Kuo, *et al.* (2001)

While these guidelines prompt designers to consider important issues, they are often too generic to be very useful. This has lead to the development of more formal DfX methodologies, such as QFD in Design for Quality (Ako, 1990), or the Boothroyd-Dewhurst technique (Boothroyd *et al.* 2002) and CSC DFA/MA methods (Dalgliesh *et al.* 2000) in DfMA. There have also been efforts to develop software systems that will help to perform DfX analysis. These include systems that apply lifecycle constraints (Abdalla, 1998), Design for Assembly (DfA) guidance (Barnes *et al.* 2004) or Design for Manufacture (DfM) guidance (Howard and Lewis, 2003) as a design is generated. These all provide useful information, but none fully address

the complicated situation facing a designer who must consider multiple virtues and lifephases.

The lack of definite information in the early stages of design is a particular problem when applying these techniques. Most DfX analyses can only be applied once the design is almost complete, and software systems often rely on having a design detailed enough to be entered on a CAD package. These methods are therefore reactive, identifying problems in a near-complete design, so that it can be revised. This is still beneficial – even late in design it is better to catch problems before subsequent stages begin – but it would be better to identify problems as early as possible. Finding ways of making these methods more proactive, so that they can be used to identify problems earlier in the design process, is a high priority in current research (Swift and Brown, 2003). This is not the only limitation of existing DfX techniques.

Each addresses only one virtue or lifephase, imposing its own preference structure on the design process, and offering no way of knowing which should take precedence when different techniques conflict. Just applying one perspective can lead to false economies. Boothroyd *et al.* (2002, pg3) give the example of separating a complex component into an assembly of simpler components. This reduces the total cost of manufacture, but the saving is outweighed by the increased cost of assembly. DfMA methodologies address this by estimating manufacture *and* assembly costs, so that trade-offs can be quantified (Boothroyd *et al.*, 2002; Swift and Booker, 2003). Other conflicts are not so easily addressed – what happens when cheaper production means greater environmental damage? Or when an aesthetically pleasing form is difficult to make? After all, cheap production is of no value if no one is prepared to buy the end product.

There have been suggestions for overcoming this problem. Huang (1996) advocates focussing only on the most important perspectives. Watson *et al.* (1996) use a QFD-style correlation matrix to investigate where different guidelines conflict with and support each other. Each guideline is then allocated a score based on the number of other guidelines it supports or conflicts with, and the higher its score, the better it is to implement. Another approach is to look for Pareto improvements – avoiding trade-offs entirely by finding guidelines that improve the design from one perspective, without making it worse against others. These approaches all consider the guidelines relative to one another, but do not relate them to the underlying purpose of the product, except by limiting which DfX are considered. As yet, *how*

interactions between all the virtues and lifephases that influence a product's performance should be addressed is still an open research question (Horváth, 2004).

One way of making Design for X tools more proactive would be to avoid making bad choices in the first place. Decision-making is important in all aspects of design: it is after all, through a series of decisions that a design takes shape. In industry, product development processes are often structured around a series of stage gates, where important decisions about the product are made formal (Agouridas and Steenson, 2004). When late engineering changes take place, it is because an earlier choice has proved unsuitable, and needs to be revised. The importance of decisions in concurrent engineering is *not* in choosing between guidelines, but in trying to make choices about the design that won't have to be revised. The reason for considering all constituents from the earliest stages of design is to identify problems with the choices made before passing the design to the next stage of development. That means considering all the relevant virtues and lifephases when design decisions are first taken: this thesis proposes that decision analysis can help to do that.

1.2 Design Decisions and Concurrent Engineering

To understand why decision analysis can be useful in design, one must understand how decision-making fits into the design process, and the concurrent engineering philosophy. Current approaches to DfX focus on decision support: providing designers with *information* to help them make informed choices. Decision analysis considers *how* information is used to take a decision, and provides tools for systematically evaluating choices. The first half of this section demonstrates the importance of decision-making in design, and the difference between the way decision support and decision analysis facilitate design decision-making. The second half looks at the current uses of decision analysis in design, and how it is affected by the concurrent engineering philosophy.

1.2.1 Design as a Decision-Making Process

Much has been written about the design process: some seek to describe how it actually takes place (French, 1985), and others to prescribe how it *ought* to take place (Pahl and Beitz, 1996; Pugh, 1990). Evbuomwan *et al.* (1996) provide a comprehensive review of both approaches. A fundamental argument within the design community is whether design should be treated as an art or a science, and by extension whether there really *is* a correct way to design. Simon (1996) argues that design is a "science of the artificial", akin to the natural sciences, and that laws of design will eventually be discovered. Suh (1990) and Hazelrigg (1996a) both follow this line of thinking, and try to express fundamental rules for design. From this point

of view, the designer starts with a stable problem statement, and begins a systematic search for the optimum solution. Schön (1991) sees design as a process of "reflection in action" that cannot be defined by rational procedures and "scientific" laws. The designer makes a series of "moves", and then reflects on the situation, applying techniques as they seem appropriate and, if necessary, reframing the problem. Each problem is unique and defies any fixed model of the design process. Although these are fundamentally different approaches to design, both have common elements.

Both involve designers generating solutions, comparing them against the problem they are trying to solve and deciding what to do next. This fits Suh's (1990) description of design as a continuous loop of synthesising designs, analysing them and deciding which to pursue (see Figure 3). Dorst and Dijkhuis (1995) suggest that Schön's view is appropriate to the early stages of design, with Simon's view becoming applicable in later stages, once the product is better defined. Regardless of which view is taken, decision-making is a critical part of the design process: designs take shape through the decisions made by designers. Nor is this just a theoretical nicety: formal decision-making is given a prominent part in the stage-gate development process adopted in industry (Agouridas and Steenson, 2004).

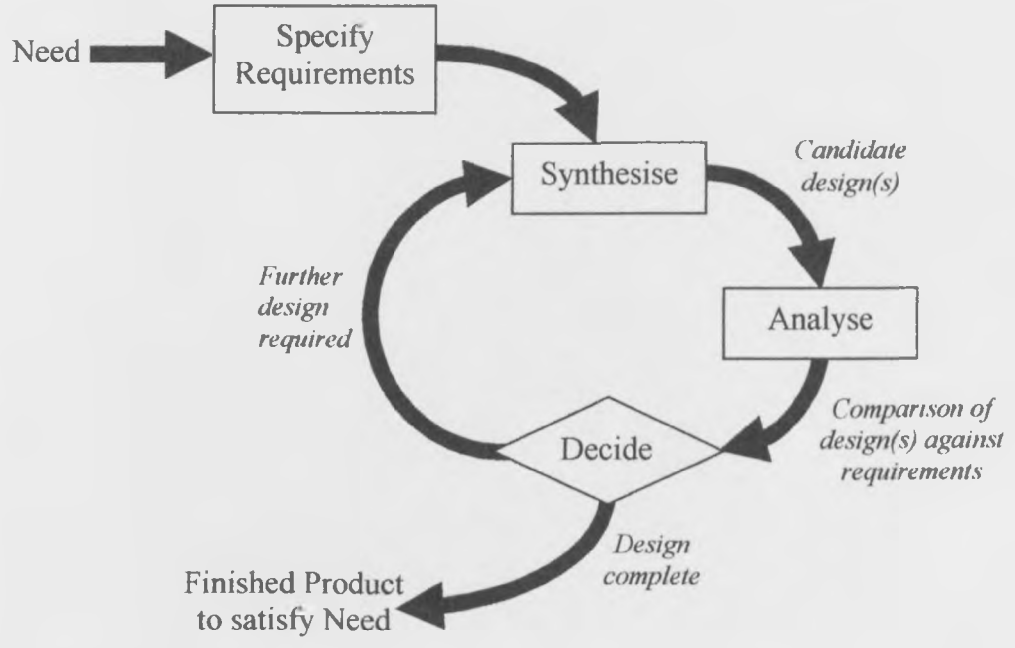

Figure 3: Suh's design loop

These decisions constrain the choices that can be made later in development, as every subsequent stage – process planning, production layout, distribution, etc. – is based on the specified design. This is the reason that design has so much influence on the eventual cost of the product. Often, decisions that seem minor end up committing millions of dollars to the eventual cost of a product because of their downstream consequences (Frise, 2004). If designers do not understand how their

choices will affect those made downstream, they cannot know when a design is actually unsuitable, and will have no reason to avoid it.

Decision support is one solution to this problem. This covers any method that provides important information needed to take a given decision. All engineering analyses – computational fluid dynamics, finite element analysis, workflow simulation, etc. – are forms of decision support. If the analysis isn't meant to inform *some* decision, then it is completely redundant. Current approaches to DfX fall into this category. Just as finite element analysis helps designers to assess where and when a structure is likely to fail, DFMA (for example) helps designers to assess whether a design can feasibly be manufactured and assembled. Even DfX guidelines are a form of decision support – highlighting issues that the designers should be considering when making choices about a design.

The measure of the quality of decision support as defined here is how well the information it provides *corresponds* with reality. For example, the measure of the quality of Design for Manufacture guidance is whether following it leads to a reduction in manufacturing cost and manufacturing defects. While decision support provides information, it doesn't specify *how* that information should be used, leaving decision-makers to apply it *ad hoc*[1]. Humans have a limited cognitive capacity (Miller, 1956) and in complex decisions, can only focus on a small portion of the available information at any time. They are also subject to biases (e.g. Plous, 1993) often subconscious, meaning that they do not necessarily make rational or optimal decisions given the information available. Decision support goes some way towards helping designers consider multiple virtues and lifephases, but there is a risk of just drowning them in information that they can't make good use of.

Decision analysis provides a complementary approach. Where decision support provides information, decision analysis provides a systematic basis for using that information to evaluate alternative courses of action (Simpson, 1998). These techniques *only* focus on how information is used: they all depend on the information fed into them being correct. The measure of a decision analysis process is therefore its *coherence* – whether it is logically consistent with what the decision-maker hopes to achieve, something not considered by decision support methods. There are many different approaches to decision analysis, from formal mathematical methods such as

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[1] It is important to understand that *ad hoc* means "Formed, arranged or done for a particular purpose only" (Oxford English Dictionary, 2002): it does not mean *wrong*. An ad hoc decision process may be very successful, but there would be no reason to assume that it would be a good basis for decisions generally – if it were, this would be due to a happy coincidence, rather than by design.

Multi-Attribute Utility Theory (Keeney and Raiffa, 1976) to simple qualitative techniques such as ProACT (Hammond *et al.*, 1999). These all provide systematic methods for structuring a decision, expressing the problem as a set of criteria to be satisfied, and comparing alternatives against each criterion in turn. As with design, there are arguments about whether decision-making should be treated as a science or an art, and whether each view is appropriate in different situations. Techniques have been developed to fit both points of view, arguing that regardless of which is taken, decision-making can always benefit from a systematic exploration of the situation. This thesis considers the use of decision analysis as a complement to the decision support currently provided by DfX techniques.

1.2.2 Decision Analysis and Concurrent Engineering

The use of decision analysis in design has been an active research area since the early 1990s. Design methodologists such as Pahl and Beitz (1996) and Pugh (1990) advocate the use of simple decision making techniques for concept and embodiment selection decisions. There has also been research into the use of formal decision theory in design (Thurston *et al.* 1994; Thurston, 2001; Fernández *et al.* 2005), which is known as *decision-based design*. Hazelrigg (1999) uses this as the basis for his "science of design". These approaches and the formal decision analysis procedures they are based on are reviewed in Section 2.2. In this section, the emphasis is on the general use of decision analysis in concurrent engineering.

There are already tools for concurrent engineering based on formal decision-making techniques such as utility theory (Zhao and Shah, 2002), fuzzy set theory (Xu *et al.*, 2004), goal programming (Fine *et al.*, 2005) and game theory (Steinhour and Krishnamurthy, 2001; Xiao *et al.* 2002; Chen and Li, 2002). All frame decision-making in mathematical terms, developing algorithms to evaluate trade-offs between given criteria, which represent the different needs of the product lifecycle. None examine decision analysis as a guiding principle for *structuring* design decisions and guiding the design process to take account of DfX information. This is not to say that such tools are fundamentally flawed – any could be used in conjunction with the work presented here – but they address a different problem. This thesis focuses on decision analysis as a *framework* for combining existing DfX techniques, and not on the mathematics of calculating trade-offs which have been substantially addressed by others (see Section 2.2). To identify whether decision analysis is a suitable tool for concurrent engineering, its coherence in that context must be assessed. To do this, it is necessary to consider what characteristics are desirable in a design decision, particularly from a concurrent engineering perspective.

This is not trivial: the characteristics of good decisions have long been a topic of discussion within the decision research community (Edwards *et al.*, 1984), and no agreement has been reached. Instead, decision researchers are obliged to state their assumptions about desirable characteristics of a decision process, and then demonstrate that the techniques they develop have these characteristics. Decision-makers can then choose techniques that best fit the characteristics they want their decisions to have.

Design is an intentional activity: it does not happen naturally, or by accident. It is always undertaken to develop a physical artefact that will satisfy a given need. Such artefacts therefore have a dual nature (Kroes, 2002), as illustrated in Figure 4. It is the match between these two natures that determines the quality of the design: a good design is one that satisfies its intended purpose. Decisions about the physical nature of the artefact should be based on its *intentional* nature – in design methodology, this is normally represented as a *requirements specification*[2].

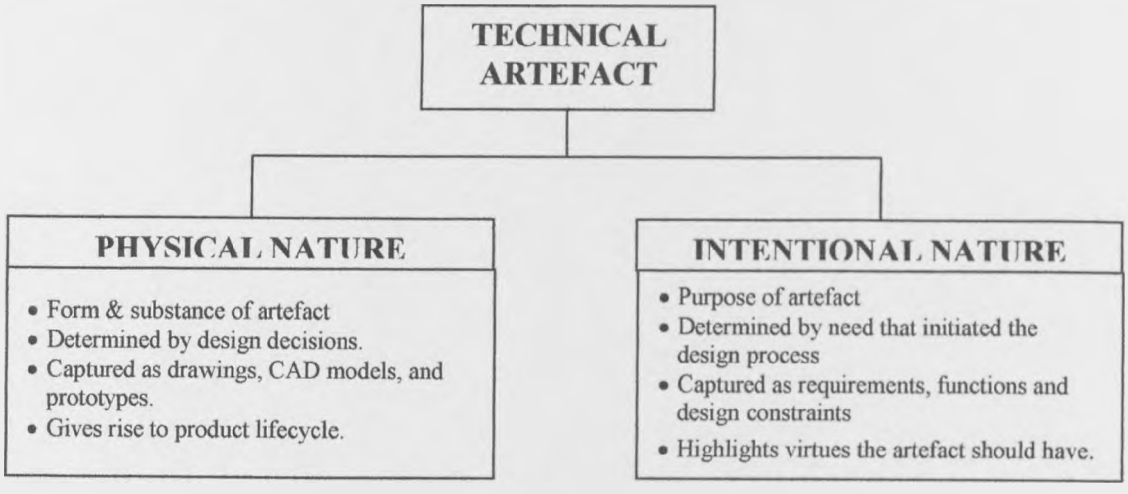


Figure 4: The dual nature of technical artefacts

Of course, there is no way of knowing for certain whether a given design will satisfy its purpose until it is complete. Furthermore, both natures tend to *co-evolve* (Brissaud, *et al.*, 2003) developing the artefact can lead to better understanding of the need, and as the former develops, the latter can be specified in greater detail. Given the high cost of making changes once a design is complete (see Figure 1), designs must be evaluated while they are still being developed. Decisions about a design's ability to achieve its purpose must therefore be made based on its intentional and physical natures *at the given time*. It may be impossible to know for

[2] Some care must be taken in using this term: here it is taken to mean a formal definition of the product's purpose, which the designers are trying to satisfy, and which may evolve over time. It does not mean a legal binding document between customer and manufacturer, although such a document might be called a "requirements specification" and might form the basis of the specification considered here.

certain whether the design will be satisfactory, but no amount of analysis or wishful thinking will provide clairvoyance. The essence of a "good" design decision is not that it avoids late changes entirely, but that it avoids choosing a design with problems that *could* have been identified at the time.

The point of considering constituents early – and therefore of every DfX technique – is to get designers to extend their evaluation beyond form and function, to the product as a whole. By doing this, potential problems for the whole lifecycle can be identified and avoided. Designers must extend their view of the designed artefact along both aspects of its dual nature:

- They must recognise that the artefact's *physical* nature depends on every phase of its product lifecycle. Its performance must be measured across the whole lifecycle, and not just its shape and substance.

- They must also recognise that the *intentional* nature they ascribe to the product must account for *all* the important virtues that its stakeholders expect of it. They cannot just evaluate designs based on their ability to perform a mechanical function.

In concurrent engineering, therefore, a "good" design decision will consider all important virtues and lifephases. Decision support makes "better" decisions a possibility – by making it possible for the designers to identify problems – but it does not guarantee that the information will be used properly. Current DfX techniques simplify evaluation by imposing a preference structure that gives a single virtue or lifephase priority over the design's intentional nature. Design for Manufacture, for example, encourages designers to choose the design that is least expensive to manufacture. To apply multiple DfX or re-impose the intentional nature of the design, the designers must make trade-offs between the imposed preference structures on an *ad hoc* basis. This thesis examines whether decision analysis can provide a structured way of bringing DfX information into a design decision without imposing a preference structure.

1.3 Research Definition

The controversy over whether design is an art or a science extends to the way it should be researched. As yet, there is no accepted paradigm for design research (Tate and Nordlund, 2001) and no unified body of knowledge on the subject (Love, 2002). Love (2000) argues that this lack of a common foundation has led to confusion, an unnecessary multiplicity of theories and terminology which has become "unhelpfully confused and imprecise". In the absence of an accepted foundation, it is important to clearly position any piece of design research in terms

of its purpose and underlying assumptions. This section addresses that need. The first half describes the focus of the research, the approach adopted and the assumptions underpinning it. The latter half provides a formal definition of the research scope and the questions that this thesis sets out to address.

1.3.1 Research Focus

There is a fundamental difference between the way research is conducted in the sciences, and the way research is generally conducted in design. Scientific research is *explanatory* (generating explanations for the phenomena observed around us) and *predictive* (using these explanations to predict phenomena). Both the natural and social sciences fit this pattern, though the former deals with objective, physical entities, and the latter with more subjective, social constructs that are open to interpretation. Design research, however, is *prescriptive*: its purpose is to improve the quality of designed artefacts by improving the design process. All design research is predicated on the assumption that the physical artefact designed is affected by the process used to design it. If this were not true, design research would have no practical application. One could argue that design research mixes the natural and social sciences: looking for causal relationships between social variables in the design process and physical variables in the designed artefact. The artefact's dual nature complicates this view: while the artefact itself may be objective, whether it is a *good* artefact is purely subjective.

This complexity is one of the reasons so many disparate approaches are taken by design researchers. Some are *descriptive*, using techniques such as ethnography (Bucciarelli, 1994; Baird *et al.* 2000) and protocol analysis (Gero and McNeill, 1998) to find out how design is conducted in practice. Others are *normative*, insisting that the way to improve design is not by studying current (and presumably imperfect) processes, but by deriving new processes logically from underlying axioms (Suh, 1990; Hazelrigg, 1999). No one has yet been able to verify underlying scientific principles of design: the *intentional* nature of designed artefacts means that there may never be such agreement. Even if there were, there is substantial evidence that idealised processes are still affected by the social behaviour of the humans that put them into practice (Bucciarelli, 1994; Badke-Schaube and Frankenberger, 1999). One cannot therefore guarantee that theoretically sound methods will lead to benefits in practice, short of studying them in use. Even then, there is still the difficulty defining exactly what constitutes a "benefit".

One solution is to concentrate on specific tasks in the design process, rather than the process as a whole. In this case, the task is treated as a "black box", with inputs and outputs to the rest of the process, and investigated in isolation. For tasks in

some domains – computer aided engineering, for example, or cost modelling – it is possible to get an objective measure of improvement. One could test whether a new cost model was more accurate than others given the same inputs, or whether an expert system could replicate expert judgement in less time. In behavioural domains (i.e. synthesising designs, decision-making, communication), the lack of an objective measure for a "good" process or a "good" design, make this more difficult to assess.

The only solution is to suggest behaviour characteristics (for example, information gathering, challenging assumptions, etc.) that seem desirable, and identify whether a given approach encourages or inhibits them. In this way, rather than saying that a particular method is a "good" or "bad" design tool, the researcher only says that "Applying method *x* tends to result in behaviour *y*". If practitioners decide that behaviour *y* is desirable, then they can adopt method *x*: otherwise, they are free to ignore it. In the absence of a science of design, it is more appropriate to talk about the consequences of applying particular methods, instead of declaring particular methods "right" or "wrong". This research will therefore propose desirable characteristics for decision-making in concurrent engineering, and investigate whether applying decision analysis leads to behaviour that is *coherent* with these characteristics.

1.3.2 Relevance, Scope and Research Question

Formal comparison of designs against criteria is given a prominent role in commercial product development processes, but criteria are often defined on an *ad hoc* basis. There is a need for systematic methods that will align the decision process with the needs of the product's stakeholders, to ensure that evaluation is complete and unbiased (Agouridas and Steenson, 2004). DfX techniques could help to satisfy this need, but only if a systematic method for relating information from multiple DfX to the purpose of a product can be found. Until then, trade-offs between the disparate preference structures of different DfX techniques will always be *ad hoc*, undermining the need to be *systematic* to ensure completeness and eliminate bias. This thesis examines the relationship between DfX and the decision-making process, to see if formal decision analysis techniques can satisfy this need.

However, it would be impossible for a single thesis to address every aspect of concurrent engineering and design decision-making: some limit must be imposed on the scope of this study.

1. Attention will be limited to *integrated product and process design* – the consideration of manufacturing implications when making design decisions. Though it is important to address *all* virtues and lifephases in design, if decision analysis cannot address just two, there is no reason to think it would be able to handle more. Accordingly, Design for Manufacture is the only DfX considered in depth here.

2. However, given the importance of addressing other virtues and lifephases, any principles put forward for using decision analysis in this way must be extensible. So, while this thesis only addresses the use of decision analysis in integrated product and process design, it must also address the possibility of extending this use to other virtues and lifephases.

3. Designers take many decisions about the content of a design (i.e. the physical nature of the designed artefact), and about *how* they will design it (Krishnan and Ulrich, 2001): far more than could be investigated in a single thesis. This work only demonstrates its methodology (see below) for embodiment decisions (Pahl and Beitz, 1996), although it could in principle apply to others.

4. The order in which decisions are taken – and what should be determined in each decision – is not addressed in this thesis. It is assumed that the designers determine what is synthesised in each iteration of the design loop, and therefore what is to be decided upon. The ordering of decisions *is* important, as it may influence the eventual choice, but this is a secondary consideration. If decision analysis is not suitable for integrated product and process design, then this issue will be irrelevant.

5. This thesis is in the domain of engineering design, not decision research. It contributes to the body of knowledge on concurrent engineering. While it draws upon knowledge from the field of decision research, it does not try to make a contribution. The quality of given decision analysis techniques in more general circumstances will not be considered, and no methods for decision analysis will be developed.

6. Although the strategic and objective levels of concurrent engineering are important, and may interact with the performance of the tactics adopted, they will not be investigated in this research. Equally, different tactics may interact with one another. Again, this issue will not be considered: these are issues for future investigations.

Given the focus of this research, and the limitations placed on its scope, the question posed in this thesis is:

"Can decision analysis incorporate Design for Manufacture information in design evaluation without imposing a preference structure on the decision?"

Answering this question is not trivial. A set of research questions should be *relevant, interconnected, specific, clear* and *answerable* (Punch, 1998). Sections 1.1 and 1.2 have already demonstrated the *relevance* of this question to academics and practitioners. Since it is a single question, it is automatically *interconnected.* However, "decision analysis" refers to a body of techniques, rather than a particular method, so it is not *specific.* The phrase "incorporate Design for Manufacture information in design evaluation" is not *clear*, as there is no commonly accepted definition for what this means. Finally, given the problems for design research discussed in Section 1.3.1, it is impossible to provide a definitive *answer* to this question. Any answer to this question will always be dependent upon a set of assumptions, and a particular view of the world. This does not mean that such research is impossible, and should not be attempted. Rather, it means that any answer will be conditional on a set of assumptions, and it is important that these are clearly stated and justified.

To this end, the research question can be decomposed into a set of four more specific objectives:

1. A set of ***desiderata*** for decision-making in integrated product and process design must be established, to show what "incorporating Design for Manufacture information in design evaluation without imposing a preference structure" means. These provide a formal definition of the characteristics decision analysis must be coherent with if it is to be considered useful in integrated product and process design.

2. A ***methodology*** for applying decision analysis principles to design decision-making is needed to show exactly what is meant by "decision analysis" and how it relates to DfX techniques. It is this methodology, rather than the vague concept of "decision analysis" that will be tested.

3. A formal ***protocol*** for comparing the methodology with the desiderata is needed. This provides a formal definition of what "success" is considered to be.

4. To bring these elements together, an ***application*** is needed. This means applying the *methodology* to a design decision, and using the *protocol* to assess whether it remains coherent with the *desiderata* in practice.

While a definitive answer to the research question is impossible, defining these four elements permits a systematic investigation, with the conclusions of this thesis rooted in clear assumptions. In the absence of an accepted body of knowledge and methods in design research, researchers can determine the value of these findings to themselves by examining the underlying assumptions. The rest of this thesis is concerned with answering the question posed above, by addressing these four objectives.

1.4 Research Strategy and Thesis Structure

The content of this thesis follows directly from the question it seeks to answer, and its structure reflects the objectives associated with answering this question. This section provides an overview of the thesis' structure, and how it addresses the research question. The first half of the section discusses the strategy adopted in this research. It describes the methods used to answer the research question and fulfil its associated objectives. The second half highlights the information contained in the remaining chapters, describes their structure, and shows how they relate to the objectives.

1.4.1 Research Strategy

To answer the research question governing this thesis means intervening in the design process, trying to improve the way designers evaluate designs by applying principles from decision analysis. Leaving aside the difficulties of knowing what an "improvement" is, which will be defined by the ***desiderata***, this still poses problems for anyone trying to conduct research in the area. While the designed artefact itself is a physical system, the design process is what Checkland (1981) terms a *human activity system*, and studying interventions in such systems is not easy. For one thing, while they are a convenient concept for making sense of the world, such systems are difficult to define and bound objectively. Different participants in the system may have different views about what is within the system, what it is trying to do, and what part they play in it. The output of the system is affected by issues such as personality, the worldviews of the participants in the system (Bucciarelli, 1994), and external pressures on the participants (Badke-Schaube and Frankenberger, 1999).

Checkland (1999) highlights two particular problems in studying these systems. Firstly, experiments can never be replicated, as the system depends on the individuals within it, and no two are exactly alike. Even repeating an experiment with the same people causes problems, because the participants learn. Secondly, Checkland (1999, pA32) argues that "no generalizations about methodology-in-use can ever be taken seriously" as the way a methodology works in practice depends on

three interacting factors (see Figure 5). The actual performance depends upon *how* the given user(s) applies the methodology to the given problem situation. Failures may be down to the way the methodology has been applied. Success may be down to the innate abilities of the user – who might have achieved an equally good result with another methodology. If the methodology leads to successful outcomes over a large number of applications, then it may be accepted as a suitable way of solving a given problem. In some cases, it is possible to do this by setting up a large number of laboratory studies to test the methodology with different individuals in different circumstances. However, the sort of decisions that this thesis is concerned with are complicated and time-consuming, and not easy to replicate out of context.

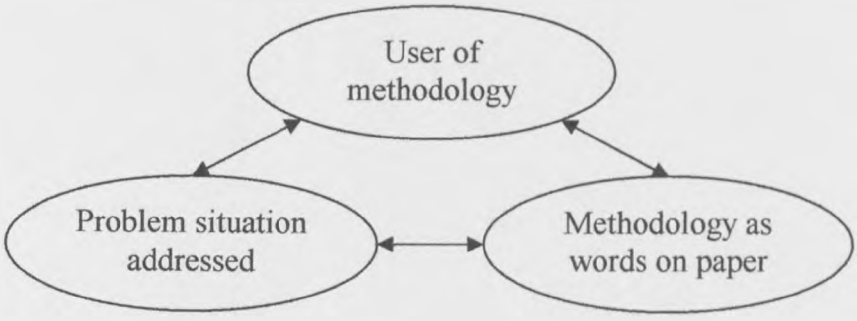


Figure 5: The three interacting elements in applying any methodology (after Checkland, 1999)

Instead, the approach adopted must be to try a limited number of studies, and see if the methodology proposed *can* satisfy the desiderata. Successes and failures must be carefully investigated, to identify their causes, and see if they are inherent to the methodology, or down to the way it has been applied. In this way, one begins to learn about the methodology and its suitability. If, after these limited studies, the methodology has been repeatedly unsuccessful, and the causes of failure are not errors in its application, then it is unlikely to be worth studying further. If applications are repeatedly successful, then one can conclude that it *is* a suitable way – but not that it is the *correct* way - of satisfying the desiderata. This is still valuable information, as it provides a tool for tackling the given situation, worthy of developing and studying further.

In light of this, the objectives given in Section 1.3.2 can be expanded to cover the steps that will be taken to achieve them. The ***desiderata*** are necessary to have a formal declaration of what this research considers desirable in a design decision. In a sense, these desiderata are arbitrary, as they are asserted by the researcher. However, the research will have no value unless the desiderata are justifiably of interest to practitioners. Thus, each desideratum must be derived logically from the literature on design and decision-making. The ***methodology*** faces a similar problem, as it is also arbitrary. One could argue that finding out what *doesn't* work has value,

or that trying something expected to fail might throw up an unexpected success. However, with limited resources for research, it is foolhardy to waste them on testing methodologies that one expects to fail, unless one is investigating *why* they fail. To avoid wasting resources, therefore, it is necessary to justify logically how the methodology proposed will satisfy each of the desiderata. This makes the desiderata and methodology logically *coherent*, ensuring that they are justifiable and not just mindless assertions. Logical coherence is necessary to show that a methodology is worth investigating, but not sufficient to show that it works.

Because design is a human activity system, it is necessary to study the methodology in use, before drawing any conclusions about its value. This is why ***applications*** are necessary. It is not possible in a single thesis to get enough applications to *prove* that a methodology will generally satisfy the desiderata in practice. Nevertheless it is possible to prove that the methodology *can* satisfy the desiderata in practice, or show that the methodology is unlikely to satisfy them in practice. However, even deciding whether or not the desiderata have been satisfied will depend on qualitative data that are open to interpretation. Adopting a formal ***protocol*** helps to avoid bias, or arbitrary conclusions, by showing how the data gathered will be used to determine whether each desideratum has been satisfied. This forces the researcher to examine the evidence properly, not just cherry-pick the bits they like, and helps other researchers to understand how the conclusions were arrived at. In this way, they are able to determine how this research affects their own, instead of having to take the results on faith. These four elements form the basis of the thesis' structure.

1.4.2 Thesis Structure

Each of the remaining chapters of the thesis relates to at least one of the given research objectives, as illustrated in Figure 6.

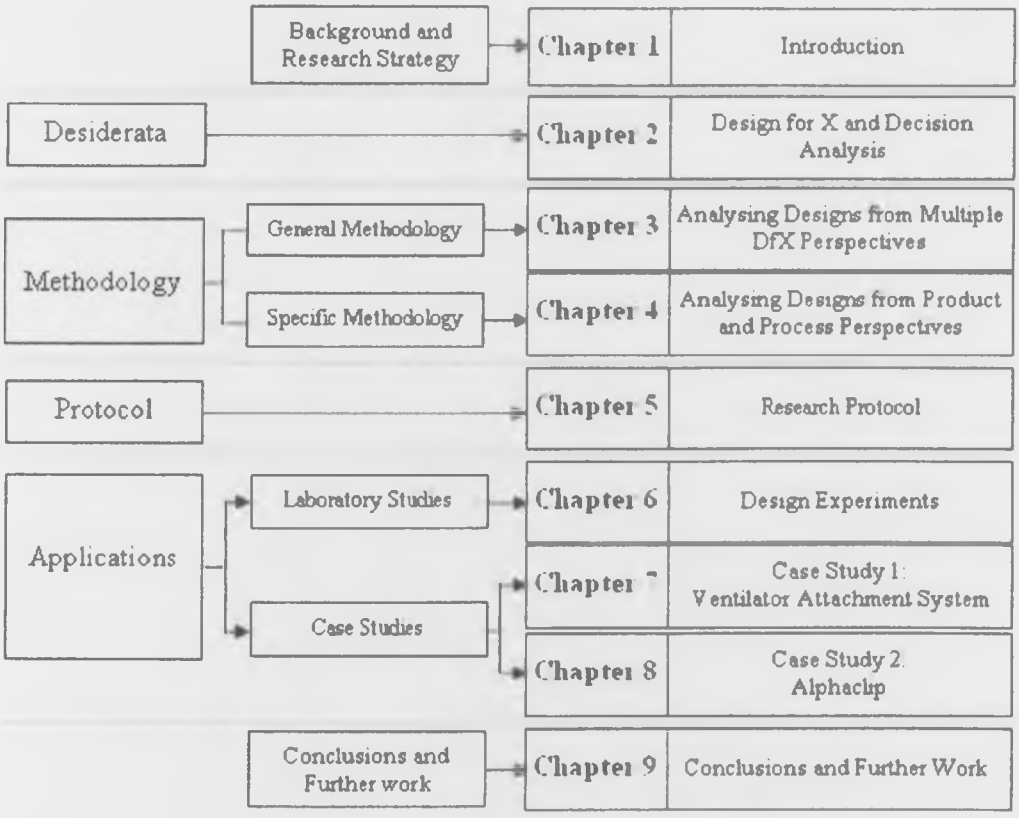


Figure 6: Relations between thesis structure and research objectives.

Chapter 2 addresses the ***desiderata***. Sections 2.1 and 2.2 provide a detailed literature review on current Design for X approaches and decision analysis techniques, respectively. These provide the basis for the desiderata and methodology, and in Section 2.3, the desiderata are formally derived and justified.

Chapter 3 proposes a general ***methodology*** for using the decision analysis techniques cited in Chapter 2 to satisfy the desiderata for *any* virtue or lifephase.

Chapter 4 then adapts this general methodology to the specific case of integrated product and process design, showing how Design for Manufacture information can be brought into design evaluation.

Chapter 5 presents a ***protocol*** for analysing the applications of the methodology in the subsequent chapters. This covers specific questions that need to be answered, how data will be collected and analysed to answer them, and how bias and threats to validity will be minimised.

Chapter 6 presents three ***applications*** of the methodology from Chapter 4 in a series of design experiments, which simulate design decisions. This allows a study of the methodology where risks are low, and the situation is easy to control and gather data from.

Chapters 7 and **8** present ***applications*** of the methodology to actual design projects, to study its use in practice and evaluate it against the desiderata.

Chapter 9 reflects on the results of these applications, and discusses the thesis' contribution to knowledge, and future work that might build on this research.

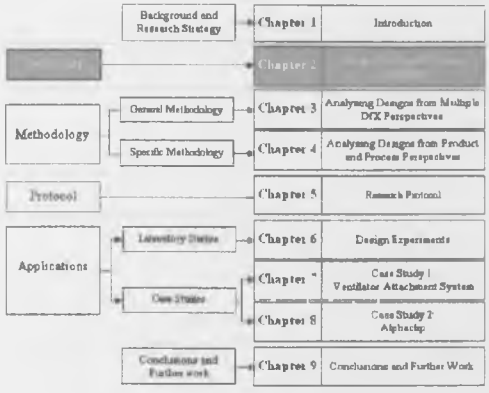
1.5 Summary

Fast-moving markets, and increasing global competition, are driving companies to adopt a *concurrent engineering* philosophy, considering all aspects of the product lifecycle throughout product development. This can be implemented in many different ways at different levels of the company, from high-level issues such as strategy or structure to tactics for carrying out specific tasks. This thesis focuses on a particular set of tactics, known as "Design for X" techniques, which help designers understand the implications of their choices for a given virtue or lifephase. However, each DfX addresses only one virtue or lifephase, trying to impose its own preference structure on design decisions, and offering no way of reconciling conflicts with other DfX. Decision-making is an important activity in design, as every aspect of a product is determined by the decisions taken in its development. There has been growing interest in the use of *decision analysis* in design, which provides a structured way of using information when evaluating alternatives against conflicting objectives.

This thesis investigates whether decision analysis can be used to incorporate Design for X information in design decisions without imposing a preference structure. Given the range of Design for X techniques available, it would be impossible to cover them all in a single thesis. Accordingly, this research restricts its attention to Design for Manufacture, concentrating on whether decision analysis can be used to evaluate a design from both product and process perspectives. Similarly, given the huge range of decisions that designers may face, it is impossible to investigate them all. This thesis therefore restricts its attention to demonstrating the use of decision analysis to bring Design for Manufacture information into embodiment design decisions.

To do this, it draws upon literature from design and decision theory to establish a set of ***desiderata*** for incorporating manufacturing information in design decisions. It then proposes a ***methodology*** for using decision analysis to bring DfX information in general, and DfM information in particular, into design decisions. It then demonstrates that this methodology satisfies the desiderata both theoretically, and in practice, through a series of ***applications*** to design experiments and case studies. Further work is necessary to determine whether this approach generalises to other DfX and other design decisions.

Chapter 2
Design for 'X' and Decision Analysis



This Chapter addresses the first objective of this thesis, reviewing the literature on Design for X and decision analysis to provide a set of ***desiderata*** for decision-making in concurrent engineering. As discussed in Section 1.4.1, to be more than just arbitrary assertions, these desiderata must be rooted in the current literature on DfX and decision making.

This Chapter is therefore divided into four subsections. **Section 2.1** describes the Design for X techniques currently used to provide decision support in concurrent engineering. It shows how these techniques influence the design process, and the different ways that they handle *virtues* and *lifephases*. **Section 2.2** considers the field of decision analysis, describing some of the available techniques, and complications that occur in applying them to group decisions. **Section 2.3** examines how these techniques relate to the design process, and reviews existing decision analysis approaches to design and concurrent engineering. **Section 2.4** then derives the ***desiderata*** which Chapters 3 and 4 will seek to satisfy, by proposing a methodology based on the decision analysis techniques discussed here.

2.1 Supporting Design Decisions from a "Design for X" Perspective

This section reviews existing Design for X techniques, which provide decision support in concurrent engineering, including the difference between techniques that consider *virtues* (DfX_{virtue} techniques) and those that consider *lifephases* ($DfX_{lifephase}$ techniques). This section is divided into three parts. The first examines the different ways in which Design for X techniques try to improve the design process, through the stages of *synthesis* and *analysis*. The second and third parts each discuss DfX techniques for *virtues* and *lifephases*, respectively. While this chapter is concerned with concurrent engineering as a whole, particular attention in this section is given to techniques supporting integrated product and process design, as these will play a significant part in the rest of the thesis. Although this review restricts attention to specific DfX techniques, equivalent support could be achieved by consulting experts

on the given virtue or lifephase, especially in a cross-functional design environment (e.g. Prudhomme, *et al.* 2003).

2.1.1 Synthesis vs. Analysis

To improve the output of the design process, one must improve the three main activities of the design loop (see Figure 3, on page 9). This means *synthesising* better designs, providing more accurate *analyses* and providing better *decision* mechanisms. Improving just one of these activities is of limited value. The quality of the designs generated is a limiting factor on the decision – even the best analysis and decision procedures are limited to choosing the best of a bad lot. Equally, generating the best design in the world is of no value if the designers choose not to pursue it because of inaccurate analyses, or biased decision mechanisms. Few design tools address all three, and DfX is no exception, so care must be taken with its implementation to make sure it provides real benefits. Decision mechanisms are a social issue, being either formal (voting, deferral to authority), or informal (consensus, negotiation between designers). Badke-Schaube and Frankenberger (1999) illustrate the importance of these mechanisms, by showing how designs that are *known* to be unsatisfactory can be forced through by social pressures. However, decision mechanisms are an organisational issue, and not addressed by specific DfX techniques, which instead focus on improving *synthesis* and *analysis* from their given point of view.

Supporting *synthesis* is a proactive way of applying *Design for X*, as it takes place before designs are analysed or decisions are taken. 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 *synthesis* is through the use of guidelines (such as those in Table 2, on page 6), indicating qualities to be sought or avoided when proposing designs. This works in exactly the same way for both *virtues* and *lifephases*: guidelines just indicate qualitatively what makes a design *better* from that point of view. There, is however, no way of resolving conflict between guidelines at the *synthesis* stage - trade-offs can only be investigated through *analysis*.

Some *Design for X* techniques provide less ad hoc support for synthesis. Some use the results of analysis to explore alterations and improvements to designs *before* making any decisions about which to pursue, an approach Pugh (1990) advocates for design in general. The Lucas DFA/MA approach (Lucas Engineering Systems, Ltd, 1993) is one example of this, using 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). There are also methods for actually synthesising designs to have specified properties. Shape Grammars, for example, can be used to create designs that conform to a given a style or brand image (Chau, 2002). Forward kansei engineering systems (Nagamachi, 2002) can be used to generate designs conforming to a particular emotional response. Nevertheless, even these more formal approaches are either restricted to one *virtue* or *lifephase*, or rely on bringing *analysis* into the synthesis stage. Any method hoping to accommodate multiple virtues and lifephases must support the *analysis* stage of the design loop.

To understand how DfX techniques support analysis, it is necessary to understand what analysis actually involves. Because the design process is a human activity system, it is what Vickers terms an *appreciative system* (Vickers, 1965; expanded by Checkland and Casar, 1986), illustrated in Figure 7. To take actions, designers must first appreciate (perceive and make judgements about) the situation they are in, and what they are trying to achieve. This means making judgements in terms of *fact* (what is the case, and how the world behaves), and *value* (what is desirable or undesirable): both relate to the dual nature of the designed artefact. Factual judgements (how the design is expected to perform) are derived from its physical nature, while value judgements (whether that performance is acceptable) are based on its purpose. Decision support therefore helps designers firstly, to determine the expected behaviour of the design; and secondly, to relate this behaviour to the values underpinning the design project. These two approaches illustrate the difference between the support provided by $DfX_{lifephase}$ and DfX_{virtue} techniques, summarised in Table 3.

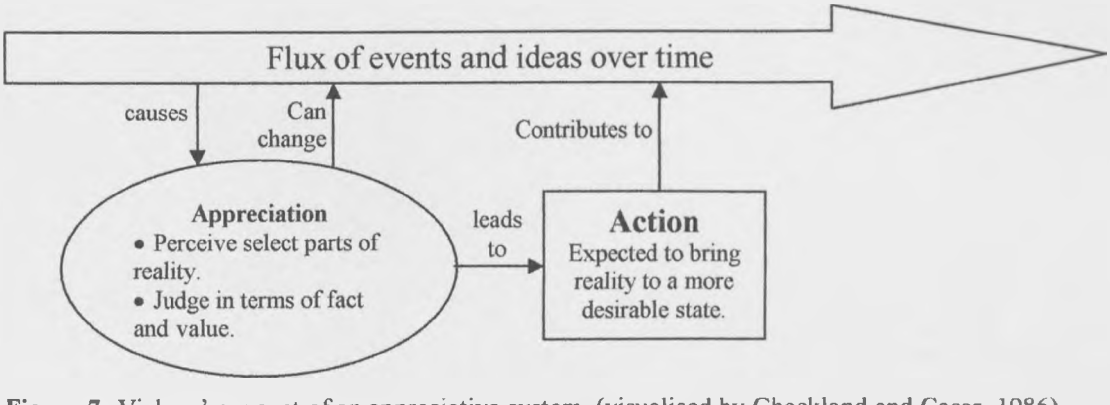


Figure 7: Vickers' concept of an appreciative system, (visualised by Checkland and Casar, 1986)

Table 3: How DfX_{virtue} and $DfX_{lifephase}$ support synthesis and analysis

DfX Type / Design Activity	Virtue	Lifephase
Synthesis	• Guidelines	• Guidelines
Analysis	• Metrics • Guidelines	• Feasibility Checks • Prediction of likely choices. • Guidelines

Virtues represent the intentional nature of an artefact, while lifephases are part of its physical nature: analysis compares one against the other, as illustrated in Figure 8. Analysing a design from the perspective of a virtue means considering how that virtue relates to the artefact's physical nature. Analysing designs from the perspective of a lifephase means considering how that stage relates to the intentional nature of the artefact. This leads analysis from each point of view to take a different approach.

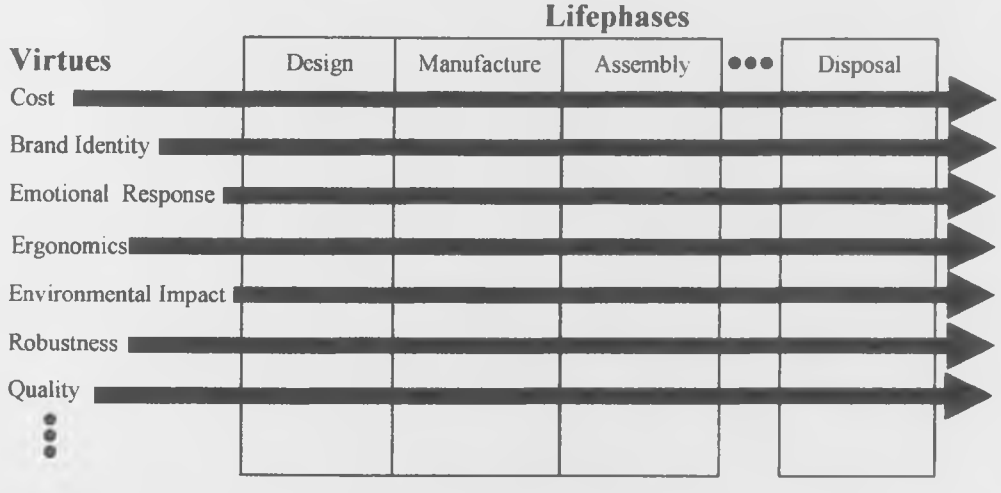


Figure 8: Relationship between virtues and lifephases

2.1.2 Design for Virtue

The virtues relevant to a given design depend on its *intentional* nature, and are therefore subject to judgements in terms of *value*. Design for X techniques that address virtues do not dictate which virtues the artefact should have, but rather how to check that the given virtue has been satisfied. These techniques help designers to understand which attributes of the physical artefact affect its ability to satisfy its purpose, with respect to the given virtue. It is worth noting that the virtues addressed by DfX techniques do not cover the full *intentional* nature of the product. They do not, for example, cover the functions or actions that the product must perform, which are addressed by the engineering sciences. Rather, they extend the 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 (Prudhomme *et al.* 2003). Just as the engineering sciences help designers predict how well designs will perform their physical functions; these techniques help designers predict how the design will perform against these less tangible virtues.

Design for X techniques support analysis with respect to virtues in two ways: through *qualitative* description of how physical properties affect the virtue, and through *quantitative* models of that relationship. Qualitative support for almost any virtue can be provided through design guidelines (such as those in Table 1) highlighting characteristics that have a positive or negative effect on that virtue. Quantitative measures depend on the virtue being considered. Failure rate can be taken as a quantitative measure in Design for Reliability, with simulation tools being used to predict when failures will occur (Edson and Tian, 2004). Backwards kansei engineering systems (Nagamachi, 2002) use semantic differential scales to predict emotional responses to a product based on its physical characteristics. Design for Environment normally uses multi-attribute metrics (Veroutis and Fava, 1996) as environmental impact must be considered on several dimensions (resources consumed, waste generated, etc.). In Design for Quality, Taguchi Loss Functions (Taguchi, 1986) help quantify the cost of manufacturing deviations from the specified design, while Quality Function Deployment (QFD – Ako, 1990) relates a design's physical parameters to customer requirements. Each of these methods analyses a design against just one virtue: none help designers assess trade-offs between virtues, where their needs conflict.

Given that most DfX are concerned with commercial products meant to generate profits, it is not surprising that cost is considered one of the most important virtues. In integrated product and process design, it is normally considered *the* most important virtue (Bralla, 1999). Decision support in this area normally takes the form of models that provide cost estimates based on information about a design. Unfortunately, cost estimation is extremely complicated, and many cost estimating techniques exist, spanning different disciplines. Normally, in design, these models only provide rough estimates of the *relative* cost of alternative designs, to help choose between them. As the data available in the early stages of design is so uncertain, the increased effort in using more detailed cost models does not provide a proportional benefit. Most cost estimating models provided in this field are meant to aid early selection of manufacturing processes, and therefore consider the cost of materials, manufacture and assembly. Examples of this kind of model have been proposed by Esawi and Ashby (2003), Swift and Booker (2003) and Shehab and

Abdallah (2001). Others have proposed models for estimating costs over the whole product life cycle (e.g. Koonce *et al.* 2003). Of course, such cost estimates cannot be made for the design alone, only for a given design made by a given set of processes, therefore cost estimation requires some estimate of *how* a product will be made.

Design for X techniques that address virtues support design analysis in two ways. Firstly, they highlight important issues that designers may wish to consider, making it less likely that important virtues will be overlooked when setting the analysis criteria. This helps designers make sure that their judgements in terms of *value* are complete, although they must still decide which virtues are actually relevant to their given situation. These techniques also provide qualitative and quantitative methods that help designers make judgements in terms of *fact* about how well their designs perform against the analysis criteria. However, each of these techniques only addresses one virtue, typically representing only a fraction of the product's intentional nature. To avoid making false economies, designers must analyse their designs against the product's intentional nature as a whole. These methods leave designers to make such trade-offs between competing virtues in an entirely *ad hoc* manner. Designers must also be sure that – when assessing a design's performance against these virtues – they don't leave out any important stages of the product lifecycle. It is therefore just as important to have methods that help designers assess the product lifecycle, as to have methods for assessing virtues.

2.1.3 Design for Lifephase

The lifephases that are relevant to a given design form a part of its physical nature, and are therefore subject to judgements in terms of *fact*. The exact phases of a product's lifecycle will vary from one product to another and even from component to component within a product. The purpose of using these techniques is to make sure that – as far as possible - the influence of the whole product lifecycle is considered for all the product's requirements. Therefore, designers need to understand the implications of their choices for the subsequent 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. Trade-offs do not occur between lifephases directly: rather, they are based on the phases' impact on the product's performance. These methods say nothing about which trade-offs *should* be made, but they do help to model those trade-offs.

In many cases, these techniques try to predict the choices that will be made in subsequent stages, so that their impact on the product's performance can be considered. This aspect of concurrent engineering is often addressed through

organisational approaches such as cross-functional teams or collaboration and communication (see Section 1.1.1), bringing in those responsible for these decisions. Such approaches are *ad hoc*, and this literature review is only concerned with formal techniques that help designers examine the choices made in given lifephases. This is normally done on two bases: *feasibility* (eliminating unsuitable choices given the current state of the design) and *desirability* (estimating the most desirable choice based on a given criterion). For example, a feature's "machinability" can be measured by identifying the machining operations needed to produce it, then estimating the cost of doing so: the lower the cost, the more "machinable" the feature (Brissaud and Paris, 1998). Similarly, La Trobe-Bateman and Wild (2003) propose a DFM spreadsheet to help identify likely processing routes based on manufacturing cost. However, these methods tend to consider only *one* virtue – typically cost, or environmental impact – and don't relate the lifephase to other aspects of the product's intentional nature.

In some cases, researchers treat a lifephase as if it were a virtue, particularly when that stage occurs after the product development process. For example, some researchers use special metrics to measure maintainability (Slavila *et al.*, 2004) or disassemblability (Desai and Mital, 2003) instead of relating them to other requirements. After all, these issues may be important selling points for some products, and impact the user rather than the manufacturer. Such metrics normally aggregate several evaluation criteria for the specific point of view to generate an overall index. As these metrics are dimensionless, they may help to compare designs from a given perspective, but offer no guidance in making trade-offs when they conflict. Some methods *do* relate these stages to virtues – Villalba *et al.* (2004) use a profit-to-loss measure to assess the economic feasibility of recycling, for example, while Shu and Flowers (1999) estimate the cost of remanufacture – but these tend to use a single virtue as the metric for assessment. However the effect is quantified (whether by virtue, or a specific index), one must still know what will happen at that lifephase to assess the design's performance.

The basis for evaluating designs with respect to manufacture or assembly is normally the feasibility and cost of making them. This cost depends on many factors beyond the shape and material of a design: the processes used, for example, or even the factory layout or inventory management system adopted. Design for Manufacture guidelines tend to be process specific as well, since features that are easy to produce using one process may be extremely difficult to make with another. Booker and Swift (2003), Boothroyd *et al.* (2002) and Bralla (1999) all provide detailed guidelines for designing to suit a given process. Also, given that combinations of processes can be used to make a product, almost *anything* can be

made if one is willing to spend enough time and money on it. It is therefore impossible to apply these methods until likely process chains have been identified. There are various ways around this. Booker and Swift (2003) suggest likely processes for making a component based on its material and estimated rate of production. Maropoulos *et al.* (2003) restrict attention to the use of existing facilities. This is where methods for identifying appropriate manufacturing processes early in design, such as the Ashby method (Ashby, 1999; Lovatt and Shercliff, 2001; Edwards, 2003), are beneficial. It is only once likely processes have been identified that approximate cost models for manufacturing and assembly can be used.

Thus, Design for X techniques that address lifephases support the design process in two ways. Firstly, they help designers understand the consequences of a given design for the choices made at that stage. Secondly, they help designers interpret these consequences for the product's performance in terms of a virtue (e.g. cost, environmental impact), or a special index (e.g. "maintainability", "disassemblability"). It still left to the designer to come up with an ad hoc process for making trade-offs between these virtues when different lifephases bring them into conflict.

2.2 Decision Analysis

Decision support provides information, but does not say how it should be used: decision analysis provides systematic methods for using this information to evaluate alternatives. This section examines the decision analysis techniques available, and how they relate to design evaluation. One difficulty in discussing decision-making is that different people use the term "decision" in slightly different ways. Designers can also face a huge range of decisions in the course of a design project. For the purpose of this thesis, a decision is taken to be an explicit choice from a set of options (Hazelrigg, 1998). The only design decisions considered here are situations where designers have generated two or more alternative designs, and are deciding which to develop further.

The section is divided into two parts. The first describes the tools and techniques currently used in decision analysis, while the second discusses the complicating factors introduced when these methods are applied to group decisions.

2.2.1 Decision Trees and MCDM Algorithms

Like design, decision analysis is not a well-defined area: it covers a wide range of techniques and philosophies for making decisions. The term originally meant the

application of theories derived from von Neumann-Morgenstern (vN-M) utility theory (see below) (Howard, 1992), but is often used to cover other prescriptive techniques. The common thread is that these techniques are *prescriptive*, and decision analysis excludes *descriptive* theories such as Image Theory (Beach, 1990). Even among the prescriptive techniques, this review cannot be exhaustive, and therefore focuses on the most popular methods for evaluating trade-offs in decision-making.

Decision analysis views decisions as having three main elements: *alternatives* to choose from; *expectations* about the outcomes of choosing each alternative; and *values* to determine how desirable each outcome is. It uses two main tools: a decision tree, relating alternatives to their expected outcomes; and a multi-criteria decision-making (MCDM) algorithm comparing outcomes against values. This review concerns itself with the structure of decision analysis, rather than the specific mathematics of these techniques, which will not play an important part in this thesis.

Decision Trees

A decision tree represents a sequence of decisions graphically, showing the alternatives available at each decision, and chance factors that might affect the outcome. It maps each set of choices to their potential outcomes, and indicates how likely each outcome is thought to be, providing a structured way of thinking through a decision's possible outcomes. For a simple decision, this may be quite straightforward, but will expand rapidly as the number of decisions and alternatives increase. Figure 9 shows an example of a simple decision tree.

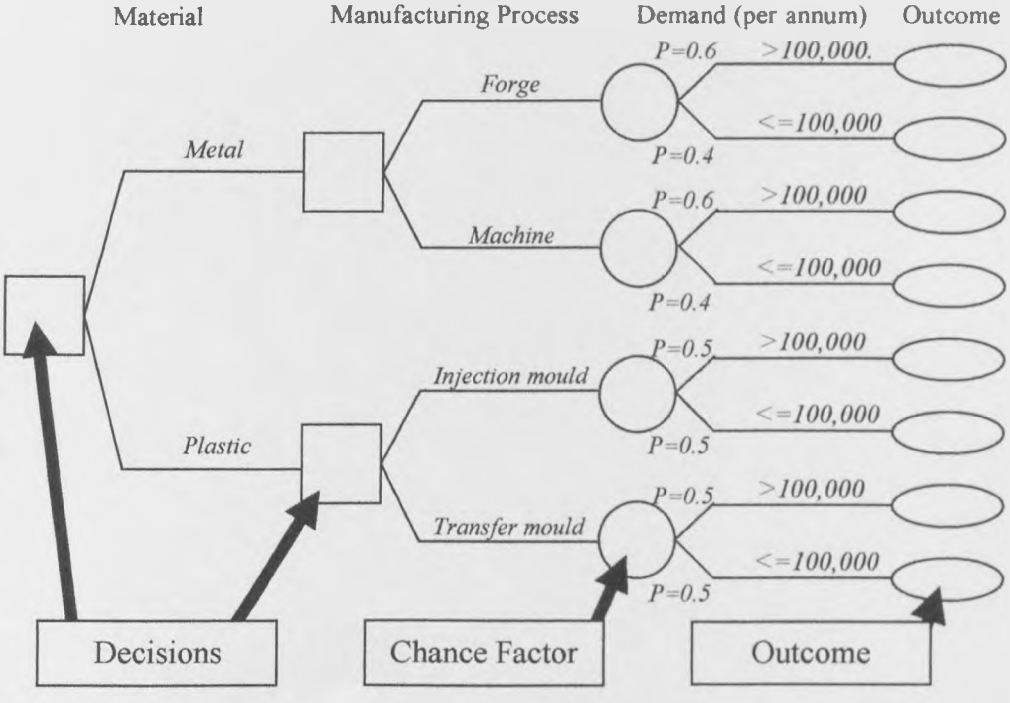


Figure 9: A decision tree

MCDM[1] Algorithms

Once the expected outcomes of the available choices have been established, the MCDM algorithm helps decision-makers evaluate how desirable each outcome is, so that the alternatives can be ranked. A huge range of algorithms are available, from simple heuristics to complex mathematical models. Each uses a scoring function for each criterion to evaluate the alternatives against it: trade-offs between the scores for different criteria are then evaluated in a variety of ways, as shown in Figure 10.

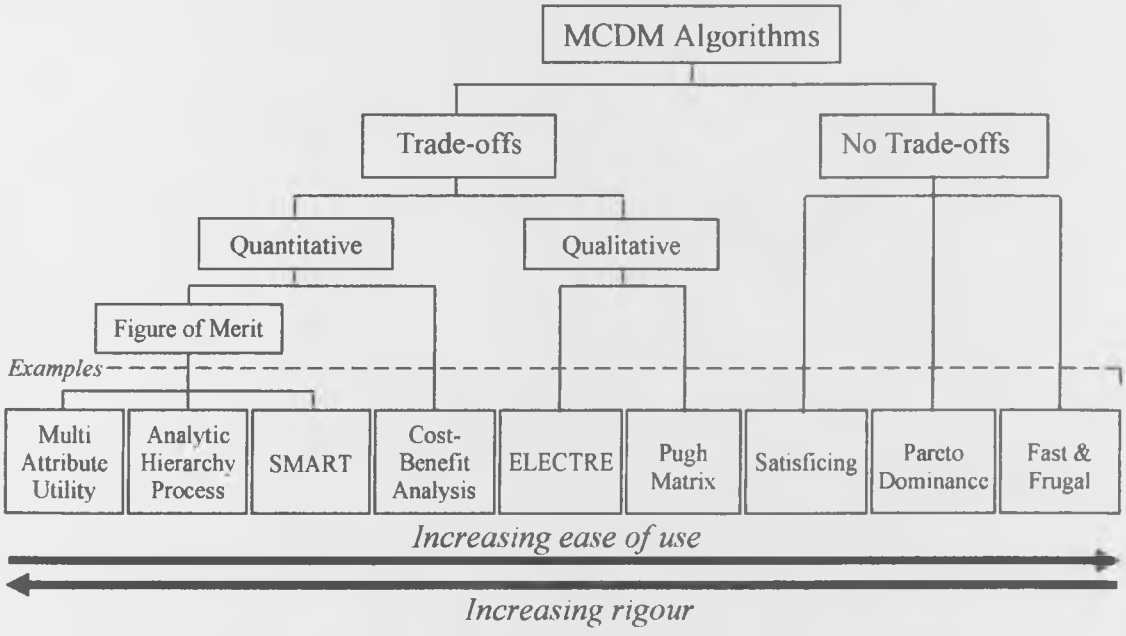


Figure 10: Example MCDM algorithms classified by their approach to trade-offs

Some algorithms avoid making trade-offs, to reduce the complexity and increase the speed of decisions. "Fast and frugal" algorithms (Gigerenzer *et al.*, 1999) rank alternatives using the single most important criterion. *Satisficing* (Simon, 1957), sets an aspiration level - a minimum acceptable threshold - for each criterion and accepts the first alternative to meet the aspiration level on every criterion. Finally, *pareto domination* eliminates alternatives that are definitely *not* the best, leaving the decision-maker to evaluate those that remain[2]. This approach is taken by some DfX techniques, as noted in Chapter 1 – trying to improve a design from one perspective, without worsening it from others.

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[1] Care must be taken with this term, as its use varies significantly across the literature. Here, for the sake of simplicity, it is taken to refer to *any* algorithm for evaluating alternatives against a set of criteria.

[2] Alternative *A* pareto dominates alternative *B* if *A* is better than *B* on at least one criterion, and at least as good as *B* on all the other criteria.

Some algorithms examine trade-offs, but do not quantify them, recognising the inherent uncertainty in making trade-offs and leaving them up to the human, rather than a decision algorithm. The Pugh matrix (Pugh, 1990) is entirely qualitative. One alternative is chosen as a datum, and the others are evaluated as better (+), worse (-) or the same (0), for each criterion. An example Pugh matrix is shown in Figure 11. Based on this, the decision-makers then eliminate the weakest designs, and reassess the alternatives against another datum. This continues until the decision-makers feel that they have sufficiently reduced the alternatives. ELECTRE (Elimination Et Choix Traduisant la Réalité: Roy, 1996) provides a family of mathematical methods, which measure the difference between alternatives for each criterion in terms of thresholds, which are then aggregated to divide the alternatives into groups. The groups are ranked relative to one another, but no attempt is made to rank the alternatives within a group.

Criteria	CONCEPTS			
	Concept 1	Concept 2	Concept 3	Concept 4
Discharge pressure	0		-	0
Self priming ability	0		0	0
Flow accuracy	0		-	0
Flow repeatability	0		-	0
Zero cross contamination	0	D	-	0
May be cleaned / sterilised by CIP /	0		-	0
Occlusions per rev	-		-	0
Inlet / discharge	-		-	-
Load dynamics	-	A	-	-
Hose life	0		-	0
Bearing replacement time	+		+	+
Hose burst bearing protection	0		-	-
Pump envelope (inc GMU)	0	T	-	0
Pump mass (inc GMU)	0		-	0
GMU purchase cost	0		-	0
Fits affective design	+		0	+
Material Costs	+	U	0	+
Assembly time	+		0	0
Assembly ease	0		-	-
Surface tolerance requirements	+		+	+
Disaster-proof design	+	M	0	+
Processes technically scaleable	0		-	+
Compatible with standard GMU	0		-	0
Easily comparable with competitors	+		+	+
Possesses traditional 'hallmarks' of	0		-	0
Performance against indirect	0		-	0
Sum +'s	7	0	3	7
Sum 0's	16	26	5	15
Sum -'s	3	0	18	4
Action	Proceed	Proceed	Eliminate	Proceed

Figure 11: Example Pugh Matrix

The most popular MCDM techniques quantify trade-offs by translating an alternative's performance against the different criteria into a single common measure of value. In Cost Benefit Analysis, benefits are quantified as a financial measure based on how much one would be willing to pay to receive them. Costs are either quantified on their actual financial cost or, for non-monetary drawbacks, on the basis of how much one would be willing to pay to avoid them. Other methods calculate a "figure of merit" for an alternative by measuring and combining its performance against the different criteria. Numeric values are assigned to represent the alternative's performance against each criterion (higher scores indicating better performance), and a weight to indicate the relative importance of each criterion. These are then combined in a weighted sum, to give an overall score for each alternative, the higher the better. Where a criterion can be related to a measurable attribute of the alternatives, a mathematical function can be used to translate the measurement directly to a score. Where a criterion is subjective, or not easy to relate to a measurable property of the alternatives, the designers must come up with a surrogate way of measuring scores. There a variety of methods for doing both, based on different ways of assessing these scores and weights.

The original mathematical formulation for utility was put forward by von Neumann and Morgenstern (1947), based on a series of axioms to which they felt rational decision makers should conform. This measures the decision-maker's preferences over a single criterion under risk and was extended to multiple criteria by Keeney and Raiffa (1976). This theory has a solid axiomatic basis, and is normally accepted as the normative "gold standard" of decision-making, but is often criticised for being too complicated to apply. This has lead researchers to develop simpler, more pragmatic methods for calculating utility over multiple attributes.

Two popular alternatives to von Neumann-Morgenstern Utility are the Analytical Hierarchy Process (AHP) (Saaty, 1980) and the Simple Multi-Attribute Rating Technique (SMART) (Edwards, 1977). Like vN-M Utility, AHP has an axiomatic basis, though this is less restricting than the vN-M axioms. AHP uses a structured hierarchical process to decompose an overall goal into a set of criteria, and pairwise comparisons to assign weights to criteria and scores to alternatives. SMART is a simplified version of multi-attribute utility theory, where weights are estimated directly, and scores are assigned by assuming a linear utility function. Both methods are simpler than vN-M utility but critics argue that they are less theoretically sound.

While the mathematics and mechanisms underpinning each algorithm differ, all fit the model shown in Figure 12. Preferences must be framed as a set of formal evaluation criteria, and a score calculated for each alternative according to how well it satisfies these criteria. For all MCDM, these scores are ordinal, not cardinal: they give a rank ordering of the alternatives, rather than an absolute measure of satisfaction.

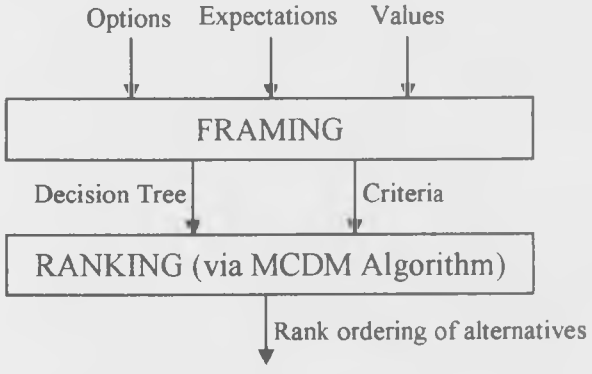


Figure 12: Black box model of MCDM algorithms

There is no agreement on which method is "correct" in practice, and given the same criteria and the same alternatives, different methods can produce different rankings (Zanakis *et al.* 1998). VN-M Utility's strong axiomatic basis means that it is generally accepted as the normative "gold standard" for decision-making (Edwards, 1992) but its prescriptive value is still open to question. However, studies by Edwards and von Winterfeldt (1986) suggest that this argument may be irrelevant in practice, because of the *principle of the flat maximum*. This states that there is a limit to how precise any of these techniques can be, especially given the difficulty in verifying that the data fed into them is correct. Instead, alternatives are either so close together that it doesn't matter which is chosen, or far enough apart for even a simple technique to separate them. In short, the process of systematic analysis, and the insights this generates are more valuable than the specific numbers and rankings that emerge from these techniques.

A limiting factor in any decision is that humans are subject to *bounded rationality*: there is a limit to how much information we can actually consider (Simon, 1957). A decision tree could potentially go on forever, and there will always be more information that could be brought into a decision. Thus, any algorithm will end up working with incomplete information, and its answers can only be "correct" within certain limits. Part of the decision analysis process is helping decision-makers focus on the most important factors in the given decision.

The mathematics underpinning decision algorithms *are* important, and care must be taken that the chosen algorithm does not conceal or discard information

without the decision-makers realising it (Scott and Antonsson, 1999; Saari and Seiberg, 2004). But there is also a trade-off between effort and accuracy: any algorithm will lose its normative strength if there is not the time or resources to apply it properly (Payne *et al.* 1993). In the early stages of design, detailed information will be limited, and there is no sense in paying for a complex analysis when the necessary information isn't available. Furthermore, Franssen (2005) demonstrates that there is no general algorithmic solution to multi-criteria decision-making: decision-makers must instead select an algorithm that suits their situation, and be aware of its limitations. Matters become even more complicated once multiple decision-makers are involved.

2.2.2 Decision Analysis in Group Decisions

These algorithms assume that there is a single decision-maker, yet most design is carried out in teams. This applies especially to concurrent engineering, where cross-functional development teams may be in place, and many stakeholders in the product lifecycle need to be considered. This section discusses some of the complications introduced when applying decision analysis to a group decision.

The most famous, and perhaps most serious, problem encountered when applying decision analysis to group decisions is *Arrow's Impossibility Theorem* (AIT) (Arrow, 1973 – see Appendix One for a full description of this theorem). Arrow demonstrated that there was no mathematically consistent way of aggregating the preferences of multiple decision-makers as soon as three or more alternatives are available. Arrow's work was mainly concerned with social decision-making, such as voting in elections, but the mathematical issue applies just as much to any decision analysis technique. Hazelrigg (1996b) identifies this as the source of all sub-optimality in engineering design, and a serious problem for techniques beyond decision analysis, such as Total Quality Management and Quality Function Deployment. Scott and Antonsson (1999) argue that AIT does not apply to design decisions, where trade-offs are made between criteria, not individual preferences, because designers work to an imposed specification. However, Franssen (2005) demonstrates that AIT applies to every MCDM algorithm – even where there is only a single decision-maker – and applies as much to their use in design as anywhere else.

Game Theory (von Neumann and Morgenstern, 1947) provides one way around AIT, by modelling decisions between *competing* decision makers, who are treated as "players" each seeking to maximise their "payoff". Each player controls a set of decisions which affects their own payoff *and* the payoffs to the other players. Each decision-maker must therefore take account of the choices the other players

will make, but there is no requirement for equity: each player pursues their own best interest. Payoffs are not necessarily financial: other measures of preference can be used, and vN-M utility was developed for exactly this purpose. Game Theory provides a set of tools for analysing these situations, letting decision-makers estimate how the others will respond if they take a given course of action.

Because these approaches focus on the mathematics of decision analysis they do not address the *social* aspects of decision-making, which are important in *any* human activity system, including design. While judgements in terms of *fact* may be reconciled by reference to objective data, judgements in terms of value will always be open to debate. Bucciarelli (1994) stresses the importance of recognising design as a *social* process, conditioned by the experiences, views and interpersonal relationships of the designers, which cannot be reduced to an algorithm. Badke-Schaube and Frankenberger (1999) also highlight the importance of experience, social competence and informal hierarchies in design decisions. To back this point of view up, Bucciarelli (1994, pp151-165) cites the example of a design team trying to apply a Pugh matrix, but failing to even agree the criteria. Bucciarelli argues that the criteria are a social – as well as a technical – issue, determined by the most vocal members of the group. Even the question of getting a shared understanding of what the concepts and criteria mean is difficult. Yet, Bucciarelli argues that this application was a success: the team didn't make a choice, but arrived at a much closer understanding of one another's point of view. The Pugh method acted as a facilitator to the discussion, a way of raising and presenting arguments, to highlight disagreement and stimulate discussion.

The whole question of group decision-making becomes even more complicated once the issue of shared understanding is included: who sets the criteria? Are different individuals *really* agreeing to the same thing? Or are they attaching different meanings to the terms and ideas used? Where cross-functional design teams are being used, or advice from other lifephases is sought, these social issues and different points of view become particularly important. This further calls into question the quantitative value of any numbers generated by a decision analysis algorithm, but does not make decision analysis useless. Rather, it shows that the main benefit of formal decision analysis lies in providing a framework for discussion, that the *process* is more important than the mathematics. This supports Edwards' principle of the flat maximum: that it is more important that a formal method is used, than exactly which algorithm is adopted.

This issue is not unique to design: decision-making in any human activity system faces these problems, and the same conclusions apply (Munda, 2004). Mingers and Rosenhead (2004) point out that problem-solving and analysis

techniques rely on well-defined problems, and are less able to cope with "unstructured" problems. They cite the characteristics of "unstructured" problems as:

- multiple actors,
- multiple perspectives,
- incommensurable and/or conflicting interests,
- important intangibles,
- key uncertainties.

Design problems exhibit these characteristics, especially in the early and intermediate stages of design, where traditional analysis methods are difficult to apply (Finger and Dixon, 1989) and the problem itself is evolving. Nevertheless, Mingers and Rosenhead (2004) point out that there are still techniques that can be applied to investigate these complicated, unstructured problems in a systematic way. These methods place more emphasis on a reflective process and developing understanding than on the mathematics employed in making a decision.

Despite their focus on the mathematics of decision-making, decision analysis techniques can be used in exactly this way. Bucciarelli's (1994 pp151-165) example of the Pugh method demonstrates how the process of deriving the numbers and criteria helps designers to develop a shared understanding of the situation. Phillips (1984) argues that the models developed in decision analysis should be *requisite*, rather than *optimal*: just enough to solve the problem. Phillips approaches this through a method known as *Decision Conferencing*, getting decision-makers to work as a group to develop a shared decision model. This circumvents AIT by not aggregating the decision-makers' preferences: rather, through discussion and negotiation, they arrive at a decision model that they can all subscribe to. The goal of decision conferencing is "not...the identification of an objectively best solution, but...the achievement of shared understanding, the development of a sense of common purpose, and the generation of a commitment to action" (Mingers and Rosenhead, 2001, p533). This thesis therefore examines the use of decision analysis not as a mathematical process for reaching an optimal balance between different lifecycle concerns, but as a structured way of bringing those concerns together in design decisions.

2.3 Decision-making in Engineering Design

Given the importance of decision-making in the design process, it is not surprising that decision analysis has often been applied to design decisions: this section reviews these applications. The first half discusses general applications of decision analysis to engineering design decisions and proposes a general model of

how decision analysis is used in design. The second half examines the specific case of game theory as a tool for concurrent engineering, and raises an objection to this approach.

2.3.1 Decision Analysis in Engineering Design

This thesis focuses on a specific class of decision: the explicit analysis of a set of designs when the designers are deciding which to pursue further. The level of detail of the designs increases with each design decision, while the level of uncertainty about the finished design decreases. Design methodologists find it convenient to distinguish between *conceptual* design, *layout* (or *embodiment*) design, and *detail* (or *parametric*) design (Pugh, 1990; Pahl and Beitz, 1996). The boundaries and definitions of these stages are not well-defined (especially in practice), and there is often iteration between (and within) the stages. It is possible for different aspects of a design to progress through these stages at different rates: for example, some components might be almost complete while others are only concepts. Nevertheless, it is important to understand that the methods and techniques suitable to parameter design are less useful in the early, more uncertain stages of design, and vice versa.

From a decision analysis point of view, the basic elements of the decision remain the same: only the level of detail and the level of certainty change. Each design decision adds more detail to the proposed *physical* nature of the artefact, and the alternatives available in each decision are the different elements that could be added. As it is unlikely that complete design alternatives will be generated before any choices are made, each alternative normally addresses only a subset of the physical nature of the overall design. The set of alternatives are therefore the result of the *synthesis* stage of the design loop. Conversely, the *criteria* in a design decision represent the *intentional* nature of the artefact, and are therefore drawn from the requirements specification laid out for the design. Other elements (the personal taste of the designers, what makes their life easier in the next stages, interpersonal politics), can influence the choice made, but these biases should be avoided. Any application of decision analysis to the design process must analyse the proposed designs' performance against the requirements specification, and avoid influences that don't stem from the artefact's intentional nature.

Given the importance of decision-making in design, a field known as *decision-based design* has developed to study the use of decision analysis in the design process. The most prominent work in this area has been done by George Hazelrigg, who has proposed both a framework for decision-based design (Hazelrigg 1996a, 1998), and an axiomatic basis for engineering design (Hazelrigg, 1999). Hazelrigg's

axioms are based on the von Neumann-Morgenstern axioms, arguing that design decisions must conform to these axioms to be considered rational. Importantly, he adds one final axiom: only *real* alternatives can be considered in engineering design. Hazelrigg's framework (see Figure 13) measures utility across the projected profit that the design will generate for the company, arguing that this is the *only* attribute of interest to commercial manufacturers. This is based on demand forecasts derived from the attributes of the design, and the price set for the product. Hazelrigg's framework considers decision-based design from a normative, theoretical perspective: it provides an abstract pattern for design to follow, but does not specify techniques for putting this theory into practice.

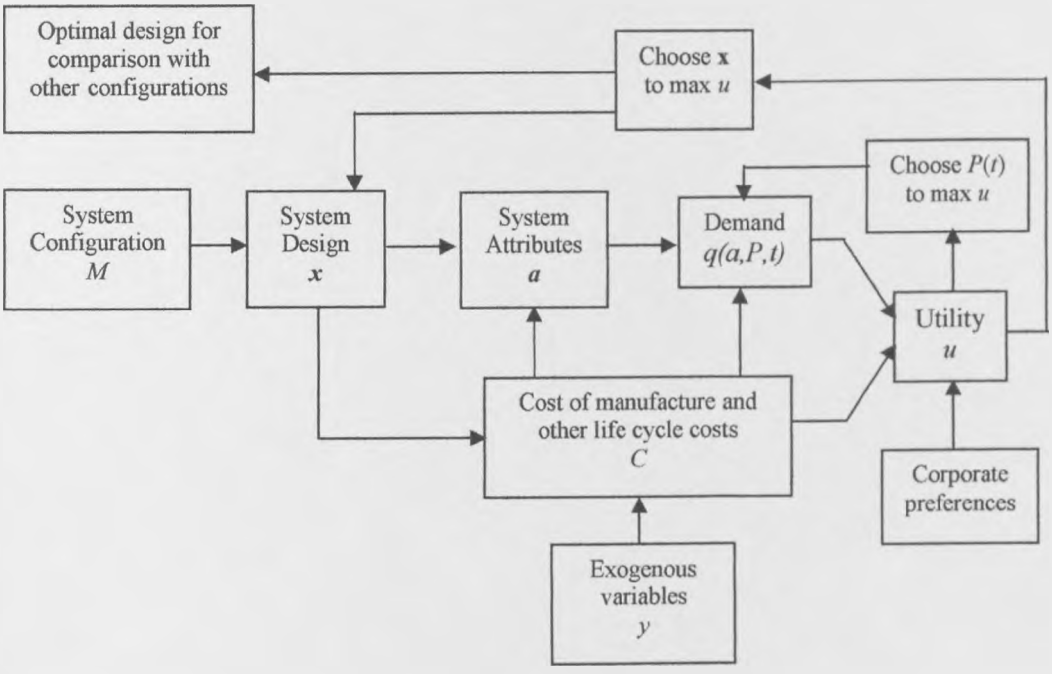


Figure 13: Hazelrigg's framework for Decision-Based Design

Several researchers have translated the theory behind decision-based design into prescriptive methodologies and tools for design practice, normally by taking existing methods and replacing their measures with vN-M utility. Gu *et al.* (2002) have incorporated Hazelrigg's framework into Renaud and Tappeta's (1997) work on Multi-objective Collaborative Optimization, replacing the normal "objective function" with Hazelrigg's utility measure. Similarly, multi-attribute utility has been applied to Muster and Mistree's Decision Support Problem Technique (Fernandez *et al.*, 2005), Quality Function Deployment (Thurston and Locascio, 1993) and Optimization (Thurston *et al.* 1994). In all these cases, the "ad hoc" measure used by the original method is replaced with more rigorous vN-M utility. However, these methods are all concerned with the selection of parameters, in the *detail* stage of the design process.

Some researchers have examined the use of decision analysis techniques in the earlier stages of design. Design methodologists such as Pahl and Beitz (1996) or Pugh (1990) advocate the use of simple decision algorithms such as the weighted objectives tree for concept or embodiment selection. Hsiao (2002) applies the analytic hierarchy process to concept selection, while Wang (2001) uses fuzzy outranking, based on ELECTRE, for the same purpose. Thurston and Carnahan (1992) suggest that the effort of applying utility theory and the uncertainty about a design in its early stages make methods such as fuzzy ratings more appropriate. Thurston (2001) also argues that the most appropriate tool for a given design decision depends upon the phase of design, and the complexity of the decision. This reflects the conclusions from general decision analysis: that there is no single "correct" technique and that decision-makers must instead choose the most appropriate method for their situation.

Regardless of which algorithm is adopted, all fit the same general model (as shown in Figure 12), and therefore fit into the design process in the same way. However, there is an important difference between conventional decision analysis and the way candidates are normally evaluated in design. Designers often screen out proposals that do not meet certain minimum requirements (Scott and Antonsson, 1999; Agouridas and Steenson, 2004), effectively including a Screening stage, prior to Ranking, as shown in Figure 14.

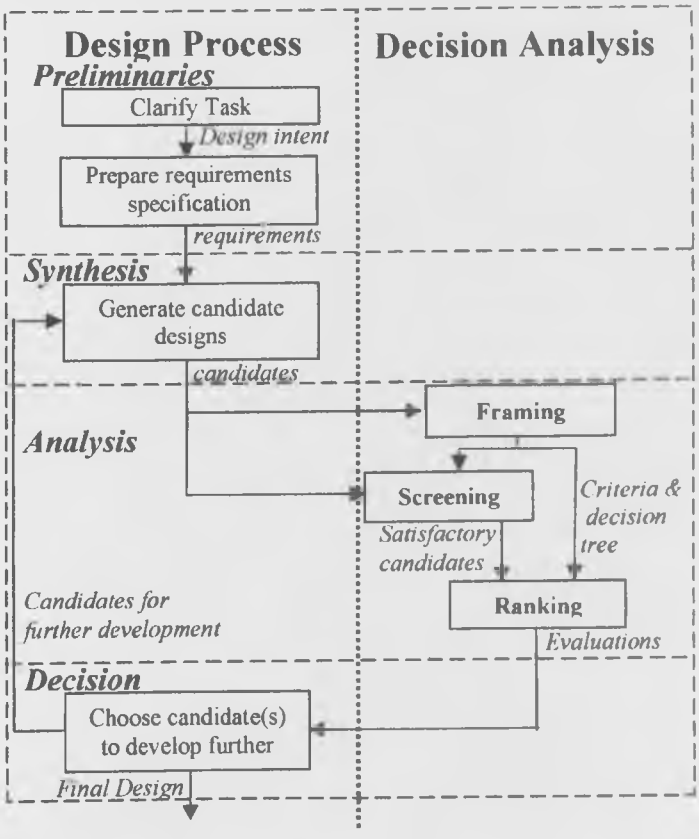


Figure 14: Decision analysis in the design process

This is the approach to decision analysis adopted for the purpose of this thesis, and forms the basis of the methodology presented in the next chapter. However, this only addresses design – there is still the question of how decision analysis can be extended in concurrent engineering to allow early involvement of all constituents.

2.3.2 Game Theory and Concurrent Engineering

In concurrent engineering, designers are expected to take account of the choices made at every stage of product development, as they all affect the performance of the finished product. Several researchers argue that this is analogous to game theory, and have suggested ways of using it to implement concurrent engineering (Vincent, 1983; Steinhour and Krishnamurthy, 2001; Xiao *et al.* 2002; Chen and Li, 2002). All treat each lifephase as a separate player, with their own goals and control of decisions related to their lifephase. This highlights the relationship between lifephases and virtues: the lifephase defines which decisions a player controls, but without a related virtue, there is no way to evaluate their payoff. Manufacturing players, for example, do not optimise "manufacturability", but "manufacturing cost". By not requiring equity, game theory circumvents AIT, and because each player formulates their own pay-off function, conflict can be resolved mathematically without recourse to interpersonal agreement or negotiation.

Despite these benefits, and leaving aside any objections about the difficulty of formulating payoff functions, two objections can be made to the use of game theory in concurrent engineering. Firstly, it only addresses lifephases, as virtues don't control any decisions: there is no player to represent "environmental impact" or "reliability". The "design" player could be subdivided into a set of players representing these virtues, each controlling any design decisions that affected their given virtue. However, some decisions may affect multiple virtues (material selection, for example, may influence function, environmental impact and cost) – so control cannot be easily allocated. Virtues could be reflected in the payoff functions of the players who controlled the relevant decisions, though this still leaves the question of how trade-offs between them should be assessed. Secondly, as shown in Chapter 1, the purpose of concurrent engineering is to get *all* stages of product development thinking about the product as a whole: every lifephase and every relevant virtue. Design does not "win" if they get a design that is very functional, but impossible to make; and manufacturing does not "win" if they achieve a cheap design that no one will buy. This may be how the actual participants see the product development process, but it is hardly to be encouraged. Game theory may be a legitimate way of modelling the behaviour of decision-makers with whom one *cannot* co-operate, but placing players in competition contradicts a core principle of concurrent engineering.

Nevertheless, these two objections can be overcome. If one could propose a structured way of incorporating virtues into the players' payoff function, then both lifephases and virtues would be covered. If constructing payoff functions is taken not as the solution to a mathematical problem, but a chance to investigate different viewpoints in a structured manner, then the second objection disappears. At this point, the approach ceases to be game theory, and becomes *decision conferencing*, which is the approach adopted in this research to satisfy the desiderata described in the next section.

2.4 Desiderata for Analysing Designs from a Product and Process Perspective

With no accepted standard for "good" or "better" designs, it is important to express clearly what these are taken to mean in the context of this research. This is necessary for other academics and practitioners to make meaningful judgements about the relevance and implications of this work to their own. It also helps to avoid researcher bias by providing a formal standard against which the outcomes of this research can be evaluated, and a justification for that standard. This is done by defining and justifying a set of desiderata, which establish exactly what combining decision analysis and DfX should achieve.

In decision-making, rationality is generally accepted as something that decision-makers should conform to, though there is no absolute standard for what constitutes "rational" behaviour. Watson and Beude (1987) suggest that the best solution is to argue that "we are rational when, having adopted rules which our statements or actions should conform to, we act in a way that is consistent with them..." The situation is complicated in design, as the designers do not satisfy their own preferences, but those of their organisation and its hypothetical "customer". Supply chains make this matter even more complicated, as multiple "customers" at different stages of the supply chain may need to be considered. There is one simplifying factor: the intentional nature of the product being designed.

As the purpose of any design process is to fulfil this specification, the specification can therefore be taken as a basis for rationality in the design process. The view taken in this research is that the goal of any rational designer is to fulfil the given specification. Any designer not conforming to this standard is acting contrary to the goals of the design process and can therefore be considered *irrational*. As design is a social process, then any individual designer may rationally respond to personal preferences or political pressures, but such behaviour is to be acknowledged, rather than encouraged. Prescriptive methodologies must encourage

the designers to reach a conclusion that is "rational" given their specification, despite these social issues.

The desiderata need to reflect three important factors. Firstly, the proposed methodology must be compatible with the design process. It must reflect the intentional nature of the product, and must not contradict the approach to design evaluation shown in Figure 14. Secondly, it must incorporate "early involvement of constituents", as this is the purpose of Design for X techniques. Finally, there are two additional constraints that decision process should obey in order to be valid: that a decision process should be logical, and should draw on available information[3] (Olewnik and Lewis, 2005). Together, these are addressed by the following set of eight desiderata: to allow extension of this work beyond IPPD, they address DfX in general and not just DfM.

Desiderata for Compatibility with the Design Process

(see Sections 2.2 and 2.3)

1. Criteria used for evaluation should be based only on the requirements specification.

As the intentional nature of the product is the only rational basis for making choices about it, then this should be the only source of evaluation criteria. Any additional criteria, not related to the purpose of the product, will only bias the evaluation away from the purpose of the product. For the purpose of this thesis, it is assumed that the intentional nature of the product is captured as a formal requirement specification, which should provide the basis for evaluation criteria. If designers feel that criteria *not* derived from the requirements specification are important enough to warrant inclusion in evaluation, then the requirements specification should be updated to reflect them.

[3] Olewnik and Lewis also state that the decision-methodology should not impose a preference structure on the designer. This is already addressed by the argument that decisions should be based only on the requirements specification, and is reflected in the first desideratum.

2. Criteria used for evaluation should represent the full requirements specification as completely as possible.

Just as additional criteria not related to the intentional nature of the product can bias a decision, so can omitting aspects of the intentional nature. Evaluation should be as complete as possible, and therefore should include criteria for as many of the requirements as possible. This "as possible" is important: given that the requirements specification applies to the finished product, it may not always be possible or necessary to evaluate an incomplete design against every single requirement. Nevertheless, requirements that are omitted should be left out *only* because they are not appropriate for the given decision.

3. Designers should be free to define the context of evaluation by defining the alternatives to be considered.

Given the huge range of decisions that designers might face, and in the absence of a comprehensive taxonomy of design decisions, it is not for the methodology to impose what the designers can evaluate, and when. Instead, it should be up to the designers to decide when they wish to evaluate the designs they are generating.

4. Designs that cannot satisfy the minimum requirements specification should be eliminated from the choice entirely.

Proposals that cannot fulfil the intentional nature of the design are entirely redundant, and it is common practice in design to screen out such proposals rather than wasting effort in ranking them.

5. The decision-makers should be left free to choose a ranking algorithm to suit their needs.

Decision research recommends that decision-making should be adaptive, choosing an algorithm to suit the given situation. Just as the methodology should not dictate when designers should face a decision, it cannot dictate which algorithm they should use.

Desideratum for Early Involvement of Constituents

(See Section 1.1.1)

6. The designers should consider the whole product lifecycle when evaluating the design.

This is the purpose of concurrent engineering. Notice that virtues do not need to be covered by this desideratum: if a virtue is important, it should be reflected in the requirements specification, and will be covered by the first and second desiderata. In IPPD this reduces to considering manufacture when evaluating the design.

Desiderata for a Valid Decision Process

From Olewnik and Lewis (2005).

7. The methodology should not introduce any inconsistencies into the decision process.

To be rational, a decision-making process must be internally consistent. Care must be taken that bringing DfX information into the decision analysis process does not introduce any inconsistencies that might interfere with the decision process.

8. The methodology should only draw upon available information.

Logically, evaluation can only be based on information that is available at the time: otherwise, the evaluation would have to be based on guesswork. This is particularly important in design, where the alternatives being evaluated are not fully detailed. The methodology should therefore only require the designers to use information provided by existing Design for X techniques.

These eight desiderata indicate what the proposed methodology must do if it is to be deemed acceptable, and provide a formal basis for its evaluation. In short, the methodology must bring early involvement of constituents into the existing design evaluation process without introducing any logical inconsistencies or demanding information that is not available. These desiderata provide the basis for checking the *coherence* of the methodology. Chapter 3 will propose a way of satisfying them by

extending the existing design evaluation process to incorporate information provided by Design for X techniques.

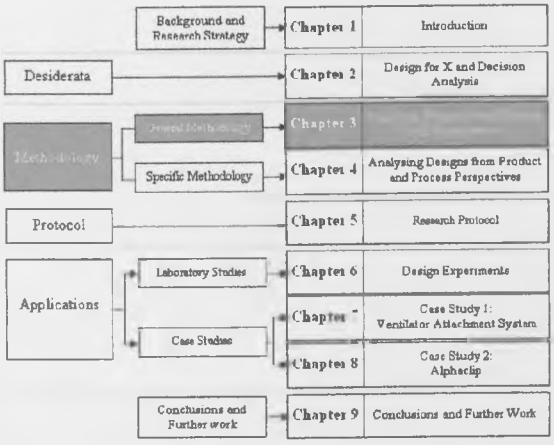
2.5 Summary

Design for X techniques support two design activities: *synthesis* (by generating designs suitable for the virtue or lifephase) and *analysis* (by evaluating designs against the virtue or lifephase). Decision analysis only applies to the latter, so it is here that this thesis concentrates. DfX supports the analysis of virtues and lifephases in different ways. DfX_{virtue} techniques prompt designers on important issues that they should consider in the decision, and also provide metrics for evaluating the physical nature of the design against the virtue. As it is impossible to evaluate a design against a lifephase in itself, $DfX_{lifephase}$ techniques help designers to understand how their choices will affect those made at the given lifephase. They often incorporate some element of virtue as a metric (for example, in DfM, this is manufacturing cost), so that designs can be evaluated.

This distinction between the way virtues and lifephases are handled by DfX techniques reflects the two main tools in decision analysis: the decision tree and the MCDM algorithm. Decision trees map out the alternatives and expectations in a decision, and therefore $DfX_{lifephase}$ techniques can help designers to construct and navigate decision trees. MCDM algorithms evaluate the expected outcomes of each alternative against a set of criteria, which can incorporate the metrics provided by DfX_{virtue} techniques. Many MCDM algorithms are available, but there is no consensus on which is correct, and the mathematical foundations of these techniques do not hold in group decisions. Therefore, it is accepted that the value of these algorithms comes not from their normative, mathematical correctness, but from the structured approach they provide to evaluation. The use of decision analysis in design is already a subject of research, and the Game Theory is often suggested as a way of applying decision analysis to concurrent engineering.

There is no agreed way of evaluating decision-making techniques, so this chapter has proposed eight *desiderata* that a design decision should satisfy in concurrent engineering. These are based on the need to fit in with the design process, to consider all constituents in design, and a set of constraints on decision analysis. However, this still leaves the issue of *how* DfX information can be used in conjunction with decision analysis, which the next chapter considers.

Chapter 3
Analysing Designs from Multiple DfX Perspectives



If the limitation of existing DfX techniques is that they only consider a single virtue or lifephase, then to have any additional value, new methods must be extensible to *any* virtue or lifephase. Although the scope of this thesis is limited to integrated product and process design, a more general methodology is needed that could apply, in principle, to *any* virtue or lifephase. This can then be adapted to the specific case of integrated product and process design. This chapter begins to address the second objective of this research, by proposing such a methodology, and comparing it with the desiderata that it is intended to satisfy.

This Chapter is divided into four sections. **Section 3.1** discusses the purpose of the proposed ***methodology***, and how it will fit into the design decision-making process. **Section 3.2** discusses the relationship between DfX techniques and decision analysis, and how this can be used to bring DfX information into a formal decision-making process. **Section 3.3** embodies this relationship as a five-stage methodology for using DfX information in design decisions. **Section 3.4** then compares this methodology with the ***desiderata*** on a logical basis, to show that the methodology is logically coherent.

3.1 Overview

In order to propose a methodology, one must understand its purpose and the process it will fit into: this section considers both. The first half reviews the purpose of the methodology; the second discusses the assumptions about design decision-making and decision analysis that underpin it.

3.1.1 Purpose of the Methodology

The methodology proposed in this chapter addresses one of the perceived shortcomings of existing DfX techniques: that there is no coherent way of relating them to one another, or to the overall purpose of the product. The central argument

of this thesis is that decision analysis provides a way of bringing DfX information into design evaluation without imposing a preference structure. The methodology is a way of testing this argument, by using the main tools of decision analysis – the decision tree and MCDM algorithm – to link DfX information with design evaluation. To preserve the benefits of decision analysis – its rigor and structure – an equally rigorous and structured way of bringing DfX concerns into decision analysis is needed.

While DfX techniques are available to support both synthesis and analysis, decision analysis tools only apply to the analysis stage of design (see Figure 3, page 9). A design whose synthesis has been influenced by a DfX tool will still be analysed, so decision analysis is compatible with both approaches. It is also worth noting that the methodology cannot make a decision on the designers' behalf: the analysis only *informs* the choice. Therefore, this methodology is only concerned with the analysis stage of the design loop.

This chapter presents a methodology in the sense defined by Checkland (1999): a set of principles of method, based on decision analysis. It provides an approach to solving the given problem, which can be implemented as methods, but there are many different ways that the same methodology could be put into practice. The methodology presented here is general enough to accommodate a range of DfX and decision analysis techniques, and does not prescribe which should be adopted. Instead, it provides a framework for using them together in a way that satisfies the desiderata and fits into the design decision-making process.

3.1.2 The Basic Design Decision-Making Process

As there is no commonly accepted definition of the design process, it is necessary to state that the assumptions about the design process and design decisions that will underpin this methodology. The previous chapter, Section 2.3.1 showed how decision analysis is normally applied in the design process (see Figure 14, page 41), a model which this methodology is built upon.

The first and second desiderata assume the existence of a formal requirements specification, which should act as the basis for *every* design decision. The methodology assumes that this specification has already been developed and clarified before any decisions are taken and offers no guidance or constraints on how this should be done. It also assumes that – for any given decision – the specification remains stable. While requirements may evolve during design, it is assumed that they do not change mid-decision, and that if they do, the relevant part of the analysis can be repeated. Formal guidance on this issue is beyond the scope of the methodology.

The third desideratum requires that the designers, not the methodology, should define the set of candidate designs to be chosen from. The methodology places no limits on this and offers no guidance on how designs should be generated, or what level of detail they should be at before they can analysed. It assumes that the candidate designs have been generated, so that a decision exists to be taken. It is up to the designers, not the methodology, to determine when they face a decision. Furthermore, the set of candidates could contain just one design, in which case the decision is whether to take it further, or generate more designs (a *satisficing* strategy, see Section 2.2.1). It is not up to the methodology to dictate what kind of decisions designers can take: rather, the methodology must respond to the kind of decisions that they *are* taking.

If a formal process is being used, then the decision must fall into this pattern. Otherwise, the decision would be implicit and not addressable through any methodology, as it – and its rationale – would be hidden.

The simple decision analysis approaches advocated by design methodologists can be applied at any level of detail, while more complex algorithms may be less appropriate early in design (Thurston and Carnahan, 1992; Thurston, 2001). By leaving the designers free to choose a decision algorithm, in accordance with the fourth desideratum, the methodology can avoid imposing limits on the scope of the decision. However, the requirements given in the requirement specification apply to the finished design, and may not be suitable for evaluating incomplete designs. While this is not a limit imposed by the methodology, it is an issue that the methodology must take account of. This means that the *criteria* used to take a decision need not be the same as the *requirements* that the designers seek to satisfy – only representative of them. Therefore, the methodology must address how designers get from the requirements specification to a set of criteria that are suitable for the decision they are taking. This issue has not received much attention in the field of decision analysis or design, except in the work of Keeney (1992).

Keeney argues that decision-making should be *value-focussed* – that decision-makers should start by thinking about what they want to achieve, rather than being anchored by the alternatives they perceive to be available. This frees the decision-makers up to "think outside the box", perhaps finding new alternatives as they reframe the decision. However, Keeney also notes that – to make reasonable comparisons between the alternatives – the criteria also need to be based on the alternatives that are being compared, and measures that can be applied to all of them. This is exactly the problem faced here, and the methodology draws upon Keeney's solution (see Section 3.3.1, below).

In order to bring DfX information into decision analysis, the methodology must reflect how this information relates to the *expectations* and *values* of a decision. The *alternatives* (the design candidates) are determined by the designers, in accordance with the third desideratum: how they are influenced by DfX information is therefore beyond the scope of this research. Expectations relate to the decision tree, and are therefore related to product development choices and their consequences: the information provided by $DfX_{lifephase}$ tools. Values, on the other hand, are provided by the requirements specification, with Keeney's work on value-focussed thinking bridging the gap between the requirement specification and the status of the candidates defined by the designers. DfX_{virtue} techniques are tied to the intentional nature of a product (see Section 1.2.2), and help to highlight issues that should be considered for inclusion in the requirements specification. They also help to relate elements of the requirements specification to measurable design characteristics, so that criteria for evaluation can be established. In this way, they can be incorporated in a decision through the MCDM algorithm, and related to the outcomes identified by $DfX_{lifephase}$ techniques. The next section considers this relationship.

3.2 Bringing DfX Information into the Decision

Though many decision analysis techniques exist, and some are already used in design, as yet the relationship between DfX and decision analysis has not been investigated. This section addresses the issue by expanding on the links between DfX and decision analysis tools highlighted in Section 3.1.2, to explain how they can be used in design decisions. This section is divided into two halves, the first focussing on DfX_{virtue} techniques, while the second focuses on $DfX_{lifephase}$ techniques.

3.2.1 DfX_{virtue}

As virtues relate to a design's intentional nature (see Section 1.2.2), they reflect the values that should guide design decisions, and can be incorporated into the MCDM algorithm as criteria. Which virtues are relevant to a design will depend on its purpose, and DfX_{virtue} tools should be chosen on the basis of the requirements specification. If a virtue is relevant, it should be reflected in the requirements, and considered supplemental to it. If a virtue does not warrant being included in the requirements specification, then it is not important to the purpose of the design and should not influence design decisions.

Once virtues are reflected in the requirements specification, they will automatically be included in the decisions, provided the first and second desiderata are satisfied. Furthermore, the support provided by DfX_{virtue} techniques can help

designers to translate elements of the requirements specification into criteria suitable for the given decision.

The support provided by different DfX_{virtue} techniques will vary, and there may be several different techniques available for a given virtue. Where metrics are provided, these can be used as quantitative measures for criteria and preference across them measured normally, using the MCDM algorithm adopted. If no metric is provided, or it cannot be applied at the current stage of design, then the designers will have to construct surrogate measures instead. The qualitative support provided by DfX_{virtue} techniques, such as guidelines, can assist designers in formulating appropriate surrogate measures.

Table 4 shows some examples of the metrics provided by DfX_{virtue} techniques, which flag up important issues and help designers develop evaluation criteria for the given perspective. Once the criteria are established, no further action is needed: the virtue will be reflected in screening and/or ranking, as appropriate.

Table 4: Metrics provided by DfX_{virtue} techniques

Virtue	Example Metric	Source
Environmental Impact	Dimensionless multi criterion Environmental Metric *(based on: Depletable Material; Energy; Global Concerns; Hazardous Material; Local Concerns)*	Veroutis and Fava (1996)
Cost	Parametric Cost Estimates; Activity Based Costing	Roy (2003)
Quality	Taguchi Loss Function	Taguchi (1986)
Reliability	Failure Rate	Edson and Tian, (2004)
Affective Design	Backward Kansei	Matsubara and Nagamachi (1997)

3.2.2 $DfX_{lifephase}$

$DfX_{lifephase}$ techniques help designers navigate the decision tree, so that they can consider how their decisions affect downstream choices, and how these affect the design's performance. Not every requirement will be affected by every lifephase, so the decision-makers need to consider which requirements each lifephase will influence. Sometimes, $DfX_{lifephase}$ techniques provide a metric such as manufacturing cost, or a maintainability index (see Section 2.1.3) to help choose between designs. These can be treated exactly like the metrics provided by DfX_{virtue} techniques. If they are relevant to the design's purpose, that can be reflected in the requirements specification, and will be included in the criteria for the decision. This section considers the other aspect of $DfX_{lifephase}$ support: understanding downstream choices and their consequences. Whereas virtues can be included in the evaluation when criteria are established, a normal phase in decision analysis, establishing the feasible and probable choices at each lifephase requires an additional stage: *validation*.

This gets designers to think about the options available at each lifephase, and to consider which are feasible for each proposed design: effectively, creating a decision tree. This is carried out separately for each lifephase, so a design evaluation may include a series of validation stages, covering manufacture, assembly, end-of-life, etc. Each validation stage involves four steps, using information provided by $DfX_{lifephase}$ techniques.

STEP 1: *Identify the important choices to be made, and the options available, at the given lifephase.* This helps the designers to draw the next stage in the decision tree. For example, Design for End-of-life (Rose *et al.* 2002) highlights possible end-of-life strategies: disposal, reuse, servicing, remanufacture and recycling.

STEP 2: *Eliminate choices that are infeasible for each candidate design.* This restricts the decision tree to realistic outcomes. For example, it is pointless to adopt a servicing approach to extend the life of a product whose technology becomes obsolete before it wears out.

STEP 3: *Eliminate infeasible candidates.* If there are no feasible choices at the given lifephase, then the candidate is not feasible, and should not be developed further. Designers always have the choice of revising the design, or looking at ways of expanding the range of available choices. In this way, designers can avoid pursuing candidates that are already expected to be dead-ends.

STEP 4: *For each candidate, identify the most likely choices at the given lifephase.* At the evaluation stage, the goal is to evaluate a design based on its expected lifecycle, not to make every development decision simultaneously. Therefore, decision-makers may wish to restrict their attention to a small number of lifephase choices for each candidate. In Design for End-of-Life, for example, appropriate strategies are selected by comparing the wear-out life of a product against its technology cycle (Rose *et al.* 2002).

Table 5 shows some examples of the decision support that $DfX_{lifephase}$ techniques provide that can be used in Validation. At the end of this process, the designers will have a set of candidates that are expected to be feasible, and the likely lifephase choices associated with them. These can be passed on for screening and ranking, with the expected lifephase choices used to help evaluate the design against the relevant requirements. In this way, $DfX_{lifephase}$ information is incorporated into the decision tree, while DfX_{virtue} information is brought into the MCDM algorithm. This can be done for any number of virtues or lifephases, and provides a structured way of incorporating both in a decision.

The next question is how validation can be incorporated into the design decision-making process, to form the proposed methodology for using DfX_{virtuc} and $DfX_{lifephase}$ techniques in design evaluation.

Table 5: Feasibility and desirability estimation by $DfX_{lifephase}$ techniques.

Lifephase	Choices	Feasibility Assessment	Basis for Selection	Source
End-of-Life	End-of-Life Strategies (Reuse; servicing; remanufacture; recycling; disposal)	Comparison of Wear-out time with technology cycle	Minimise environmental impact.	Rose *et al.* (2002)
Assembly	Available joining processes	Compare process capability with characteristics of joint;	Minimise assembly cost	Swift and Booker (2003)
	Possible Assembly sequences	Feasibility of physically assembling parts in the given sequence	Minimise assembly cost	Barnes *et al.* (2004)
Manufacture	Available manufacturing processes	Comparison of process capabilities with characteristics of component	Minimise manufacturing cost	Swift and Booker (2003)

3.3 The Methodology

This section presents a methodology that builds upon the design decision process described in Section 3.1, to incorporate the needs of DfX techniques described in Section 3.2. The methodology has five stages, illustrated in Figure 15, which are described in the three parts of this section. This relates DfX information to the design loop as shown in Figure 16. The Preliminaries and Framing, described in Section 3.3.1, lay the foundations for the decision, by gathering the necessary information, checking the completeness of the requirements specification, and deriving from it criteria for the decision. Screening and Validation, described in Section 3.3.2, eliminate designs that are either unsatisfactory, or infeasible. Finally, Ranking, described in Section 3.3.3, takes the surviving designs, which are expected to be both feasible and satisfactory, and uses an MCDM algorithm to estimate which is the most promising.

Like any decision analysis process, this methodology does not take decisions on the designers' behalf, nor does it calculate the "correct" choice. Rather, it takes the designers through a structured process that gets them to relate DfX information to the designs they are evaluating, and the purpose the design must fulfil. It is not the numbers generated that are important, but the insights that the designers receive from going through the process.

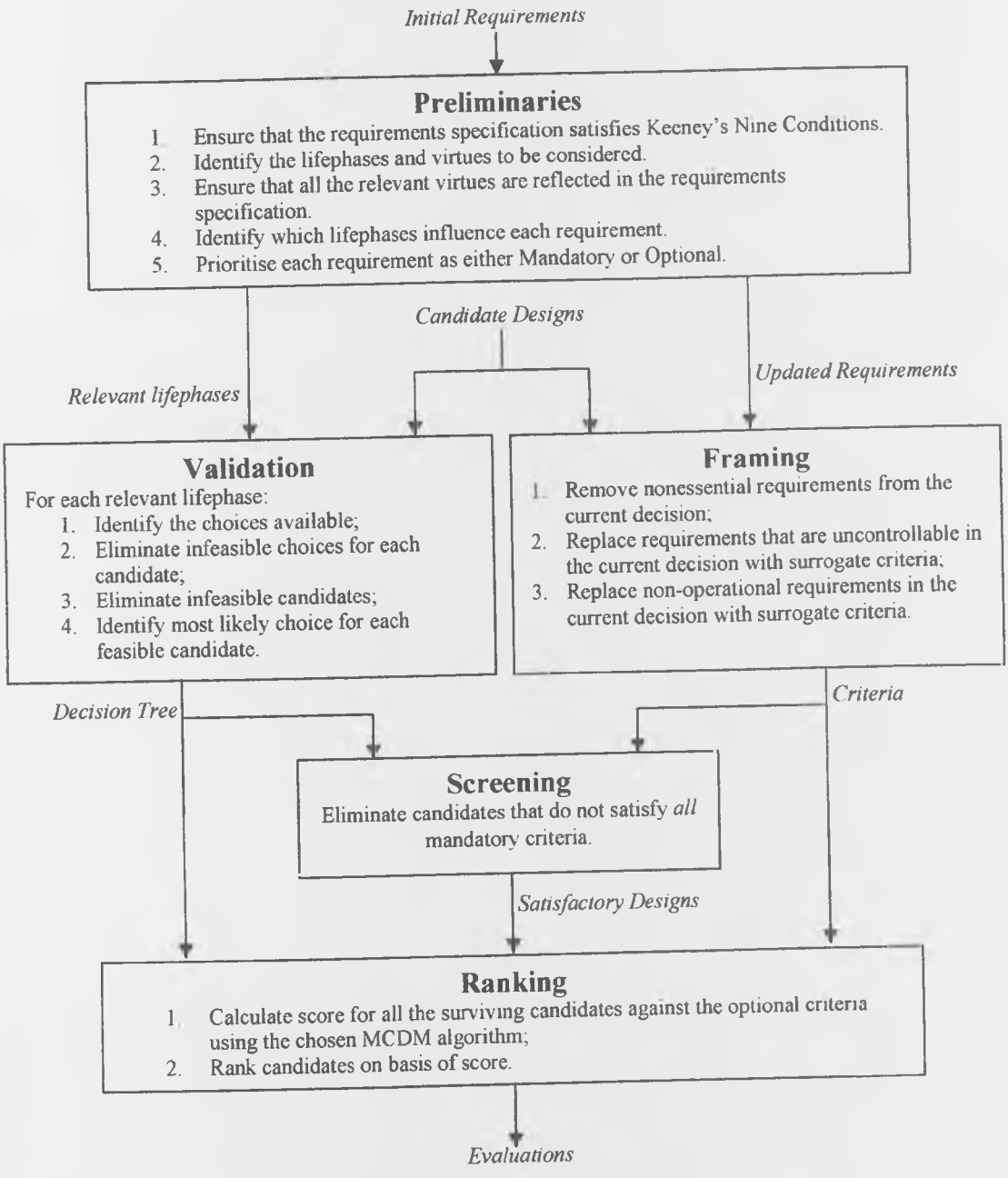


Figure 15: Methodology for incorporating DfX in design evaluation.

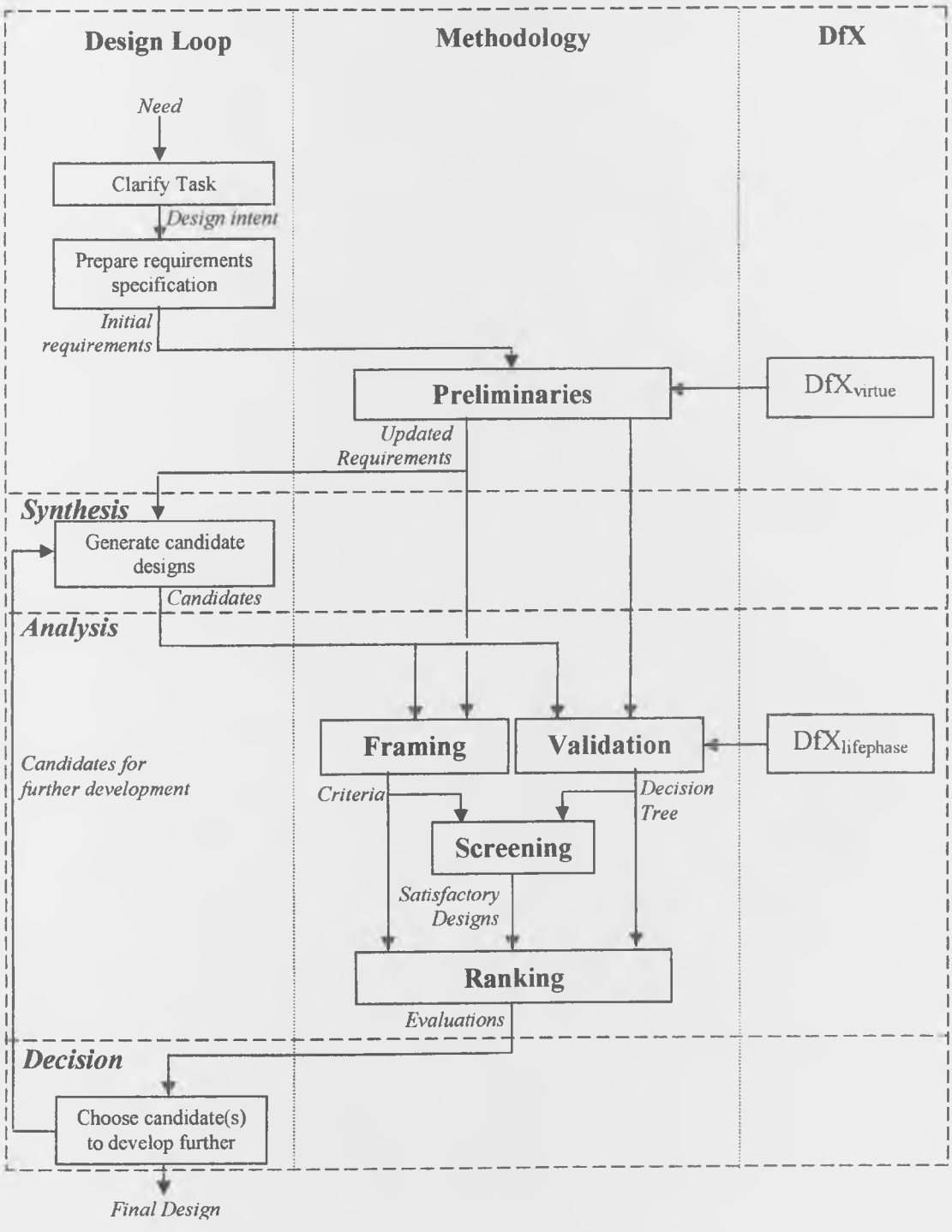


Figure 16: Relationship between the design loop, the methodology and DfX

3.3.1 Preliminaries and Framing

In any decision, it is critical that the criteria used to evaluate the alternatives are suitable: the first two stages of the methodology try to ensure this. Applying a formal decision process means that evaluation criteria are made explicit, and can be examined to avoid bias or inaccuracies that might prejudice the decision. The criteria for assessing the finished design are defined in the requirements specification, and it is essential for all stages of design that these requirements are as

accurate as possible. However, by their very nature, the designs being considered in most design decisions are incomplete, and the requirements may not be suitable for evaluating them at this stage. Such requirements cannot be ignored or left out of the analysis. Instead, surrogate criteria are needed that *can* compare each requirement against the designs in their current state. In the proposed methodology, the Preliminaries ensure that the requirements for the project are acceptable, while Framing translates these requirements into criteria that are suitable for the current decision.

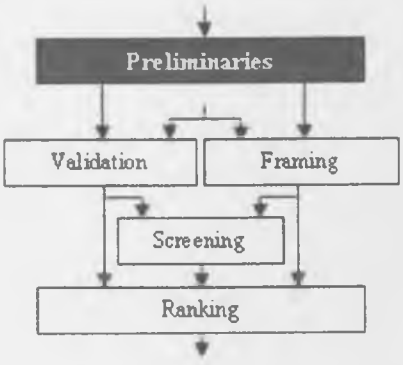
This raises the question of exactly what makes a set of criteria suitable for a given decision, especially when judgments in terms of value are subjective. However, while the intentions embodied by the criteria cannot be judged objectively, the way they are presented in the decision is open to assessment. Keeney (1992) argues that to be useful, a set of criteria should satisfy the nine conditions set out in Table 6. These provide a basis for assessing the suitability of a set of criteria to the given decision.

Table 6: Keeney's nine conditions for evaluation criteria

1. **Essential** – Every criterion's satisfaction should depend on which alternative is selected.
2. **Controllable** – Every criterion's satisfaction should depend *only* on which alternative is selected.
3. **Complete** – The criteria should represent all the important consequences of the decision.
4. **Measurable** – Every criterion should include an objective measure of effectiveness.
5. **Operational** – It should be possible to apply the specified measures of effectiveness to the outcome of the decision.
6. **Decomposable** – Preference over one criterion should not depend on the satisfaction of another.
7. **Nonredundant** – There should be no double-counting of criteria.
8. **Concise** – the criteria should be the minimum necessary to satisfy the seven conditions above.
9. **Understandable** – the criteria should be phrased in a way that the decision-makers can understand, and agree on.

From here on, *requirements* will be used to describe those criteria applied to the project as a whole, while *criteria* will only refer to those applied to a given decision. Requirements persist throughout the design project, and apply to every decision taken, although they may be adapted and refined as time goes on. Criteria, on the other hand, apply only to the current decision, and must be redefined for each new decision (although the same criterion might turn out to be suitable for more than one decision).

Preliminaries



The Preliminaries are independent of any given decision and need only occur once per design project, as their results will apply throughout. They can occur at any stage after the initial requirements have been specified, and before the first decision is taken using the methodology. They verify that the requirements are suitable for decision analysis, and that the necessary information is available for applying the methodology. This involves five steps:

1. Ensure that the requirements specification satisfies Keeney's Nine Conditions. Because the requirements specification forms the basis for evaluation throughout design, the requirements themselves should be acceptable as criteria for the finished product.

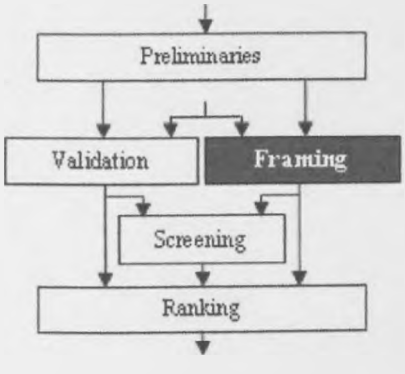
2. Identify the virtues and lifephases that are relevant to the product.

3. Ensure that all the relevant virtues are reflected in the requirements specification. To ensure the completeness of the requirements specification.

4. Identify which lifephases influence each requirement. As the performance of an alternative cannot be assessed against the requirement until the choices at the relevant lifephases have been estimated.

5. Prioritise each requirement as either mandatory or optional. This is standard design practice (Pahl and Beitz, 1996, Pugh, 1990), and indicates whether the requirement should be used for screening or ranking. The designers may also wish to prioritise the optional requirements, if appropriate, based on the MCDM algorithm they have adopted.

Framing



Unlike the Preliminaries, Framing (and the other stages of this methodology) must be repeated with each new decision taken. The purpose of framing is to translate the requirements specification into a set of criteria that are appropriate for the current decision. Three of Keeney's conditions pose particular problems for evaluating incomplete designs against requirements specifications, and each has a different solution.

***Essential*:** The current decision may determine no aspects of the design relevant to the requirement, in which case that requirement is *nonessential* for that decision. As it does not help to discriminate between alternatives, it can be safely omitted from the analysis. There is no harm in retaining it, but it increases the effort required for analysis, without providing any benefit. If a requirement is nonessential, then it does not measure an important consequence of the decision, and can be omitted without compromising the completeness of the criteria for the given decision.

***Controllable*:** Even if the current decision has some bearing on the satisfaction of a requirement, that satisfaction may also depend upon subsequent decisions. In this case, it is impossible to evaluate the requirement's satisfaction at the current stage, but it cannot be ignored. Instead, one or more surrogate criteria must be used as an indicator of the alternatives' expected performance against the requirement. They may measure related factors (such as volume, where weight cannot be calculated), or may be simple stand-ins (expert judgement, simulations). It is important that some criterion is used to represent the requirement; otherwise the criteria will be incomplete.

***Operational*:** Even if the decision determines all aspects of the design that affect the requirement, it may not be possible to measure the alternatives' performance because they do not physically exist. In this case, alternative criteria must be adopted as indicators. These may be simulation results, expert judgement, or other forms of estimated quantity. For example, if the requirement calls for focus group approval, but no focus group is available, then the designers must look for other ways of evaluating the design. Again, it is important that the requirement is represented by some criterion, for the sake of completeness.

If a requirement does not violate *any* of these three issues, then it may be used as a criterion for the current decision. Surrogate criteria inherit the priority of the requirement that they represent, and the influence of the same lifephases must be considered.

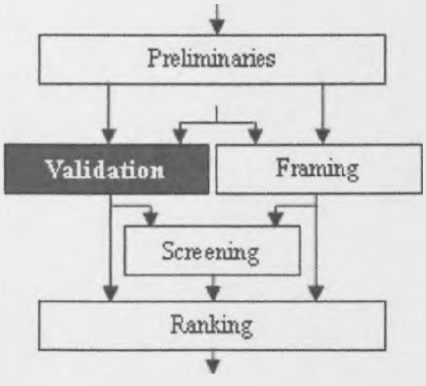
With the criteria for the specific decision established, the designers must assign scoring functions to each criterion. For mandatory criteria, these will

be aspiration levels (see satisficing, under Section 2.2.1). For optional criteria, this will depend on the MCDM algorithm adopted for ranking: the relevant procedure for that algorithm should be used. At this point, the designers should have a set of criteria that are suitable for applying to MCDM, and can be related to the DfX tools representing the virtues and lifephases the designers feel are important. The next question is how these criteria can be used to evaluate the design.

3.3.2 Screening and Validation

As noted in Section 2.3.1, Screening and Ranking are standard stages of design decision-making. They can be used to address all the important virtues the designers wish to consider by including them among the criteria applied to the decision in Framing. However – as noted in Section 3.2.2 - addressing lifephases requires a third step: Validation. At this stage the influence of the available alternatives on the given lifephases – and the influence of those lifephases on the criteria identified in Framing – must be considered.

Validation



The purpose of *validation* is to help designers use $DfX_{lifephase}$ tools to establish the likely choices that will be made at the given lifephase. This helps them navigate the decision tree, by identifying the likely outcomes of choosing each alternative, and helps them to consider the implications of these lifephases for the evaluation criteria. More importantly, from a concurrent engineering perspective, it helps them to identify any "dead ends" in the decision tree, such as designs that are impossible to manufacture or assemble. Section 2.1.3 argued that $DfX_{lifephase}$ techniques normally have two aspects: predicting likely choices at that lifephase, and measuring the design relative to a given virtue. *Validation* uses the former; *Screening* and *Ranking* the latter. The precise techniques used will depend on the lifephase and DfX tool in question and a separate Validation stage is required for each lifephase under consideration.

Regardless of the exact techniques used, each Validation stage will involve three activities:

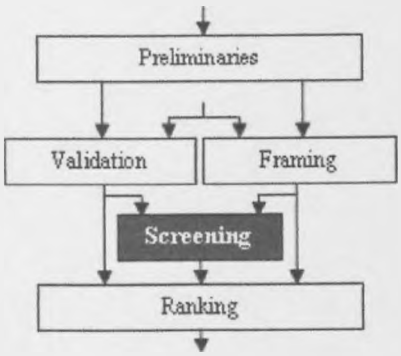
1. **Identifying the choices available at that lifephase:** what implementation choices are available?

2. Measure of absolute satisfaction: is it feasible to implement this choice with the given design?

3. Measure of discrimination: which of the feasible choices is the most promising, for the given design?

In this way, the output of each *validation* stage is – for each design alternative – an indication of which choices are feasible for that design, and which is the most promising, or the most likely to be chosen. Designers can then eliminate (or revise) designs that represent "dead ends", and can consider these predictions when *screening* and *ranking* the alternatives. This is where the need to relate requirements to the lifephases that influence them, carried out in the Preliminaries, becomes important.

Screening

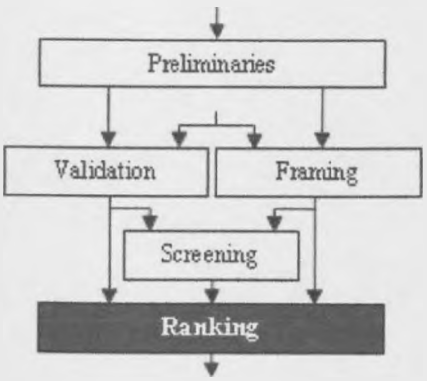


The purpose of *screening* is to eliminate alternatives whose outcomes are expected to be unacceptable, and there are several reasons for wanting to do this. Firstly, it saves effort: there is no sense in going through detailed trade-offs between two alternatives when you already know that one of them is never going to be accepted. Secondly, given the uncertainty about which MCDM algorithm is correct, and the difficulty of getting accurate numbers, screening reduces the risk of choosing an unacceptable alternative. After all, one reason for advocating concurrent engineering is to avoid later rework, so the earlier a problematic alternative can be identified and avoided, the better. In Screening, each candidate design is compared with each of the *mandatory* criteria in turn, and the candidate either *satisfies* or *violates* the criterion. The choice is binary: the candidate either passes or fails on that criterion, and if it fails on even one criterion, then the candidate is eliminated from further consideration. Of course, the designers may choose to adapt the design to make it acceptable, and re-evaluate it. The screening stage, therefore, partitions the set of design candidates into a set of *satisfactory* candidates, to be ranked, and a set of *unsatisfactory* candidates, which are abandoned.

Because screening does not involve trade-offs between criteria, each criterion can be considered independently. This allows flexibility in the order of Validation and Screening activities. While a criterion that is affected by a given lifephase

cannot be considered until the Validation for that lifephase has taken place, it is possible to alternate between validation for a lifephase, and then screening against criteria relevant to that lifephase. This would help to reduce the amount of effort needed for analysis. For example, a design that cannot be manufactured at a reasonable cost could be eliminated even before analysing it against assembly issues. Criteria that are not related to any lifephase, that is, those that depend only on the choices of the designers, could be used for screening before *any* Validation took place. Of course, exactly what order lifephases and criteria should be considered in is difficult to prescribe. Designers may wish to focus on the simplest lifephases first, as this increases the effort that can be saved by eliminating designs before complex analysis is needed. No prescription is made, but it *is* worth noting that Validation and Screening can be interwoven, and the design experiments (see Chapter 6) will demonstrate the benefits of doing this. Whichever approach is taken, by the end of Validation, the designers should be left with a set of designs that they are confident are feasible and are expected to be satisfactory. These are then carried forward for Ranking.

3.3.3 Ranking



Like Screening, Ranking is common to most prescriptive design methodologies, and is the only stage addressed by most decision analysis techniques. Screening sets out to identify an absolute measure of whether or not a given design is satisfactory. Ranking, on the other hand, sets out to discriminate among the satisfactory designs, obtaining relative measures of their value, so that the most promising can be identified. This is done on the basis of the optional criteria, by considering the trade-offs between them using whichever MCDM algorithm the designers are most comfortable with. The output of this stage is a ranking of the designs, based on their relative utilities, which the designers can then use as a basis for their decision. The final choice – the *decision* stage of the design loop – is still left to the designers themselves, based on the results and insights generated by going through this process. The designers are under no obligation to rank the surviving designs at all: if they choose to *satisfice* – or if only one design survives to this stage - then they can omit ranking altogether.

How ranking proceeds will depend upon the MCDM algorithm chosen. For an algorithm such as SMART or MAUT, scoring functions will already have been set up in framing, so that all that remains is to estimate attribute levels against the non-mandatory criteria. This may require mathematical modelling, or consulting expert

opinion – either way, the measure should have been specified when the criterion was established. For algorithms such as ELECTRE or AHP, where pairwise comparisons between candidates are needed, these would take place at this stage. In accordance with the third desideratum, this methodology does not prescribe which MCDM algorithm the designers should adopt: it is up to them to select the one best suited to their needs.

Once the decision has been taken, the designers can proceed to the next stage of design. There are two ways in which the analysis they have carried out could be used. The first is to simply ignore the information, and begin analysis afresh. The most promising design may have been identified, but the estimates of its performance are just that – estimates, and they may be subject to change in subsequent stages. No amount of analysis or wishful thinking can prevent changes occurring once a design is investigated in further detail – they can only make such changes less likely. Alternatively, the designers could use the information from Validation to constrain subsequent decisions based on their choice. This would require the co-operation of the relevant product development functions, and would also increase the amount of rework needed if earlier assumptions about the design's performance proved incorrect. However, it would allow true concurrency in the design process. Once again, this thesis makes no prescription, as which approach is best will likely depend upon the circumstances. For example, in the later stages of design, or for a well-understood product, locking-in decisions may be desirable, but in the early stages of development the potential for later changes is high, so it may be best to leave the choices of future lifephases open, at least until the design is more developed. Of course, there is nothing to stop designers keeping the likely choices in mind, without actually committing subsequent lifephases to them.

3.4 Comparison of the General Methodology with the Desiderata

This Chapter has provided a methodology for including DfX concerns in design decision-making through the use of decision analysis techniques. The next step is to determine, whether the methodology *can* be put into practice, and secondly, whether it can satisfy the desiderata when put into practice. First, however, one must verify that the methodology satisfies logically the desiderata if it cannot satisfy them in theory, there is no reason to think it will in practice. However, before considering the practical question of whether it works, one must actually determine whether there is any reason to believe in theory that the methodology will actually satisfy the desiderata. There is no point in going to the time and effort of implementing the methodology, if one just expects it to fail in any case. Therefore,

this section provides a comparison of the methodology described in this Chapter with the desiderata set out in Chapter 2, considering each in turn.

1. Criteria used for evaluation should be based only on the requirements specification.

This is addressed through the **Preliminaries** and **Framing**. The Preliminaries ensure that, if any additional virtues are considered relevant, then they are added to the requirements specification. Framing only takes criteria from the requirements specification: additional criteria are added only when they are necessary to represent a requirement that is unsuitable for the given decision.

2. Criteria used for evaluation should represent the full requirements specification as completely as possible.

This is addressed through **Framing**, which uses all the requirements, unless there are specific factors that make them unsuitable for the given decision. Even then, requirements are only left out if they are nonessential: otherwise, they are replaced by surrogate measures.

3. Designers should be free to define the context of evaluation by defining the alternatives to be considered.

This is addressed through **Framing**. By matching the requirements to the state of the designs being considered, the methodology can be applied at any stage of the design process. Also, as Figure 16 shows, the methodology does not interfere with the *synthesis* of designs. While the Preliminaries ensure that virtues are reflected in the requirements even before designs are generated, this does not constrain how detailed a design must be for evaluation.

4. Designs that cannot satisfy the minimum requirements specification should be eliminated from the choice entirely.

This is addressed through **Screening**, a standard stage in design evaluation which the methodology retains.

5. The decision-makers should be left free to choose a ranking algorithm to suit their needs.

This is addressed through **Framing** and **Ranking**. As the methodology is based on the structure of decision analysis, rather than the mathematics of any specific MCDM algorithm, it is compatible with any MCDM algorithm.

6. The designers should consider the whole product lifecycle when evaluating the design.

This is addressed through **Validation**. Validation gets the designers to think about the influence their decision will have on those taken downstream, and to use $DfX_{lifephase}$ tools to estimate what those choices are likely to be.

7. The methodology should not introduce any inconsistencies into the decision process.

The methodology does not interfere with the design evaluation process. It follows the standard pattern, design evaluation (see Figure 14, page 41). The only added stage, Validation, takes as its input DfX information, and outputs it as a decision tree, which is a normal input to the evaluation process.

8. The methodology should only draw upon available information.

The only information that the methodology uses that is not a standard part of design evaluation is the DfX_{virtue} and $DfX_{lifephase}$ information used in the Preliminaries and Validation. Even then, the information it calls upon is that provided by existing tools, as discussed in Section 2.1.

Therefore, all eight desiderata are satisfied by the proposed methodology. As any application of a methodology depends upon *who* applies it, and the situation they apply it to, this does not guarantee that the methodology will satisfy the desiderata in practice. For example, if a designer makes an erroneous judgement in screening, they might potentially allow a design that violated the requirements specification to be carried forwards. However, this would be due to human error, and not due to an inherent problem with the methodology: the designer is not *forced* to accept the flawed design. To find out whether the methodology *can* satisfy the desiderata in practice, it must be put into practice. To be put into practice, it must be translated into a usable method, populated with appropriate DfX and decision

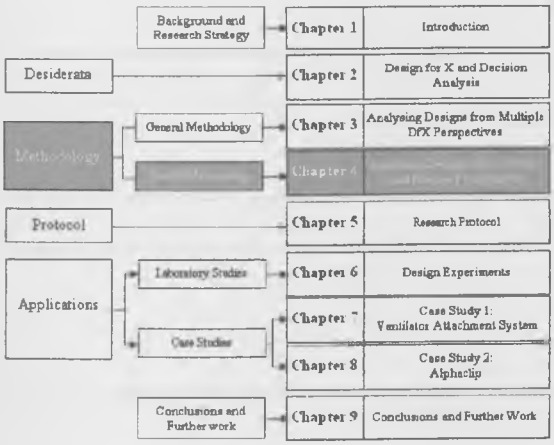
analysis techniques. The next chapter, therefore, translates this general methodology into a methodology for integrated product and process design, which can then be implemented.

3.5 Summary

The methodology presented here provides a way of applying DfX techniques in decision analysis, so that designs can be evaluated against their purpose, and not an imposed preference structure. The support provided by DfX techniques can be related to the tools of decision analysis: $DfX_{lifephase}$ can help construct and navigate decision trees, while MCDM algorithms can incorporate DfX_{virtue} metrics. Whereas DfX_{virtue} can be incorporated directly into the Preliminaries (through the construction of the requirements specification) and Framing, a new stage, Validation, is required to incorporate $DfX_{lifephase}$. This provides an explicit process identifying the expected choices at the given lifephase and estimating, for each design, which choices are feasible, and which is most likely to be chosen. This gives designers an indication of what is likely to happen if they choose a given design, so that they can take this into account when making evaluations.

It has been shown that this methodology logically satisfies the eight desiderata set out in Chapter 2. However, this chapter has not considered the details of how a given DfX technique would be applied using this methodology, a necessary step if the methodology is to be tested. The scope of this thesis restricts attention to integrated product and process design, so it is incorporating Design for Manufacture techniques in design evaluation that will be considered. Chapter 4 translates this general methodology into a specific methodology for using DfM information in design decisions, which is then applied in subsequent chapters.

Chapter 4
Analysing Designs from a Product and Process Perspective



This chapter translates the methodology presented in Chapter 3 into a specific methodology for evaluating designs from both product and process perspectives. It is the nature of methodologies that they provide only guiding principles, rather than specific techniques, and can be implemented in many different ways. The implementation presented in this chapter is one *possible* way of applying the methodology, and may not be the best, or most appropriate to all circumstances. Nevertheless some form of implementation is necessary to test the methodology. The remaining chapters of this thesis focus on testing the methodology presented here, and using this to draw conclusions about the more general methodology. Chapter 5 goes into further detail about the process of testing and deriving conclusions about the methodology.

This chapter has four sections. **Section 4.1** translates the general methodology to the specific case of integrated product and process design by highlighting the tools needed to put it into practice. The rest of the chapter discusses additional tools that are necessary to use DfM information in evaluation, and proposes a set of tools to satisfy this need. **Section 4.2** discusses the demands that a design places upon the processes used to manufacture it, and how far these can be determined for an incomplete design. **Section 4.3** then discusses how these demands can be compared with the capabilities of available processes to identify whether they can be satisfied. **Section 4.4** discusses how this information can be put together in a systematic way to test the feasibility of proposed designs, and identify suitable process chains for their manufacture. Finally, **Section 4.5** compares this implementation with the desiderata, to demonstrate that they are not contradicted by any of the tools adopted.

4.1 Applying Product and Process Perspectives

This section considers the implications of using the general methodology to apply product and process perspectives in design evaluation, and follows the same structure as Section 3.3. The first part considers how the preliminary and framing

activities change in the context of IPPD. The second discusses how DfM information can be applied in Validation, and how the screening stage can be divided when manufacturing is considered. The third part discusses ranking in an IPPD context, and the specific MCDM algorithm which will be adopted for the purpose of testing the methodology. Figure 17 shows how these stages fit together in the new methodology derived for IPPD.

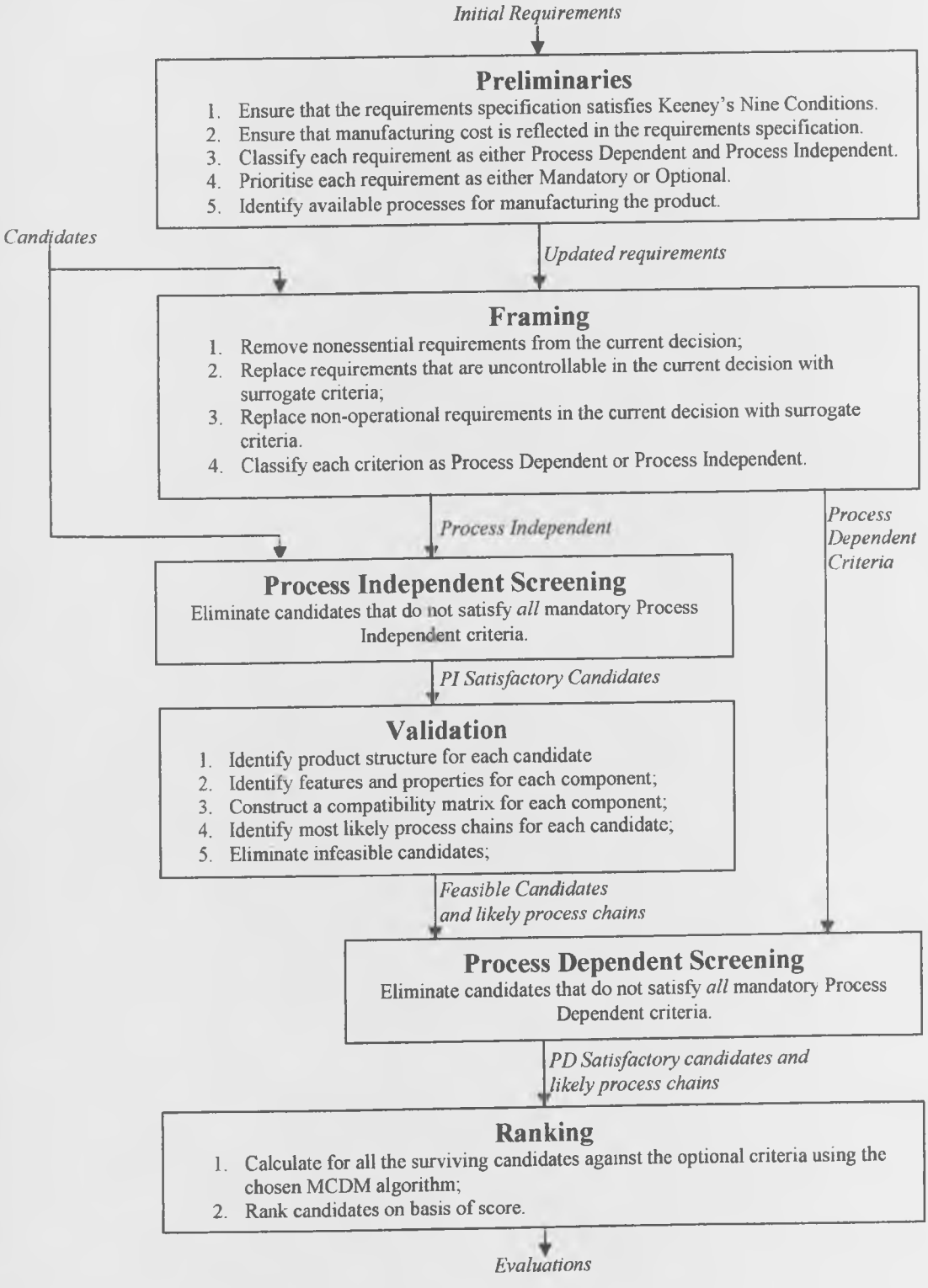
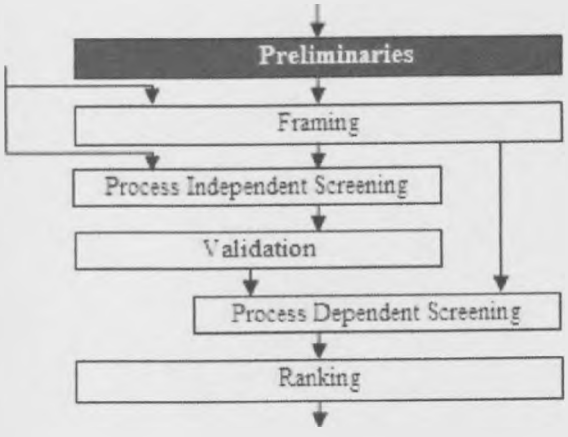


Figure 17: Methodology for integrated product and process design

4.1.1 Preliminaries and Framing

Given that integrated product and process design deals with a lifephase (manufacturing), rather than a virtue, it is addressed mainly through the validation stage (see Section 3.1.2). However, as noted in Section 2.1.3, it is impossible to evaluate designs against a lifephase, so $DfX_{lifephase}$ tools normally incorporate a virtue. For DfM tools, this is normally manufacturing cost, as this is "the most complete measure of manufacturability" (Bralla, 1999, p1.81), and this must be reflected in the preliminaries and framing.

Preliminaries



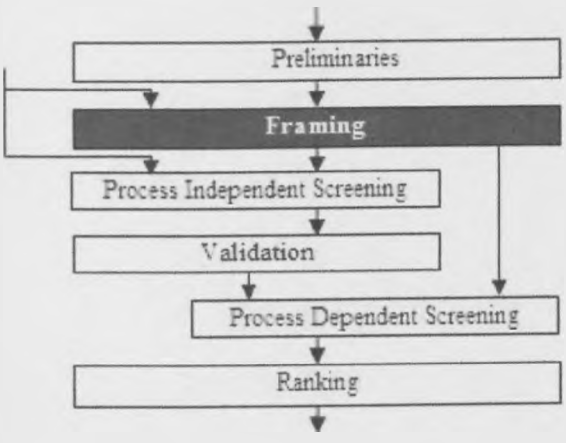
Restricting attention to IPPD eliminates the need to identify the virtues and lifephases to be considered: in IPPD, these are manufacturing cost and manufacturing by default. Therefore, in IPPD, designers should ensure that manufacturing cost is reflected in the requirements specification. A range of manufacturing cost estimation tools are available (e.g. Esawi and Ashby, 2003; Swift and Booker, 2003; Boothroyd *et al.*, 2002; Shehab and Abdallah, 2001; La Trobe-Bateman and Wild, 2003; Koonce *et al.*, 2003), any of which would be suitable for this methodology. For the purpose of testing the methodology, Swift and Booker's Design Costing Methodology has been adopted, except where participants favoured another approach (see Chapter 8), as this was the most familiar to the researcher.

Identifying which requirements are affected by each lifephase simplifies to identifying those requirements affected by the way the product is manufactured. For this purpose, requirements can be classified as either *process dependent* (PD –where satisfaction depends on the process chosen to make the product), or *process independent* (PI – where satisfaction depends only on the design of the product). No requirement relates *only* to the process used to make the product, as the choice of process depends upon the specified design.

A new stage can be added to the preliminaries: identifying limits on the available manufacturing processes. This is a *preliminary* step, as it only needs to be done once for any given design project. Assuming it is kept up-to-date, the same information can be applied to any design decision in that project. The nature of

these constraints will depend upon the scenario. Where new manufacturing facilities are to be purpose-built, for example, there may be no constraints at all. In other situations, the developers may wish to keep with particular manufacturing facilities, or stick with processes that they are familiar with. Approaches such as the Ashby method (Ashby, 1999; Lovatt and Shercliff, 2001) or the PRIMA selection matrix (Swift and Booker, 2003) may be used to limit the set of processes based on available information about the product. These constraints do not have to be absolute, and can be relaxed later on, if they prove problematic.

Framing



Framing does not change significantly in IPPD. If the influence of manufacturing has been reflected in the requirements specification, then it should automatically be reflected in the criteria developed in Framing. However, criteria must also be assessed to see if they are *process dependent* or *process independent*. Where a requirement is suitable in its current form, it retains its classification; where surrogate criteria have to be established, their classification will depend upon the requirement they represent. For a *process independent* requirement, *all* the criteria representing it should be *process independent*. If the requirement is not affected by the way the product is manufactured, then there is no sense in interpreting it through criteria that are. For a *process dependent* requirement, at least one criterion must be *process dependent*, although there may also be *process independent* criteria. The only exception to this is where the *process dependent* aspects of the requirement are *uncontrollable*, *nonoperational*, or *nonessential* to the current decision.

There are two reasons for separating criteria and requirements into *process dependent* and *process independent* classes. Firstly, this helps to flag up where a criterion requires some knowledge of the process used to manufacture the product to make appropriate evaluations. It also allows the screening process to be split around Validation, to reduce the effort involved (see Section 4.1.2).

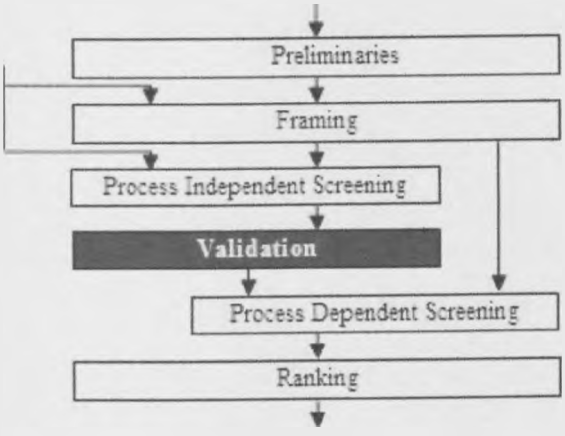
Once Framing is complete, the designers will have a set of criteria for evaluating the designs, which remain focussed on the requirements specification, as required by the desiderata. However, the additional stages of identifying

manufacturing constraints and process dependent criteria will help the designers to assess the effects of manufacturing in accordance with the sixth desideratum.

4.1.2 Validation and Screening

The main changes in applying the methodology to IPPD are concentrated in Validation, as this is the stage that brings lifecycle considerations into the decision analysis process. Screening and Ranking do not change, although they depend on Validation to help assess *how* manufacturing will affect the designs' performance.

Validation



In an IPPD context, designers only need to consider two stages of the decision tree: the choice of design for further development, and the choice of processes for its manufacture. Therefore the output of Validation in this case is not a full decision tree, but an indication of the most likely combination of processes for making each design. If no feasible process chains can be found for a given design, then it must be deemed *infeasible*, and should be eliminated from the decision. However, such designs may be revised so that they *become* feasible, so it is also desirable for Validation to provide feedback about why a design is infeasible.

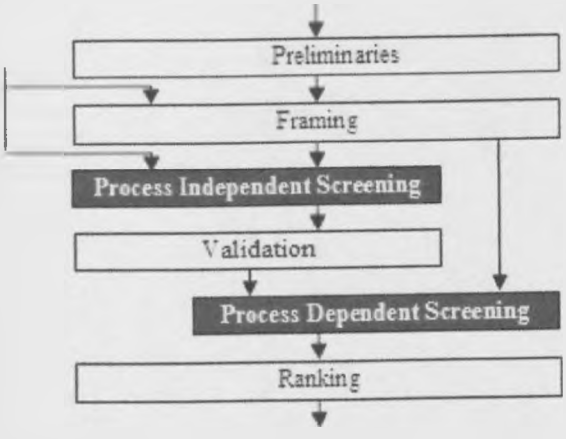
Just as screening compares designs against their intentional nature, in IPPD Validation compares the available processes against each design's physical nature to establish how each design could be made. It therefore involves three steps:

1) Identifying what is known about the physical nature of the design, at the given time;
2) Identifying which processes can produce the characteristics of this physical nature; and
3) Using this information to construct process chains for each design.

This does not guarantee the processes that will be used to make the final product: it only gives a best guess, given the information available, for guiding evaluation.

Validation can be treated as a black box: as long as the inputs and outputs are appropriate, there are many ways that it could be implemented. If cross-functional teams are in place, the designers could liaise with process planners to receive feedback about feasible processes for each design. Alternatively, designers could consult Process Selection Software (e.g. the Cambridge Process Selector[1]) or DfM Handbooks (e.g. Swift and Booker (2003), Boothroyd *et al.* (2002), Bralla (1999)) which provide qualitative and quantitative information about process capabilities and special considerations for particular processes. Handbooks can be used at any stage of design, but offer no structure for using the information they provide. Designers must reflect on the information and decide for themselves whether a given process is feasible for a given design. The subsequent sections of this chapter propose a systematic method for using DfM information in Validation that mirrors the structured approach taken by decision analysis.

Screening



The mechanisms of screening do not change in IPPD. As before, designs are compared against mandatory requirements and violating even one is enough to cause a design to be rejected. However, the distinction between process dependent and process independent criteria suggest two changes that can be made to the structure of Screening. Firstly, as noted in Section 3.3.2, Screening does not consider trade-offs, so it can be separated into process dependent and process independent stages, which Figure 17 illustrates. Only Process Dependent Screening needs to be carried out *after* Validation, as it depends on some knowledge of how the designs will be made.

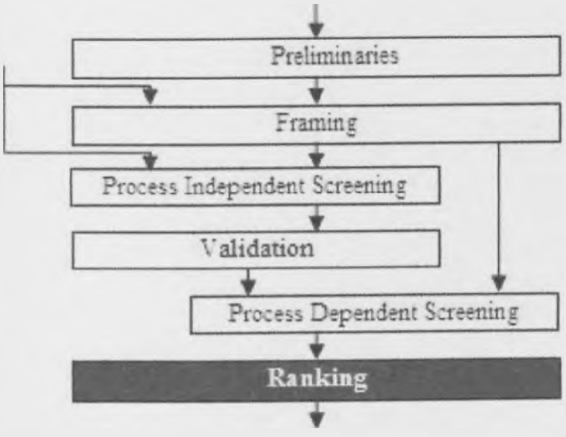
While Process Independent Screening *could* be left until after Validation, it is convenient to apply it first, as this can reduce the effort needed for evaluation. By Screening before Validation, designers can avoid validating designs that are just going to be rejected or altered because they don't satisfy the process independent

[1] See www.grantadesign.com

criteria. The other difference is that, after Validation, designers will not be screening individual designs, but combinations of designs and feasible process chains.

For the purpose of testing this methodology, each Screening stage will use an *elimination matrix* listing the relevant criteria down the side and the candidates across the top. Where a candidate is expected to violate a given criterion, an X is entered in the appropriate cell, and the candidate is deemed unsatisfactory.

4.1.3 Ranking



Because Ranking considers trade-offs, it must consider *all* the optional criteria simultaneously, and cannot be divided into process independent and process dependent stages. As with Process Dependent Screening, it is not just individual designs that will be ranked, but combinations of design and process chains. The same design may therefore be evaluated multiple times, when considering different process chains. In these cases, the distinction between process dependent and process independent criteria is again useful. Evaluations against process independent criteria only need to be made once for each design, and can then be applied to every combination involving that design. Otherwise, Ranking does not change in the context of IPPD: manufacturing choices have been considered in Validation and relevant virtues through the Preliminaries and Framing Both will automatically be reflected in the MCDM algorithm.

For the purposes of testing this methodology, SMART (Edwards, 1977) will be adopted as the MCDM algorithm for Ranking, as it is the simplest of the quantitative algorithms. This calculates a utility score based on the optional criteria, and then plots a graph of utility against cost: accordingly, any optional cost criteria will be omitted from the utility measure. This does not need to be the case: one could calculate a utility score incorporating cost, and rank candidates on that basis. However this has the benefit of separating the estimated utility (calculated with SMART) from the estimated cost (calculated using Swift and Booker's Design Costing Methodology), and forcing the decision-makers to reflect on the result rather than simply accepting the numbers generated.

4.2 Capturing the Physical Nature of Incomplete Designs

To know whether a given process is suitable for making a given design, one must have some idea of what the physical nature of that design will be: its shape, size and substance. Even when the design is incomplete, it is possible to look at what is known about it, to identify whether available processes are suitable. This is the approach taken by the Ashby Method (Ashby, 1999; Lovatt and Shercliff, 2001): as information on the design increases, more processes can be eliminated as unsuitable.

Capturing information about a design is not trivial, especially where the design is incomplete, perhaps existing only as an idea or a few sketches. It is beyond the scope of this thesis to develop and validate a full schema for design representation. The approach presented here is a simple way of capturing the information about a design so that it can be used in a structured way: no claims are made for its normative value. Other data models or approaches can be substituted, if the users prefer.

The approach presented here treats each design as a set of *properties*, which are clustered together as *features*. As each component is manufactured independently (any requirements on the interfaces between components are captured through the specified surfaces finishes and tolerances), each is validated independently. The first half of this section describes the identification of features used to cluster properties. The second half describes the identification of properties associated with those features.

4.2.1 Identify Component Features

The purpose of this stage of Validation is to describe the candidate designs in terms of the demands that they place on the processes used to manufacture them. Just as a design can be physically decomposed into its components, a component's topography can be divided into a set of features. To aid redesign, it is useful to know when a given feature: **a)** Causes a design to be infeasible or **b)** causes a design to require post-processing (therefore adding to the cost of its production). Features are only useful insofar as they provide a convenient way of structuring this information.

"Features" are a concept used in many areas of engineering design, often for different purposes, and using different definitions of the term. Brown (2003) identifies ten definitions of "feature" used in engineering design, with multiple competing taxonomies existing for each. He notes that designers are increasingly moving towards a definition of a feature as "anything on the design that is of interest". Another complicating factor, especially when dealing with form features,

such as holes or bosses, is that features can interact. Two blind holes may form a through hole; two perpendicular bosses may meet to bound a through hole, and so forth. As yet, no one taxonomy of features has been accepted, with applications having to define their own. For computer-based analysis, a formal taxonomy of features and their recognition is essential. For the purposes of this research a precise taxonomy of features is not required. As interpretation of features will be done by a human, users have the freedom to define features as they see fit and maintain their own internal consistency. It is up to the users to decide which geometric aspects of a design are worth highlighting as features.

For the purposes of this process, the component is divided into a Basic Component, and a set of Features. Any property not associated with a feature, must be associated with the Basic Component. For example, a general surface finish would apply to the Basic Component, while a surface finish that only applied to a given face would be defined as a part of a separate feature. The most important thing is that those who will be making judgements about their manufacturability understand what the feature defines.

4.2.2 Identifying Component Properties

A *property* is any aspect of a design that a process must be able to provide if it is to make the design as specified. In the early stages of design, not all of the properties will be defined, but decisions must still be made based on the information available. Because the information is incomplete, a design passed as feasible may still develop problems due to subsequent design choices. Nevertheless, Lovatt and Shercliff (2001) have demonstrated that this incomplete information can still be compared with process capabilities to eliminate processes unsuitable for a design. That is the approach taken here: using what is known to identify problems as early as possible.

The first step in assessing the feasibility of a set of designs is therefore to identify the *properties* of the design known at the time of the decision. As these properties will be used to estimate potential process chains, it makes sense to base them on the information used to establish how a design should be made. According to Halevi and Weill (1995) process selection should be based on a design's *material*, *shape*, *dimensions*, *tolerances*, *surface finish*, and *batch size*. Batch size is independent of the design itself, and can be left out of the consideration. Rather, it might represent a restriction on the processes being considered or be represented as process dependent requirement. This leaves five aspects of a component that should be considered when assessing its feasibility.

Figure 18 shows the data structure used to capture the properties of a component, and relate them to the component's features.

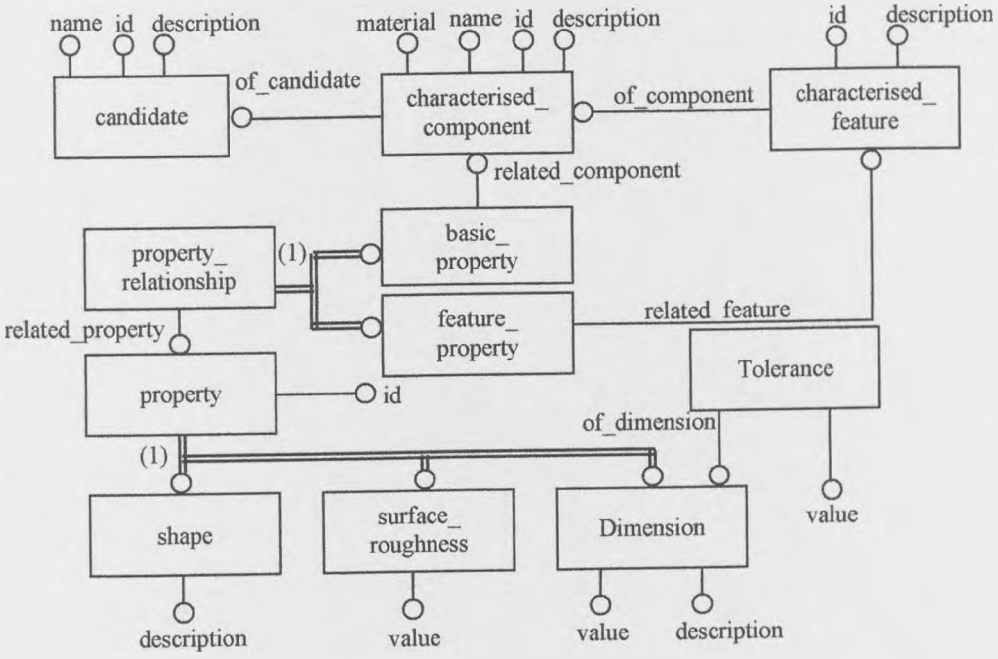


Figure 18: EXPRESS-G data model relating components, features and properties.

The five properties are as follows:

Material: This describes the substance that the component is made of: by definition, a component can only have one material property, as it is all made of one material. This means that material properties are only associated with the Basic Component: Features cannot have their own material properties. Depending on how much is known at the time of the decision, this may be captured as a specific material (Stainless Steel 316), a class of materials (stainless steel, thermoplastics, etc.) or a very general classification (metal, polymer, etc.). This can be captured linguistically.

Shape: Shape is a difficult property to capture. Although it can sometimes be defined linguistically (e.g. "hollow cylinder", "triangular prism"), it often requires sketches. Each feature can only have one shape property.

Surface Finish: This measures the surface quality of a feature. Each feature can have only one surface finish property. Surface finishes applied to the Basic Component apply to the whole component, except where a feature has its own surface finish defined, like a general surface finish specified on a component drawing. This is captured numerically, in μmR_a.

Dimension: Dimensions measure the size and location of a feature, and are typically measured in mm. These can include lengths, wall thicknesses, diameters and radii: any aspect of the feature's shape that can be measured as a distance. A

feature can have any number of dimensions. A dimension describing the feature's location must specify it relative to another feature, or at least to a given datum. For this reason, it is normal to include a description of the dimension, as well as a numerical value.

Tolerance: Each tolerance must be associated with a dimension, and each dimension can only have one tolerance. This defines the acceptable range of variation on the dimension, and is normally measured as an acceptable range about the nominal dimension, in mm.

Once a design has been described in terms of this data structure, its properties can be compared with the capabilities of available processes to identify whether or not it is feasible.

4.3 Identifying Process Violations

Having identified the processes available for manufacture, and the properties of the designs being proposed, the next step is to compare the two. Where a process is unable to provide a given property, it is said to *violate* that property. Even a single violation means that a component cannot be made by a given process, although it may still be made by a combination of processes (see Section 4.4.2). If a process causes no violations, then it is suitable for making the component and the component, based on the information available, is feasible.

This section describes how to determine whether a given process satisfies or violates a given property of a component. The first subsection describes how to identify whether the basic capabilities of a process violate a property. The second deals with properties that a process violates through *precedence*. The final subsection deals with the uncertainty in analysing an incomplete design, and how to address properties that can only be satisfied if certain constrains are obeyed in later stages of design.

4.3.1 Identifying Basic Violations

A basic violation of a property occurs when a given manufacturing process is fundamentally unable to provide the given property. One could not produce a cube on a lathe, for example, as turning will only produce axisymmetric shapes. Equally, one could not vacuum form a ceramic, as vacuum forming can only be used with thermoplastics (Swift and Booker, 2003). Injection moulding cannot reliably achieve a surface finish 0.01 μmR_a, as it typically produces parts with surface finishes in the range of 0.2-0.8 μmR_a (Swift and Booker, 2003). In all these cases, the process is simply not able to produce the required property, and therefore

violates the property, and is not a suitable way of making the product. Of course, it may be possible to use additional processes to achieve the required property, such as Electric Discharge Machining on a cast component to achieve a smoother surface finish. The use of combinations of process – termed process chains – will be dealt with in Section 4.4.

There are two ways in which violations may occur. The first is in terms of the general capabilities of the process: what shapes, surface finishes and tolerances it can achieve, what materials it can work, what size limits apply. These are relevant to all processes, and are a straightforward comparison between what the property asks for and what the process is able to provide. However, many processes also have specific considerations, such as manufacturing flaws that might occur, or features that are required to aid manufacture. Examples of these include hot tears in casting (Bralla, 1999, p5.13), or the need for draft angles in injection moulding (Bralla, 1999, p6.36). These may cause violations even where the process is theoretically capable of satisfying the requirement. For example, it *is* possible to sand cast a component with sharp, right-angle corners. However, this can cause "hot spots" which leave voids that weaken the component and should therefore be considered a violation. When considering whether a given process satisfies or violates a given property, the designers must consider both the basic capabilities of the process, and such process specific considerations.

When assessing violations, there are various places that designers could go for information, such as software, handbook, or process engineers. The designers may even wish to compare multiple sources of information. This methodology is for decision analysis (i.e. how the information is used) and therefore does not prescribe a particular decision support system for providing the information. The designers are free to decide which sources of information they trust the best.

Sometimes whether a process can satisfy one property depends on the other properties that have been specified. For example, the surface finish and tolerances a process can achieve often depend on the material of the given parts. When considering whether a surface finish property can be achieved, the question is not "can the process achieve this surface finish?", but "can the process achieve this surface finish on this shape in this material?". Without considering these interactions, it would be possible to make serious mistakes when assessing whether a process could be used to make a design. The *context* of each property must be considered by looking at the *precedence* between them: which properties *must* be satisfied before the given property is possible.

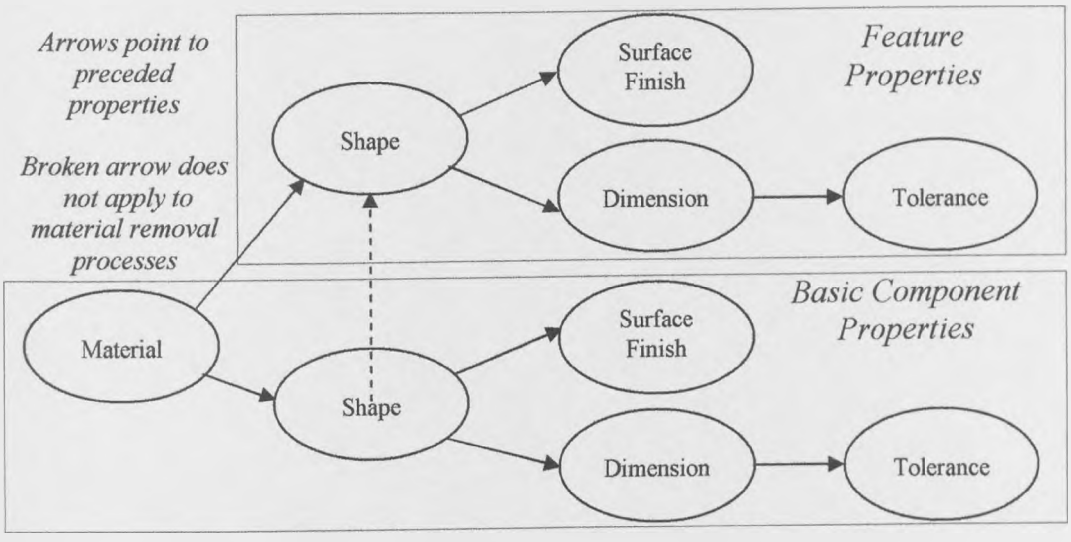


Figure 19: Precedence relationships between properties

4.3.2 Violations due to Precedence

As well as basic violations, violations may also be caused through *precedence*. This occurs when, although the process could achieve the property taken in isolation, it cannot provide the property in practice, because it cannot satisfy other aspects of the design. For example, injection moulding can achieve a surface roughness of 0.2μmR_a (Swift and Booker, 2003), but it could not provide this on a stainless steel component, as stainless steel cannot be injection moulded (Boothroyd *et al.*, 2002, p47). Even in plastic, such a surface finish would be unachievable if the shape of the part could not be injection moulded. The process *could* provide the property – just not on the component in question. This becomes important when considering process chains and post-processing.

Whenever a basic violation occurs, any property preceded by the violated property is automatically violated. Figure 19 shows the precedence relationships between different types of property. It is worth noting that precedence between the basic component and its features does not apply to material removal processes, as they can be used for post-processing. One could not cast a feature into a part that had already been machined, for example, but one could machine features into a part that had been cast. It is also worth noting that *every* property preceded by the one violated is violated through precedence, not just the one it immediately precedes. Thus, if a process cannot work the component material, it automatically violates every property of the component.

For redesign purposes, it is important to distinguish between basic violations, and those that only occur due to precedence. For example, if a small adjustment to the shape of a component would render the whole thing feasible, then it may be worth amending. If every property caused a basic violation, then just changing the

shape of the component would not render it feasible: the other properties would still need to be altered.

4.3.3 Conditional Constraints

Violations will not always be clear cut: there will often be some element of uncertainty. This may occur because of a lack of knowledge or information about the process in question. In this case, the users must either gather more information to make the assessment; decide that the risk is worth taking, and can be treated as a non-violation; or decide that the risk is not worthwhile and should be treated as a violation. Uncertainty about violations may also occur due to the incomplete state of the design. It may be possible to satisfy the property – provided the right choices are made later in design. For example, whether a given section change is a problem for processes such as casting or injection moulding will depend on the extent of the change. Similar issues arise with draft angles, fillets and chamfers: they are desirable for some processes, but may not be added until the detail design stage. This is not reason enough to reject a design, but these issues must not be forgotten if the design is accepted for further development. Accordingly, these are not treated as violations, but are recorded as "conditional constraints", which the design must satisfy if it is to be feasible. Designers can then review whether they believe the constraints are acceptable, and – if the design is carried further – keep them in mind for the subsequent stages of design. Manufacturing flaws that do not render the part infeasible (such as burrs or parting lines) should also be flagged up as conditional constraints, so the designers can consider whether they cause any problems.

4.4 The Compatibility Test

This section describes how the properties and violations identified in the previous sections can be formally represented to identify feasible designs and process chains. The basis for this is a compatibility matrix, which provides a visual comparison of each process with each property, and an indication of where violations occur. This section is divided into two parts. The first describes the compatibility matrix, and how it is constructed, while the second outlines the way this information is used to identify feasible designs and process chains.

4.4.1 The Compatibility Matrix

The compatibility matrix provides a visual comparison between the properties identified for a component, and the processes being considered for its manufacture. This is not the only way that information about properties and violations can be captured, but presenting the information visually keeps it clear and structured, rather

than encoded in a large amount of text. It lets the users see where violations occur, and make a visual comparison between the suitability of different processes, and the combinations of processes that could be used to make the component. Because each component is validated independently, each is analysed using a separate compatibility matrix. The structure of the matrix is straightforward: component properties are clustered by feature down the side, and available processes are listed across the top, as illustrated in Figure 20.

Component A		**Processes**			
Properties		Process 1	Process 2		Process *M*
Basic Component	Property *1*				
	Property *2*				
	Property *n*				
Feature *1*	Property *1,1*				
	Property *1,2*				
	Property *1,n*				
Feature *2*	Property *2,1*				
	Property *2,2*				
	Property *2,n*				
Feature *N*	Property *N,1*				
	Property *N,2*				
	Property *N,n*				

Figure 20: Structure of the compatibility matrix

Each cell of the matrix indicates whether the given process is able to satisfy the given property, by making an appropriate entry in the cell. The content of the cell depends upon whether a violation has been established. At the most basic, this need be no more than placing a cross in every cell where a violation occurs. However, for this research a more in-depth system based on colour-coding is proposed. This allows more information to be captured to inform the current decision, and the later stages of design. The contents that should be entered in each cell are illustrated in Table 7.

Condition	Description	Example
No Violation.	If the users are sure that the process can satisfy the property, then the cell should be shaded green.	
Basic Violation	If the users are sure that a basic violation will occur, then the cell should be shaded red, and an "X" entered.	X
Precedence Violation	If the users feel that the process could satisfy the property, but the property is violated through precedence, then the cell should be shaded red, but left empty.	
Possible Violation	If the users are not certain as to whether the property will be violated or not, the cell should be shaded orange but left empty.	
Conditional Constraint	If the users have identified a conditional constraint, then the cell should be shaded orange, and a number entered referring to a footnote explaining the constraint.	1

Table 7: Contents to be entered into the cells of the compatibility matrix

Footnotes for conditional constraints can be listed under the matrix, or separately. Footnotes could also be used to explain the reasoning behind violations, for example, to help designers with any alterations they may wish to make. The important thing is that the information is captured for future reference. Once the compatibility matrix for each component in each design has been structured and filled in, it can be used to establish feasible candidates and their process chains.

4.4.2 Identifying Feasible Candidates and Process Chains

For a component to be feasible, it must be possible to satisfy all its properties using the processes available. From a single glance at the compatibility matrix, it should be possible to tell whether a given process is able to satisfy all the properties for a component: there would be no red cells in the column. If one or more of the available processes can satisfy all the properties of a component, then that component is considered feasible. However, even if no single process can satisfy every property of the component, it may be possible to use a combination of processes, known as a process chain, to make the component. A process chain is suitable for a given component if, for every property of the component, at least one process in the chain can satisfy that property. If there is at least one feasible process chain for a component (even if the chain only contains one process), then that component is feasible. A given design is only feasible if all its components are feasible.

If there is only one feasible process chain for each component in a design, then the candidate is passed on for Process Dependent Screening and Ranking, based on the given process chain. If there are several possible process chains for one or more of the components in a design, then although the design is definitely feasible, there

is the question of which process chains should be considered in the subsequent stages of analysis. In this case, the designers have several choices about how they proceed. The designers could accept every process chain for the design, and treat them as separate candidates, screening and ranking them independently. As long as the number of possible permutations of process chains for the candidate is relatively small, this is acceptable. However, if the design contains a large number of components, each with several possible process chains, the number of permutations soon becomes unwieldy. For example, a design featuring five components, each with three possible process chains, would leave 243 possible combinations to be considered – and that for just one design.

An alternative approach is to examine how the choice of process affects the Screening and Ranking of the design. For example, if a given process on a given component is going to lead to problems that will screen the design out, then any set of process chains including that process for that component could be eliminated before evaluating the design as a whole. Alternatively, if the only issue that the process used to make the design would affect is cost, then the designers could select the process chain for that component with the lowest predicted cost. Finally, one could simply estimate which process chains were most likely to be used in practice (for example, avoiding chains where violation was uncertain, or asking for guidance from process planners). This is largely a matter of convenience, and depends upon how much detail the designers wish to go into.

The outcome of this stage is an indication of which designs are feasible; for those that are not feasible, an indication of why they are not feasible; and for those that are feasible, an indication of how they are likely to be made. Based on this information, designers can screen and rank designs, and even alter designs that have been deemed infeasible.

4.5 Comparison of the Methodology with the Desiderata for Integrated Product and process Design

This chapter has translated the general methodology presented in Chapter 3 into a specific methodology for integrated product and process design. Before putting this into practice, it is important to verify that none of the methods adopted in this chapter will violate the desiderata set out in Chapter 2. As before, there is no sense in implementing a methodology that is expected to violate the desiderata. This section provides a comparison of the methodology described in this chapter with the desiderata set out in Chapter 2, considering each in turn.

1. Criteria used for evaluation should be based only on the requirements specification.

This has not changed: the **Preliminaries** and **Framing** still draw upon the requirements specification for the evaluation criteria. The **Preliminaries** ensure that the inclusion of manufacturing cost in the analysis is addressed by including in the requirements specification, rather than adding it only to the criteria for a given decision.

2. Criteria used for evaluation should represent the full requirements specification as completely as possible.

This is still addressed through **Framing**. The act of dividing criteria into process dependent and process independent is a classification exercise, and does not affect their completeness.

3. Designers should be free to define the context of evaluation by defining the alternatives to be considered.

This is still addressed through **Framing**, and is also reflected in the approach to **Validation** taken here. Classifying criteria into process dependent and process independent does not affect the way they are measured, so the methodology can still be applied at any level of detail. By adopting a flexible approach to **Validation** that relies on human judgement, the methodology provides structure that can be applied regardless of how detailed the design is.

4. Designs that cannot satisfy the minimum requirements specification should be eliminated from the choice entirely.

This is still addressed through **Screening**. The distinction between process independent and process dependent **Screening** does not affect this, as designs surviving to **Ranking** will still have been compared against all the mandatory criteria.

5. The decision-makers should be left free to choose a ranking algorithm to suit their needs.

This is addressed through **Framing** and **Ranking**, and neither really changes in the context of IPPD. The division of criteria into process dependent and process

independent has no effect on the **Ranking** process, and does not limit the algorithms that can be used.

6. The designers should consider the whole product lifecycle when evaluating the design.

In the context of IPPD, *only* manufacturing is considered, not the entire product lifecycle. The methodology addresses this through **Validation**. The process presented here does not address other lifephases (as that is beyond the scope of this thesis), but does not prevent the inclusion of additional **Validation** stages to address them, so that the methodology presented here can still be extended to cover other lifephases.

7. The methodology should not introduce any inconsistencies into the decision process.

The only major change this chapter makes to the evaluation process – the division of **Screening** into process dependent and process independent stages - is logically consistent, as designs are screened against each mandatory criterion individually. Otherwise, the evaluation process remains exactly as it was in Chapter 3.

8. The methodology should only draw upon available information.

The only specific information required by the methodology presented here is information on process capabilities, which can be readily provided by DfM handbooks (e.g. Swift and Booker (2003), Boothroyd *et al.* (2002), Bralla (1999), etc.), Process Selection Software, or direct advice from process engineers.

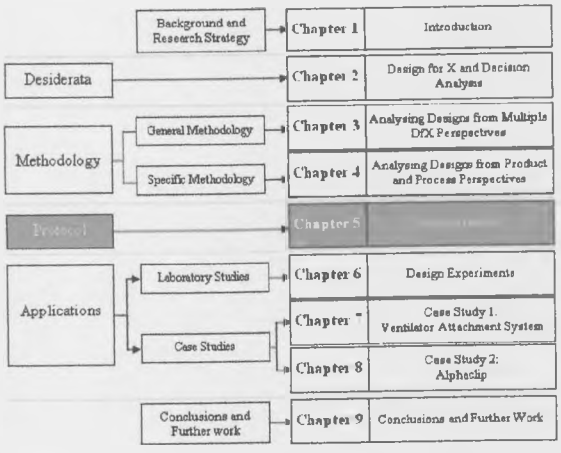
All eight desiderata are still satisfied by the methodology presented here. No contradictions have been introduced in the way it is implemented for IPPD, although it is still subject to human error. The next question is whether this methodology can actually satisfy the desiderata when put into practice, which is the subject of the next four chapters of this thesis.

4.6 Summary

This chapter presents a specific methodology for using Design for Manufacture information to evaluate designs from both product and process perspectives, based on the general methodology from the previous chapter. This involves a more detailed description of the Validation stage. It is worth noting that this represents one *possible* way of applying the methodology. Other equally valid applications may be possible, but this is the version that will be tested. As the methodology needs to be applicable at any stage of design, it cannot rely on having a fully detailed model of the product to evaluate. Therefore, a process for evaluating incomplete designs against DfM information has been presented. This involves dividing the topology of a component into a set of features, and describing them in terms of five basic properties (material, shape, surface finish, dimensions and tolerances). These properties are then compared against the available processes in a compatibility matrix, to identify which processes are able to provide each property. Based on this, potential process chains for each component can be identified.

This helps designers to navigate the decision tree over both the design and manufacturing stages, by highlighting the choices of process that are likely to follow from choosing each design. This is does not give a definite indication of the choice that will be made, but offers a best estimate given the information available, which can guide the designers. It has been shown that this specific methodology logically satisfies the desiderata set out in Chapter 2, and it is reasonable to expect that it could satisfy them in practice. However, to determine whether this is actually the case, the methodology must be applied and evaluated, which is the subject of the following chapters.

Chapter 5
Research Protocol



This chapter shows how the hypothesized relationship between Design for X and decision analysis – and the methodology derived from it – will be tested. Where Chapter 2 provided the *desiderata* that drive this research and Chapters 3 and 4 provided the *methodology* to be tested, this chapter provides the *research protocol* for comparing the two. It is one thing to demonstrate the theoretical coherence of a methodology: it is another for it to remain coherent when put into practice. This is no simple matter. Applying the methodology is necessarily a human process, and testing requires participants who will use the methodology to evaluate their designs. Human-focused research is fraught with bias, and establishing whether the methodology has been applied correctly – and whether it has satisfied the desiderata in practice – is not trivial. This chapter discusses some of the biases that can threaten the validity of such tests, and how they can be counteracted by studying applications of the methodology in a structured manner. This provides the basis for the design experiments and case studies presented in Chapters 6 to 8.

The chapter is divided into three sections. **Section 5.1** translates the research focus presented in Chapter 1 into a set of questions that the design experiments and case studies must answer, along with a strategy for answering them. **Section 5.2** discusses threats to the validity of this research, how they can be avoided, and limits on its generalisability. Finally, **Section 5.3** discusses how data will be gathered to answer the research questions, while limiting the threats to the validity of the research.

5.1 Research Design

This section discusses how the broad focus of this research can be narrowed down into a specific set of research questions. After all, the methods used in research should follow from the questions to be answered (Robson, 2002). Chapter 1 stated the focus of this research, and the assumptions that underpin it.

This section considers in detail how the methodology will be compared with the desiderata. The section is divided into two parts: the first presenting the questions

guiding this research, and the second presenting the strategy adopted for answering them.

5.1.1 Research questions

The research question guiding this thesis is:

"Can decision analysis incorporate Design for Manufacture information in design evaluation without imposing a preference structure on the decision?" (Chapter 1, page 17)

The preceding chapters have translated this question into a set of ***desiderata*** indicating what *"incorporating Design for Manufacture information in design evaluation without imposing a preference structure"* means and a ***methodology*** for doing this. This reduces the question to:

"Can the methodology satisfy the desiderata when used to evaluate candidate designs?"

The word "can" is an important part of this question, because of the inherent limitations on the external validity of this research (see Section 5.2.2). That the methodology *can* satisfy the desiderata implies that circumstances exist where it *does* satisfy the desiderata, but not that it satisfies them under *all* circumstances. It might, but it would be wrong to assume this without trying it under every circumstance that it might face. That task is far beyond the scope of this thesis, which will only test the methodology under a limited range of circumstances. The limitations of this research and their implications are considered in Section 5.1.2.

There are two elements to this question, one of *feasibility* ("can it be done?"), and the other of *desirability* ("should it be done?"). The latter can be considered at two levels: the theoretical (whether it is logically coherent), and the practical (whether it remains coherent in practice). Therefore, the overall question can be decomposed into three sub-questions, as shown in Figure 21, which can each be considered separately.

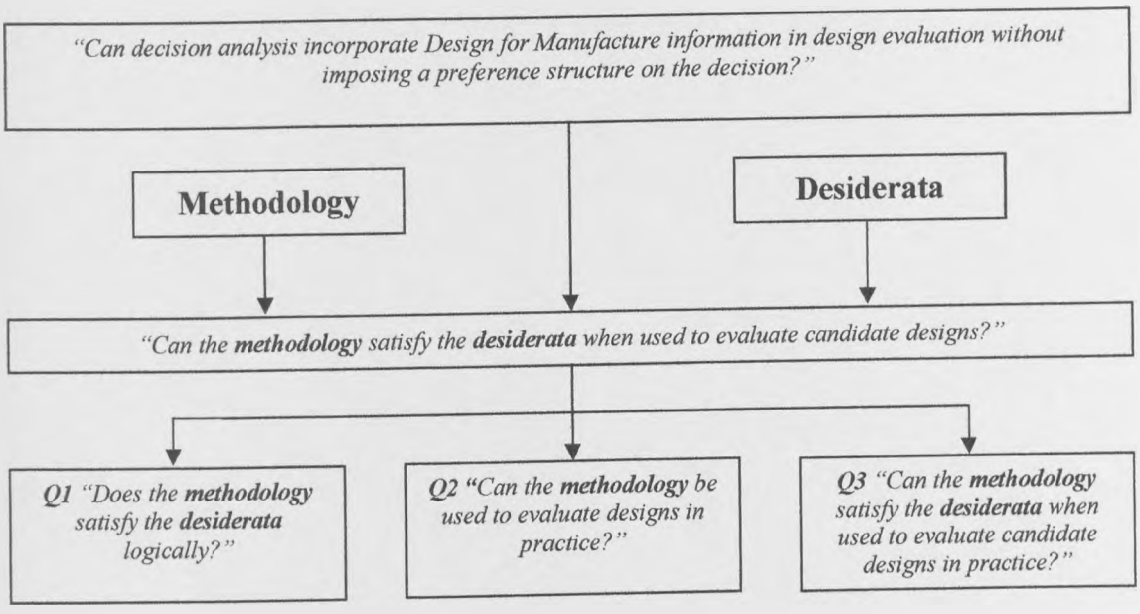


Figure 21: Sub-questions derived from the overarching research question

*Q1) Does the **methodology** satisfy the **desiderata** logically?*

This sub-question can be answered without the need for application, and therefore precedes the other two. If the methodology does not satisfy the desiderata in theory, then there is no reason to believe it will in practice, and no reason to go to the trouble of applying it. Chapters 3 and 4 have already addressed this point, showing how the methodology has been derived, and how its elements satisfy the desiderata. The issue to be addressed in Chapters 5 through 8 is whether this theoretical ideal can hold under practical conditions, and this is covered by the two remaining sub-questions.

*Q2) Can the **methodology** be used to evaluate designs in practice?*

It is important to understand that any methodology exists only as a set of words on paper. What is actually put into practice depends not only on the methodology, but also upon the person applying it, and the situation to which it is applied (Checkland, 1999, pgA33). It is important to establish whether the methodology can be put into practice as it was intended. If not, any practical results will reflect upon an ad hoc adaptation of the methodology – and not upon the methodology itself. This sub-question precedes the next: there is no sense in considering whether the methodology satisfied the desiderata, until one knows whether the method applied actually reflects the methodology. The purpose of this question is to determine whether the participants applied the methodology as intended. This question can be decomposed into five sub-questions, as illustrated in Figure 22.

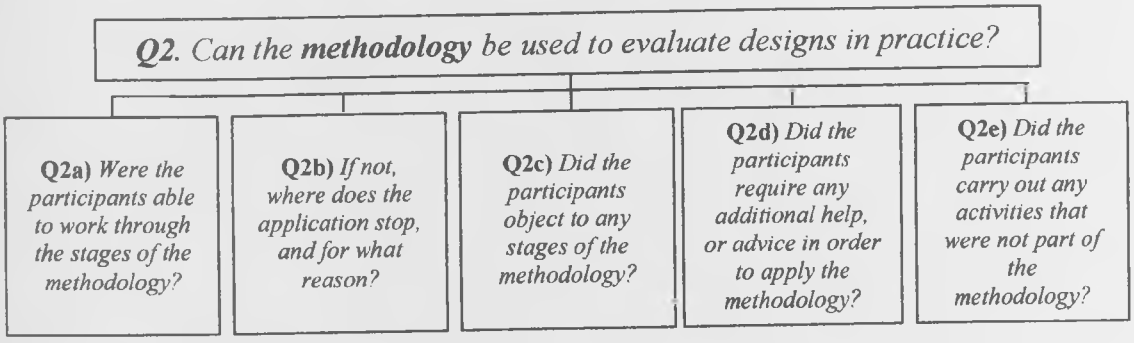


Figure 22: Decomposition of **Q2)**

Q2a) *Were the participants able to work through all the stages of the methodology?*

The methodology breaks down into a series of discrete steps, whose exact ordering may vary, but must always obey the precedence constraints shown in Figure 23. Given the iterative nature of design, it is possible that information used in early steps may be revised later and the earlier steps repeated. In this case, the preceded steps should also be repeated to allow for the change of information.

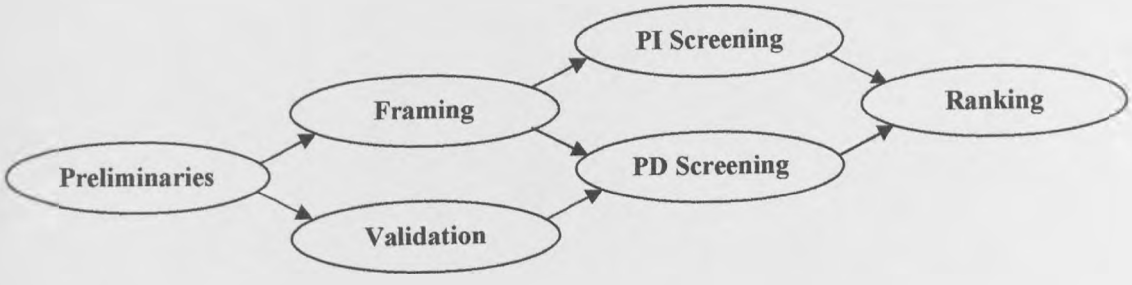


Figure 23: Precedence relationships between stages of the methodology

Failure to carry out all the stages of the methodology would call the results into question, but not *necessarily* mean that it is infeasible. One must determine whether the problems that prevented it being applied were inherent to decision analysis, or caused by the *way* in which it had been applied. If the application fails, one must establish what caused the problem, and what – if anything – could be done to correct it. This suggests two further sub-questions:

Q2b) *If the participants were not able to work through the methodology from start to finish, where does the application stop, and for what reason?* and

Q2c) *Did the participants object to any stages of the methodology?*

Even if every stage of the methodology is followed correctly, *additional* activities that are not part of the methodology may have take place, which could affect the results. This suggests two more sub-questions:

Q2d) *Did the participants require any additional help or advice in order to apply the methodology?* and

Q2e) *Did the participants carry out any activities that were not part of the methodology?*

By answering these questions, one can determine whether the methodology has been applied as described, and therefore whether the results of the application are relevant to the methodology. If stages have been omitted, or additional stages carried out, the results may still be relevant. One must look at *how* the application deviated from the methodology, and which results have been affected.

Q3 *"Can the* ***methodology*** *satisfy the* ***desiderata*** *when used to evaluate candidate designs in practice?"*

Whether the methodology *can* be applied is a question of *process*, but whether it satisfies the desiderata is a question of *content*. Given that the methodology is logically coherent with the desiderata it follows that – if it has been applied correctly – it will satisfy them in practice. However, just because the correct activities have taken place, this does not mean that they have been carried out correctly. Therefore, this question asks whether the actual content generated by applying the methodology is coherent with the desiderata.

Each desideratum set out in Chapter 2 offers its own sub-questions, as shown in Table 8. Not all of the desiderata can be considered in practical applications of the methodology. Although this methodology is theoretically able to work with any MCDM algorithm, in the design experiments, SMART was adopted, for convenience (See Chapters 6 and 7). This is not imposed by the methodology, but it does mean that there is no way in practice to demonstrate that the methodology satisfies Desideratum 5. Equally, the logical consistency of the methodology (cf. Desideratum 7) cannot be tested practically. As the methodology is logically coherent, any incoherence found in practice must be because it has not (or could not) be applied as intended, which is exactly what the sub-questions are meant to determine.

Table 8: Decomposition of **Q3)** into subquestions based on the desiderata

#	Desideratum	Relevant Sub-Questions	Comments
1	*Criteria used for evaluation should be based only on the requirements specification.*	**Q3a)** *Were any of the criteria used in the evaluation* **not** *related to a requirement from the requirements specification?*	For each criterion, it should be possible to state which requirement it represents.
2	*Criteria used for evaluation should represent the full requirements specification as completely as possible.*	**Q3b)** *Were any* essential *requirements not represented by the criteria?*	For each requirement, unless it has been deemed *nonessential*, there should be at least one criterion.
3	*Designers should be free to define the context of evaluation by defining the alternatives to be considered.*	**N/A**	In the Design Experiments, the participants cannot define the context; in the Case Studies, the designers supply the decision and therefore define the context automatically.
4	*Designs that cannot satisfy the minimum requirements specification should be eliminated from the choice entirely.*	**Q3c)** *Were any of the designs surviving to Ranking expected to violate the requirements specification?*	In the elimination matrices for PI and PD Screening no designs with violations should have been permitted to ranking.
		Q3d) *Were any designs with known manufacturing flaws permitted through Validation?*	At least one feasible process chain should be specified for every component of candidates surviving Validation.
5	*The decision-makers should be left free to choose a ranking algorithm to suit their needs.*	**N/A**	For the purpose of this thesis, SMART has been adopted as the ranking algorithm.
6	*The designers should consider the whole product lifecycle when evaluating the design.*	**Q3e)** *Did the criteria used to evaluate the designs address cost?*	For IPPD designers only need to consider cost and feasibility of manufacture. The latter is already addressed by *Q3d)*.
7	*The methodology should not introduce any inconsistencies into the decision process.*	**N/A**	Logical coherence is a theoretical concept, not something that can be tested in practice.
8	*The methodology should only draw upon available information.*	**Q3f)** *Did the participants require information not provided by available DfM sources, for Validation?*	

This gives a set of 11 sub-questions that can be used to evaluate applications against questions **Q2** and **Q3**. The next section discusses how these questions will be answered.

5.1.2 Research Strategy

This research follows a *fixed design*: the purpose of the application is to answer pre-specified research questions, not to identify or evolve new ones. The nature of these questions – their focus on human participants, rather than mathematical abstracts – means that the data gathered will be *qualitative*, and often subject to interpretation. It is therefore important that data is gathered and analysed in a structured manner, to ensure that the answers to these questions are valid. This section discusses the strategy adopted, its limitations, and what can and cannot be determined with confidence.

The need for human participation places a number of limits on what can actually be studied in this research. The success or failure of a given application of the methodology will be affected by the individuals applying it, and the particular situation to which it is applied. A single success or failure does not say anything about how successful the methodology would be if applied by different people under different circumstances (Checkland, 1999, pA12). Only after many applications by different people in different circumstances, could any generalisations about the methodology be made. Given the detail needed to study a single case (as demonstrated by Section 5.1.1), this is not feasible in a single thesis. In any case, before conducting such a wide range of studies, the question is whether the methodology *can* work: *that* is the focus of this thesis. Even a single successful application would be sufficient to show this.

The need for human participants raises other issues. For the application to be valid, it must be applied to a real problem and cannot be tested without interfering in a real situation. However, it is difficult to achieve the control necessary for internal validity (see Section 5.2.1) when studying a real situation. Conversely, imposing controls to achieve internal validity makes the situation artificial, limiting its external validity (see Section 5.2.2). To balance the two, this thesis first applies the methodology to a set of design experiments, simulating design decisions, before applying it to real situations.

Design experiments offer a safe environment for testing a new methodology. If the methodology fails, or turns out to be impractical, nothing is lost. While design experiments cannot substitute for real applications, they do provide a chance to learn about and refine the methodology before taking it out into the real world. There are three issues that make a design experiment artificial: the *participants*; the *context* in which it takes place; and the *scenario* studied. Table 9 summarises the factors associated with each issue that make design experiments artificial.

Table 9: Participant, Context and Scenario factors that limit external validity.

Participant Factors	Not all participants are experienced designers. The participants have no specific expertise in the product they are evaluating. The participants are not part of a pre-existing design team. The participants do not necessarily reflect the constitution of a "typical" design team.
Context Factors	The participants do not have the rest of the organisation to consult with – to receive clarification or guidance, for example. the participants had no stake in the outcome of the decision they were simulating.
Scenario Factors	The requirements are not necessarily representative of "typical" design requirements. The candidates are not necessarily representative of "typical" design candidates. The designers did not generate the candidates that they were evaluating.

The further one can go in mitigating these factors, the more realistic an application of the methodology becomes, and the more its results generalise. Therefore, this research will use a three-stage approach:

1) **Three Design Experiments carried out by a team of volunteers**: The first an artificial scenario, designed to be simple; the second and third to be drawn from design projects carried out at the University of Leeds. In the first two experiments, the participants will simulate a design team applying the methodology. In the final experiment, the participants will simulate a multi-functional team with designers responsible for design aspects of the decision, and manufacturing engineers responsible for providing manufacturing guidance.

2) **Case Study 1 - Student Design Project at the University of Leeds:** Although not real, the design projects carried out at MEng level at the University of Leeds are carried out by teams of undergraduates, in collaboration with industry. This allows greater realism than the design experiments, without the full risks of a commercial project.

3) **Case Study 2 - Commercial Project:** The final stage is to apply the methodology to commercial project with a company. At this point, complexity and risk are at their greatest, and information will be more difficult to collect. However, it is also a full test of the methodology, and a "successful" application would demonstrate that the methodology *can* be applied in practice.

Table 10 shows how the structure of the design experiments and case studies gradually mitigate the participant, context and scenario factors, gradually working up to a full commercial application. The rest of this Chapter will discuss the issues that must be considered in these tests, and the way that data can be collected and analysed in each test.

Table 10: Participant, Context and Scenario Factors applying to each study

Factors		Design Experiments			Case Studies	
		1	2	3	1	2
Participant Factors	Not all participants are experienced designers	●	●	●	●	
	The participants have no specific expertise in the product they are evaluating	●	●	●	○	●
	The participants are not part of a pre-existing design team	●	●	●		○
	The participants do not necessarily reflect the constitution of a "typical" design team	●	●	●	●	
Context Factors	The participants do not have the rest of the organisation to consult with	●	●	●		
	The participants had no stake in the outcome of the decision they were simulating	●	●	●	○	
Scenario Factors	The requirements are not necessarily representative of typical design requirements	●	○	○	○	
	The candidates are not necessarily representative of typical design candidates	●	○	○		
	The designers did not generate the candidates that they were evaluating	●	●	○		

● = Factor applies to this study;
○ = Factor applies partially to this study;

5.2 Validity

Research that depends upon human observation is inevitably subjective and open to biases. This section discusses threats to the validity of this research, and how they can be controlled or eliminated. Three kinds of validity are important in research, and this section is divided into corresponding parts. The first addresses *internal validity* – the logic of the research design, whether the data gathered actually relates to the research questions, and answers them as completely as possible. The second addresses *external validity* – the generalisability of this research design, and how far conclusions can be drawn about other applications of the methodology. The final section considers *construct validity* – how far the data gathered actually reflects what it is intended to measure, and therefore how reliable its answers to the research questions can be.

5.2.1 Internal Validity

Internal validity refers to the extent to which a research design can demonstrate plausibly that the given outcome was caused by the treatment applied, and not some other factor. In this case, the treatment is the methodology, and the outcome is the satisfaction (or otherwise) of the desiderata. So, this research is *internally valid* if it can demonstrate plausibly that success or failure in satisfying the desiderata is the result of following the methodology. To ensure internal validity,

this research design must ensure that the methodology has been followed as intended, which is addressed by **Q2)** (see Section 5.1.1).

Robson (2002) describes twelve threats to internal validity, which are summarised in Table 11. Only five are relevant to this research as it does not make comparisons between groups. No technique will eliminate these threats. Instead, care must be taken to minimise them in the way the research is conducted, and their implications must be considered when drawing conclusions.

Time pressures, bias, experience and outside learning are real issues, not artefacts of the research, and might well be encountered in practice. However, this research asks whether the methodology *can* work. Applications of outside knowledge or failures caused by lack of commitment may be realistic, but say nothing of value. Each threat must be addressed in a different way:

History: Given that a case study or design experiment will take place over several sessions, possibly several days apart, it is impossible to eliminate external pressures. Time pressure is a serious problem: participants who commit to taking part may later decide they do not have time, and rush the application rather than withdraw. **Q2a)** and **Q2f)** can protect against the participants cutting corners, by making sure that the methodology has been applied as described, before any conclusions are drawn. Participants may also acquiesce in order to speed up the process: this is a form of *acquiescence bias*, addressed under construct validity in Section 5.2.3.

Testing and **Maturation:** Participants will inevitably learn from applying the methodology, and while the case studies are one-offs, participants in the design experiments will carry their experience from one to the next. They may also learn outside the study, where their behaviour cannot be observed. In terms of *process*, this is not a problem: a successful application would still demonstrate that the participants *could* apply the methodology, even if their learning had made the process easier. In terms of *content* however, it is more serious. Participants will gain experience of DfM, or may look up relevant information outside the study. This is not a problem if they apply their learning in line with the methodology. However, it might lead them to eliminate designs before they have been analysed, or to eliminate those that have survived Validation when they should not have (doing the right thing in spite of, and not because of, the methodology). **Q2f)** helps to protect against this by identifying any activities – such as eliminating designs – that have occurred out of sequence.

Table 11: Threats to internal validity and their implications for this thesis.

Threat	Description	Relevance to this Research Design
1. History	Participants' environments may go through changes other than those forming a direct part of the enquiry.	Outside factors may affect the way the participants behave. External time pressures, for example, may lead to a tendency to cut corners or otherwise misapply the methodology.
2. Testing	Participants may change as a result of gaining practice and experience in repeated tests.	This is not an issue for the two case studies, but the three design experiments may see the designers gaining expertise from their exposure to DFM information.
3. Mortality	Participants may withdraw from the study.	This does not threaten the validity of this research, as no comparison between groups will be made, so group composition is not important. However, it may threaten the practicality of the research, if too few participants are left.
4. Maturation	Participants may grow, change or mature in ways unrelated to treatment in the enquiry.	Participants may learn about, related factors such as DFM, outside of the context studied, which may lead them to reconsider earlier choices beyond the context of the methodology.
5. Ambiguity about causal direction	It may not be clear whether the outcome is a result of the treatment.	Personal preferences or other pressures may cause the participants to "fudge" the results of analysis.
6. Instrumentation	If data is collected in different ways for different tests, then this may erroneously indicate a difference in outcomes.	Although comparisons between tests are not being made, care must be taken that the methods of data collection used to not prevent the methodology being applied, or artificially enforce it.
7. Diffusion of treatments	One group may learn information or otherwise inadvertently receive aspects of a treatment intended only for a second group	These threats are only relevant to experiments comparing outcomes between two groups (or the same group before and after treatment), and are therefore not relevant to case studies or design experiments, such as those adopted in this research.
8. Selection	Initial differences between groups prior to involvement in the enquiry may lead to a difference in outcomes.	
9. Regression	Participants chosen because they were unusual or atypical may regress-to-mean, reducing the initial differences between groups.	
10. Selection by maturation interaction:	Maturation effects may cause two initially similar groups to grow apart, or initially different groups to grow more similar.	
11. Compensatory equalization of treatments.	Organizational, social or other pressures may tend to "equalize" the two groups – perhaps by compensating the non-treated group in other ways.	
12. Compensatory rivalry	Participants in one group may change their behaviour because of perceived (or expected) changes in the other group.	

Ambiguity of Causal Direction: The results of evaluation may not be due to the methodology, but other factors: participants not following the methodology or manipulating results to get the outcome they wanted. The sub-questions of **Q2)** should identify whether the methodology was applied as intended, while those of **Q3)** should identify any designs that have been retained when they should have been eliminated.

Instrumentation: The way data is gathered may interfere with, or artificially reinforce, the methodology. For example, if data gathering introduces additional activities this would mean that the process observed was not an accurate reflection of the methodology (an issue considered by **Q2f**). Artificial enforcement is a less serious problem: a successful application would still show that the methodology *could* be applied. However, care would have to be taken to acknowledge this enforcement when drawing conclusions. If the measurement was enabling the methodology, then it could be included as a formal aspect of the methodology's application.

In this way, the main threats to internal validity are addressed through the research questions. In some cases, the act of answering the research question mitigates the threat – in other cases, the threat is an issue that must be kept in mind when answering the question. While there is no way of eliminating these threats completely, actively considering them reduces the risk of an invalid conclusion.

5.2.2 External Validity

External validity refers to the generalisability of a study: how far the conclusions apply beyond the setting studied. Increasing external validity normally compromises internal validity, and vice-versa, as the tight controls needed for internal validity require an artificial situation (such as a laboratory experiment). Generalisations can be made in two ways: *statistical generalisations*, which generalise conclusions from a sample to the population it represents; and *theoretical generalisations*, where generalisations are argued to hold for theoretically similar situations (Gomm, 2004).

Generalisations about the methodology can be made in three directions:

1) **Generalising to other DfX:** The methodology being tested limits its attention to IPPD, and therefore only considers manufacturing; but the general methodology (see Chapter 3) from which it is derived applies, in theory, to any virtue or lifephase.

2) **Generalising to other decisions:** Product development involves a huge variety of decisions, although this thesis restricts its attention to choices of embodiment (Pahl and Beitz 1996). In principle, decision analysis – and therefore the methodology – could be applied to any decision.

3) Generalising to other individuals: Different individuals may behave in very different ways – therefore the methodology may be more, or less, suitable for different users.

To make statistical generalisations would mean finding statistically representative samples of engineering decisions, and of engineering users. Given that the composition of the populations of engineering decisions to which the methodology *could* be applied, and the population of possible users of the methodology, are unknown, statistical sampling is not appropriate.

In this kind of qualitative research, generalisations will always be difficult to make (Gomm, 2004), as such a small-scale study will never guarantee representativeness. Nevertheless, external validity should be protected as far as possible: although statistical generalisations will not be made, there are a number of threats to external validity that can be addressed. Robson (2002) identifies four, which are summarised, with their relevance to this research design, in Table 12.

Table 12: Threats to external validity and their implications for this thesis.

Threat	Description	Relevance to this Research Design
Selection	The findings may be specific to the group studied.	A successful or failed application of the methodology by one group does not mean that it will be the same for every group. For example, a group composed entirely of designers might respond in a different way to a multi-disciplinary team.
Setting	The findings may be specific to, or dependent on, the particular context in which the study took place.	This could impact the research in two ways. Firstly, success under laboratory circumstances does not guarantee success in the greater complexity of the real world. Secondly, the decision to which the methodology is applied may affect the outcome. For example, the methodology may be successful for very simple decisions, but fail when applied to more complex decisions.
History	The findings may be affected by specific and unique historical experiences of the group studied.	This is similar to the *selection* problem, but rather than team composition, it would be the team itself that caused the problem. Factors such as the cohesiveness of the team studied, or whether the participants had previous experience with decision analysis techniques might affect the outcome.
Construct effects	The particular constructs studied may be specific to the group studied.	This is a less serious problem for this research, where the research questions and data gathering methods are fixed, and do not emerge from the study.

Robson argues that there are two ways of demonstrating that these threats are discountable: *direct demonstration* or *making a case*. Direct demonstration – repeating the study with different participants or in a different setting – is most effective, but this requires repeated studies, which are beyond the scope of this thesis. Instead, this research must rely on *making a case*, drawing generalisations only insofar as it can be shown that the setting and participants were typical. The results of this research must be carefully considered to identify any issues that make the group or decision studied *atypical*. Ultimately, though all precautions can be

taken, the external validity of this research design must be kept in mind when drawing conclusions and considering future research directions (see Chapter 9).

5.2.3 Construct Validity

Construct validity refers to how far the data gathered actually reflects what it is intended to measure. In human-focussed research, the desired data can often only be obtained indirectly. In this research, for example, it is impossible to know how easy the participants found the methodology to apply, or whether they understood what was asked of them – one can only know what they *say* on these subjects. It is always possible that they may be lying. Gomm (2004) identifies eleven threats to construct validity, summarised in Table 13, which can be divided into *participant biases*, *researcher biases* and *reactivity*. As with threats to external and internal validity, it is impossible to eliminate these threats entirely, but steps can be taken to minimise them. Each group of threats can be handled using different techniques.

PARTICIPANT BIASES

Participant biases threaten the research in two ways. Firstly, participants may not follow the methodology as intended, either through refusal (*non-response*) or through *misinterpretation* – this is already addressed by **Q2)**. Secondly, data gathered from participants may not accurately reflect their experiences. Robson (2002) suggests two ways of reducing these biases:

Triangulation: Comparing information from multiple sources, to see if they support the same conclusion. One can look for contradictions between what different participants have reported, and for contradictions between, for example, what they have said *during* the application, and any feedback provided afterwards.

Member checking: Asking participants to comment on the conclusions that have been drawn from the information gathered can also help. This will not necessarily eliminate the bias, but offers an opportunity to explore any contradictions found through triangulation in greater depth.

OBSERVER BIASES

Observer bias is the most significant threat to the validity of this research. Care must be taken to see that conclusions are drawn from real evidence, and not just the observer seeing what he wishes to see. Deliberate fraud is a particularly difficult problem to eliminate, as *any* of the techniques meant to protect against bias *could* be falsified. Nevertheless, being as open with the data as possible increases

the likelihood that fraud would be caught, and therefore reduces the chance that it will take place.

Table 13: Threats to construct validity and their implications for this thesis.

Threat		Description	Relevance to this Research Design
Participant Biases	Co-operation bias	Participants may not know the correct answer, but give an answer anyway, because one has been asked for.	Cooperation biases might appear in the application of the methodology (carrying on with the application without actually understanding what is happening; assigning weights and numbers that have no meaning), or in the feedback (giving definite answers when not actually sure).
	Self-serving bias	Participants may give an inaccurate answer that they believe to be accurate.	Participants may wrongly believe that they have applied the methodology, or completed a stage, correctly. This may also influence content judgements - for example, making an inaccurate judgement about manufacturability during Validation.
	Social Desirability Bias	Adjusting behaviour in order to create a favourable impression.	Participants may not want to raise questions when having difficulty with the application (for fear of seeming stupid), or may provide inaccurate feedback.
	Acquiescence Bias	Giving responses you believe the researcher wishes to hear.	Similar to the social desirability and co-operation biases, participants might refuse to raise complaints or comments, or provide inaccurate feedback.
	Non-response	Refusing to give any response at all.	This might manifest itself as participants refusing to follow the methodology, and insisting on approaching the problem in a different way. This is a more serious threat in the case studies, where real situations are being studied. Also, participants might refuse to cooperate with data gathering techniques.
	Mis-interpretation	Misinterpreting what is being asked for.	Participants might misinterpret the methodology and therefore misapply it, or may fill in documentation incorrectly.
Observer Biases	Fraud	Active fabrication of results.	The observer might falsify the data gathered, to support the conclusion that the methodology *does* work. Criticisms or negative feedback about the methodology might be deliberately eliminated from the report.
	Self-delusion	Unintentional fabrication of results.	The observer may look only for evidence that supports the conclusion that the methodology worked, inadvertently ignoring evidence to the contrary. Alternatively, documentation might be amended to "clarify" what the researcher believes the participants meant.
	Biased Treatment	Treating different groups in ways that reinforce the expected results.	As no comparisons between groups will be made, this is not a serious threat for this research design. However, care must be taken to note whether (and how) the researcher has stepped in to facilitate the process. A successful application with the researcher's assistance does not mean that the group could have achieved this on their own.
	Biased Observation	Ignoring data that contradicts the expected results.	If the only data available has come from the researcher, there is a risk that only data supporting the conclusion that the methodology worked will be gathered (rather than falsifying data, such as with *fraud* or *self-delusion*).
Reactivity		Adjusting behaviour because one knows one is being observed.	Participants might be more co-operative, or less vocal than they would be if unobserved. This is a particularly important issue for the design experiments, as participants may react differently in the artificial environment from the way they would respond in a real situation.

Robson (2002) identifies four methods that can help to protect against observer biases:

Audit Trail: By keeping full records of the studies in a case study database, the evidence is open for others to inspect. In particular, this circumvents the problem of biased observation - that is, only recording evidence that supports the desired conclusion.

Negative Case Analysis: This is a form of devil's advocacy – actually seeking out instances that contradict a theory, forcing the researcher to account for them. In the present case, this means examining the data collected for any evidence that *contradicts* the proposed conclusions, and adjusting the conclusions to take account of it. This provides one way of avoiding selectivity, where evidence contradicting the desired conclusion is ignored.

Member Checking and **Peer Debriefing:** Another way of to identify and reduce observer bias is to check the observer's conclusions with the participants (*member checking*) and fellow researchers (*peer debriefing*), who can provide different points of view.

Triangulation: Checking the conclusions against *all* the available data sources helps to avoid biased observation, where only the information that supports the desired conclusion is referred to.

REACTIVITY

The knowledge that they are being observed may affect participants' behaviour in any situation, but this is a particular problem in the design experiments, where the situation is entirely artificial. For example, participants might be less conservative, knowing that their choices will have no consequences. This corresponds to the *setting* threat to external validity, and limits how far generalisations can be made. However, it also poses a threat in the real world case studies, where - even though there are real stakes involved - participants may alter their behaviour because they know they are being observed. This is akin to the *participant biases* mentioned above, and Robson (2002) advocates addressing it in the same way: through *triangulation* and *member checking*.

These steps can help to ensure the validity of the research, and it is these considerations, as well as the research questions themselves, that determine which data will be gathered and how – the subject of the next section.

5.3 Research Protocol

This section discusses the data that will be gathered from each test in order to answer the research questions. This means considering firstly, what data can be gathered in each case; secondly, how this data relates to the questions posed; and finally, how the threats to construct validity can be countered. This section is divided into two parts. The first discusses the data sources available in the different tests, and how this data can be collected and recorded. The second discusses how this data can be related to the research questions, and how construct validity can be maintained.

5.3.1 Data Sources

Data is an important part of any research: it is by gathering and analyzing data in a structured way that research questions can be given valid answers. Different data collection techniques are appropriate for different situations, and the sources of data available in design experiments and case studies will differ. The design experiments provide a controlled environment, where all communication and decision-making can be observed and recorded, which isn't possible in the case studies. The difference between these two settings and the data that can be collected from them is discussed further below.

Yin (2003) identifies five sources of evidence that can be used in a case study: documents, archival records, interviews, observation, and physical artefacts. No archival records are available in the design experiments, and no relevant archival records were available in the actual case studies. The other four sources can be applied to both the case studies and design experiments (which simulate a case study in a controlled environment).

Documentation

Although the formal documentation involved in a design project will vary from one situation to another, the methodology has a number of flows and outputs that can be captured. Table 14 lists 19 pieces of documentation that should be generated in applying the methodology, regardless of whether it takes place in a laboratory or a real-world setting. To help participants apply the methodology, and to facilitate document gathering a database and set of supporting spreadsheets have been developed, which capture this information (see Appendix Two). Each document can be assessed to see if it is complete, incomplete (missing known information), incorrect (containing information known to be wrong) or empty (containing no information). The completeness and correctness of these documents can then be

used to evaluate whether the methodology has been followed correctly and how successful it has been.

Table 14: Documents generated working through the methodology.

STAGE	ACTIVITY	DOCUMENTATION GENERATED
Preliminaries	Ensure that manufacturing cost is reflected in the requirements specification.	1. A list of requirements with priorities and classifications.
	Classify requirements as process dependent or process independent.	
	Prioritise Requirements	
	Identify manufacturing processes to be considered.	2. A list of processes under consideration;
Framing	Establish criteria.	3. A list of criteria with classifications.
Process Independent Screening	Eliminate candidates not satisfying mandatory PI criteria.	4. An elimination matrix comparing the candidates against the mandatory PI criteria.
Validation	Identify product structure for each candidate	5. A list of candidates under consideration; 6. A list of the components making up each candidate;
	Identify component features	7. A list of the features associated with each component;
	Identify component properties	8. A list of the properties associated with each feature;
	Identify Basic Violations	9. A compatibility matrix for each component comparing its properties against the capabilities of the available processes.
	Identify feasible process chains for each candidate.	10. A list of process chains for each component
	Select the most likely process chain for each candidate.	11. A list of the recommended process chain for each component
	Eliminate infeasible candidates.	12. A list of feasible candidates
Process Dependent Screening	Eliminate candidates not satisfying the mandatory PD criteria.	13. An elimination matrix comparing the candidates against the mandatory PD criteria.
Ranking	Draw a graph of cost vs. utility.	14. A graph of cost vs. utility

In the design experiments, this is the only documentation that will be generated. In the case studies, documents generated for other purposes - such as minutes from meetings – can also be gathered and studied, although the documentation available will depend on the individual case. Such documents will support the field notes taken by the observer (see below).

Interviews

Interviewing allows data to be gathered from the participants outside the context of applying the methodology. Interviews can either be conducted as a face-to-face conversation (with varying degrees of structure) or administered as a questionnaire. There is a trade-off between the richness of data gathered, and the complexity of analysis: in-depth interviews provide more data, but are more difficult to analyse. In this research, two types of interview can be used: a simple questionnaire (see Appendix Three) to be filled out after each laboratory session, and an in-depth semi-structured interview at the end of each study. The

questionnaire asked participants about the main activities of the methodology, to be triangulated against other data sources. The interview provides an opportunity for member checking: presenting participants with the conclusions of each study, and asking for feedback.

Observation

Observation data can be gathered manually (through notes taken by an observer), or mechanically (on audio or video). The former is more flexible, but the latter provides a more complete *audit trail*, as it is not subject to observer biases. Mechanical recording is easy in the design experiments, which occur in a fixed location. To provide a rigorous analysis without swamping the reader with data, these recordings will be subject to protocol analysis[1] (Ericsson and Simon, 1993), identifying the activities taking place at each stage of the methodology. In the case studies, mechanical recording was impractical as many activities occurred beyond the observer's presence (meetings the observer was not able to attend, individual work which could not be observed) or on an informal basis (e.g. chance conversations in the office, communications (such as telephone calls) to which the observer did not have access). This meant that field notes – and the use of other documents such as minutes or e-mail communications – played an important part in recording events.

Physical Artefacts

This is the least valuable of the four data sources, as the methodology does not generate any physical artefacts beyond the documents already captured by the software. Artefacts may be generated by other stages of design but this research is not concerned with the design process. Nevertheless, sketches or notes made by the

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[1] Protocol analysis is a structured way of analysing verbal data, such as a recording or transcript, by breaking it down into segments of equal length, and identifying the activity taking place in each. Activities that can be assigned are listed in a "verbal protocol" which may be pre-specified, or developed specifically from the activities in the given recording. In this research, the verbal protocol was drawn from the activities specified by the methodology, and expanded to account for other activities that were identified. This verbal protocol is specified in Table 17 in Chapter 6.

participants may be helpful in clarifying events, and therefore may support field notes or recordings.

Table 15 shows the availability of these data sources in the design experiments and case studies. "Other" documentation, field notes and physical artefacts inform the observer's account of the case studies but, being unstructured and context dependent, are not suitable for formal analysis. Similarly, member checking is used as an opportunity for the participants to voice any disagreements with the experiments' conclusions, rather than being subject to in-depth study. The next section discusses how these data sources relate to the research questions.

Table 15: Data sources that can be used in the laboratory and real world settings.

Data Source \ Setting		Laboratory	Real World
Documentation	Documents drawn from Support software	✓	✓
	Other Documentation		*
Interview	Feedback questionnaire	✓	
	Member Checking Interview	*	
Observation	Audio recordings	✓	
	Field notes		*
Physical artefacts		*	*

× = data gathered for formal analysis;
* = data gathered in support of other data sources, not subject to formal analysis.

5.3.2 Data Sources and Research Questions

The final step before applying the methodology is to discuss how the data that can be collected from such applications can be used to answer the research questions. The relevance of each data source to each question is shown in Table 16. Because the data that can be collected in the laboratory and the real world are different, this does affect which questions can be answered in each setting. This section will discuss each of the research questions in turn, and how the relevant data can be used to answer them.

***Q2** Can the **methodology** be used to evaluate designs in practice?*

Q2a) *Were the participants able to work through all the stages of the methodology?* and

Q2b) *If not, where does the application break down, and for what reason?*

These two questions are closely related, and are both answered by examining the three data sources to see which activities have been carried out and which (if any) have not.

Documentation (Software): If all 14 documents have been completed, then this supports the argument that the stages of the methodology have all been carried out. If the documents associated with a stage are empty, then this would suggest that the relevant stage had been not completed. Finally, if one or more documents for a stage were incomplete, then this would suggest that the given stage had not been completed correctly.

Table 16: Relevance of the available data sources to the research questions

Question	Documentation (Software)	Interview (Questionnaire)	Observation (Recordings)
Q2a) *Were the participants able to work through all the stages of the methodology in the required sequence?*	✓	✓	✓
Q2b) *If not, where does the application break down, and for what reason?*	✓	✓	✓
Q2c) *Were there any stages of the methodology that the participants felt uncomfortable or unhappy with carrying out?*		✓	✓
Q2d) *Did the participants require any additional help or advice in order to apply the methodology?*		✓	✓
Q2e) *Did the participants carry out any activities not considered by the methodology?*			✓
Q3a) *Were any of the criteria used in the evaluation not related to a requirement from the requirements specification?*	✓		
Q3b) *Were any essential requirements not represented by the criteria?*	✓		
Q3c) *Were any of the designs surviving to Ranking expected to violate the requirements specification?*	✓		
Q3d) *Were any designs with known manufacturing flaws permitted through Validation?*	✓		✓
Q3e) *Did the criteria used to evaluate the designs address cost?*	✓		
Q3f) *Were the participants able to gather all the information that they needed for the evaluation?*			✓

✓ = The specified data source is relevant to the given question

Interview (Questionnaire): The questionnaire administered in the design experiments asks for a simple "yes" or "no" answer from each participant about whether each activity was completed. Any comments provided may help to understand why any activities were not completed.

Observation (Recordings): The protocol analysis will track which activities occur at each point in the recording. This makes it possible to identify which stages of the methodology have been attempted, and which have not.

Q2c) *Did the participants object to any stages of the methodology?*

Interview (Questionnaire): The participants can state any objections to the tasks they were asked to carry out.

Observation (Recordings): By examining the recordings for comments made by the participants, it is possible to identify any that indicate that they were uncomfortable or unhappy with carrying out a particular task.

As these data sources will not be available in the case studies, the answer to this question can only be given based on the researcher's account from field notes and "other" documentation.

Q2d) *Did the participants require any additional help or advice in order to apply the methodology?*

Interview (Questionnaire): The participants can provide comments to indicate where they felt they needed additional help or advice in order to apply the methodology.

Observation (Recordings): The recordings can be examined for any points where the researcher had to break his role in the experiment to provide additional help or guidance.

As these data sources will not be available in the case studies, the answer to this question can only be given based on the researcher's account from field notes and "other" documentation.

Q2e) *Did the participants carry out any activities not considered by the methodology?*

Observation (Recordings): As the protocol analysis must account for all the activities that take place in each experiment, it will be possible to identify any activities which occur that are not part of the methodology.

As these recordings, and therefore protocol analysis, will not be possible in the case studies, the answer to this question can only be given based on the researcher's account from field notes and "other" documentation.

*Q3 "Can the **methodology** satisfy the **desiderata** when used to evaluate candidate designs in practice?"*

Q3a) *Were any of the criteria used in the evaluation* **not** *related to a requirement from the requirements specification?* and

Q3b) Were any *essential* requirements not represented by the criteria?

Documentation (Software): The documentation captured by the software should indicate which criteria were actually used in Screening and Ranking, which requirement each one represents. The researcher's field notes must support this by keeping track of the justifications given for each requirement omitted, so that it can be seen whether they *were* deemed nonessential.

Q3c) *Were any of the designs surviving to Ranking expected to violate the requirements specification?*

Documentation (Software): The software will provide a list of the designs that survived to ranking and the judgements the participants have made about whether each design will satisfy each requirement. Obviously, as there are no absolute standards for a satisfactory design, this is a subjective judgement. However, the documentation will highlight whether designs which the participants expected to violate one or more of the mandatory requirements were retained for Ranking.

Q3d) *Were any designs with known manufacturing flaws permitted through Validation?*

Documentation (Software): The software will provide a list of which candidates the participants deemed feasible, as well as the compatibility matrices that they used for Validation. The judgements in the compatibility matrix should be based on the DfM information available. If these judgements are factually incorrect because the information is incorrect, this is a problem with the information, not the methodology. The methodology is only concerned with decision analysis, and therefore judgements can only be compared against the information available to the participants. In the design experiments, this is a controlled factor (see Chapter 6); in the case studies, these judgements must be compared with the DfM sources adopted in each case.

Q3e) Did the criteria used to evaluate the designs address cost?

Documentation (Software): This lists the criteria used to evaluate the design, so it is a simple matter to verify whether cost is included.

Q3f) *Were the participants able to gather all the information that they needed for the evaluation?*

Observation (Recordings): The protocol analysis should identify any complaints about available information raised by the participants.

As protocol analysis will not be possible in the case studies, the answer to this question can only be given based on the researcher's account from field notes and "other" documentation.

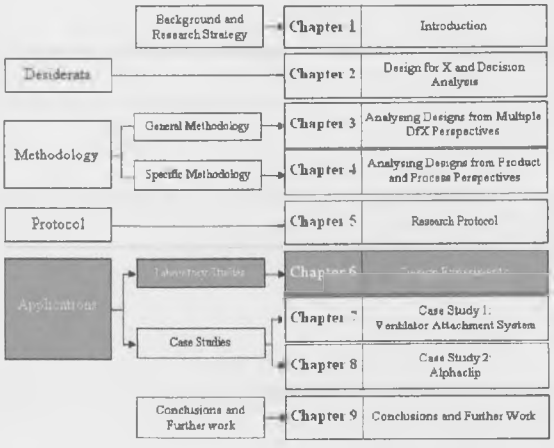
5.4 Summary

While the previous chapters have shown that the proposed methodology logically satisfies the desiderata, this does not mean that it is robust to the complexities of real world decision-making. Whether the methodology can satisfy the desiderata *in practice* can only be determined by studying it in use, but such human-focussed research is not straightforward. The success or failure of a methodology is dependent upon the people who apply it, and the problem it is applied to – not just the methodology itself. The data that must be studied is often subjective and open to bias. Therefore, this Chapter has provided a research protocol, explaining how uses of the methodology will be studied. This specifies the questions that will be asked of each study, how data will be gathered and how this relates to the questions posed.

The methodology will be studied through a series of three design experiments, which simulate design decisions, and two case studies – one a student project, and one a commercial project. The design experiments provide an opportunity to study the methodology in an artificially controlled environment, where internal validity is easier to ensure, and there are no costs for failed applications. This provides a safe environment in which to learn about the methodology, before applying it to the greater complexities of the case studies. The case studies provide greater external validity than the design experiments, as they are real cases, with real risks and outside pressures. The student project offers fewer risks than the commercial project, an opportunity to study the methodology beyond the laboratory, before applying it to a commercial case. Given the huge range of problems and users that the

methodology might encounter, it is impossible to determine in a single thesis whether it would be suitable for them all. Instead, the commercial case demonstrates that real circumstances *do* exist in which the methodology is able to satisfy the desiderata.

Chapter 6
Design Experiments



Before testing the methodology in the complexities of the real world, it is advisable to try it out in the laboratory, where *internal* and *construct* validity are easier to ensure. This chapter describes a series of three design experiments carried out with a group of volunteers. The purpose of these studies is to determine whether the ***methodology*** can satisfy the ***desiderata*** under the idealised conditions of the laboratory. The limited *external validity* of these tests has already been discussed, but if the methodology cannot be made to work under idealised conditions, then there is no sense in taking it further. As with any methodology, success in these limited conditions does not generalise. The purpose of these tests is to show that the methodology *can* be used to satisfy the desiderata before it is applied to real cases.

This chapter is divided into three sections. **Section 6.1** discusses the purpose of the design experiments and the manner in which they were conducted. **Section 6.2** describes the results of each experiment, providing a qualitative account of the events that happened, and presenting the data gathered. **Section 6.3** uses these results to provide answers to the research questions based on the research protocol presented in Chapter 5.

6.1 Purpose and Procedure

This section provides an overview of the design experiments described in this chapter. Although the exact decisions studied in each experiment differ, the reasons for the experiments and the procedure used to carry them out was the same. This section is therefore divided into two parts: the first defines the objectives of these experiments; the second explains how they were conducted.

6.1.1 Objectives of the Study

A design experiment simulates design activities under laboratory conditions, so that they can be studied. In this case, it is the evaluation process that was simulated, presenting the participants with a set of designs to be evaluated against a set of requirements. Design experiments are artificial, and not necessarily representative of real design behaviour (see Section 5.1.2), but they provide two

important benefits over case studies. Firstly, they offer greater control – all activities take place where they can be recorded, and the methods and tools available to the participants can be restricted to suit the research. Secondly, they offer a safe environment for studying new methods, as the experiment will generate knowledge about the methodology, regardless of the outcome. Both are relevant to this research: the experiments provided a chance to learn about the methodology before applying it to a real situation, and allowed greater internal validity.

These experiments served two purposes: to learn about the methodology (which is the purpose of this research); and to learn about its implementation (in preparation for the subsequent case studies). As a methodology is a set of principles, it can only be studied through its implementation, as method, might be done in a variety of ways (see Section 1.4.1). It is important to understand whether problems encountered are inherent to the methodology, or a consequence of the way it has been applied. Even if the methodology is acceptable, problems caused by the way it has been implemented must be corrected before it is applied outside the laboratory. A laboratory study can be repeated, whereas a failed case study could have serious consequences for the participants.

The laboratory is an idealised situation: it is impossible to rule out problems that might be caused by the greater complexity of the real world. However, design experiments offer an opportunity to go as far as possible in identifying problems before applying the methodology to case studies. If problems are identified, then the design experiments must be iterated until a solution to the problem can be found. If, after repeated attempts, no solution can be identified, then the methodology must be declared infeasible, and not worth carrying further. Conversely, if an implementation can be found that is successful in the laboratory, then – while success in the real world is not guaranteed – the implementation is worth carrying forward to case studies.

The design experiments have three objectives:

1) To determine whether the methodology *can* be applied under idealised laboratory conditions, by answering the sub-questions of **Q2)** (*Can the methodology be used to evaluate designs in practice?*);

2) To determine whether the methodology *can* satisfy the desiderata when applied under idealised laboratory conditions, by answering the subquestions of **Q3)** (*Can the* ***methodology*** *satisfy the* ***desiderata*** *when used to evaluate candidate designs in practice?*); and

3) To develop an implementation of the methodology that *can* satisfy the desiderata under idealised laboratory conditions, based on the answers to **Q2)** and **Q3)**.

These objectives are the same for each design experiment – the purpose of studying three different scenarios is to test the methodology under increasingly realistic circumstances (see Table 10, page 95). The outcome of this chapter is therefore an indication of whether the methodology has the potential to be feasible in practice, and issues that should be considered in its implementation.

6.1.2 Procedure

This section discusses the basic procedure followed in each design experiment. The same procedure and participants were used in every case. Only the scenario being evaluated – and, if necessary, the implementation of the methodology (see above) – changed.

Participants

It is difficult, perhaps impossible, to define the profile of a "typical" designer or design team, and therefore difficult to say who should take part in the experiments. It is also difficult to persuade a team of experienced designers to spare the time needed for these experiments (some 45 hours). Participants were therefore recruited from postgraduate students at the University of Leeds' School of Mechanical Engineering. As statistical generalizations will not be made from these experiments, the composition of the participants is not critical, and convenience sampling is acceptable. All the participants had engineering degrees and industrial experience. In particular, one had worked as an automotive design engineer, and another as a production manager in the printing industry. The team therefore reflected an engineering education, and included experience of commercial design and production environments.

Four participants were chosen, enough to allow group interactions, and cover absences. Though participants would inevitably learn about the methodology with each experiment, their experience would only increase the chances that they would apply the methodology as intended. It does not change the compatibility of the methodology itself, so there was no need to use different participants in each experiment.

The Setup

All three experiments followed the same pattern. Participants were presented with a scenario, which involved comparing a set of designs against a set of requirements, and were asked to use the methodology to do this. They were provided with:

1) A laptop computer with the software described in Appendix Two;

2) A handout describing the scenario, including the candidates to be evaluated, and the requirements they were to be evaluated against;

3) A handout describing the methodology; and

4) A copy of "Process Selection: From Design to Manufacture", which provided the PRIMAs (Process Information Maps) – information about process capabilities and limitations - for Validation (Swift and Booker, 2003);

For the purpose of the experiments, it was assumed that the handouts and PRIMAs provided all necessary information. Where additional information *was* required, it was provided by the researcher. These experiments were concerned with process, not content, and as they had no real world consequences, the effort required for additional calculation or analysis could not be justified. All work on the experiments took place in the laboratory, so that discussions could be recorded, and all data was captured using the support software. Initially the researcher was present only as an observer, but after the first iteration of Experiment 1 (see below) the researcher acted as a facilitator, guiding the participants through the process.

Data Sources

As noted in Chapter 5, the experiments provided three sources of data:

Documents: Because the participants used the Support Software to apply the methodology, it provided documentation described in Table 14, page 104.

Questionnaire: The questionnaire shown in Appendix Three was given to each participant to fill in at the end of each session, allowing simple yes or no answers about each activity, and any additional comments they wished to make.

Observation: Audio recordings of each session were taken, for subsequent analysis.

The audio data was difficult to analyse due to its quantity and its qualitative nature. Protocol analysis (Ericsson and Simon, 1993) was used to examine events in the recordings in a structured way. This meant dividing each recording into five-minute segments, and allocating one of the activities from the verbal protocol in Table 17 to each segment. In Section 6.2, this data is presented visually, as a graph of the activity occurring in each segment, for each of the recordings.

Table 17: Verbal protocol for analysing audio recordings of each experiment

Activity Number	Activity	Rationale
0	*No activity*	Activities that are identified on the recordings but have no bearing on the evaluation process.
1	*Unrelated Discussion:* Banter (jokes, discussing outside issues), or discussions not directly relevant to the methodology or the scenario (the size of font used in the software, for example).	
2	*Organisational Issues:* Activities that relevant to the methodology, but not a direct part of it: reading handouts, reviewing the outcomes of earlier stages, etc.	
3	*Classify Requirements as process dependent or process independent.*	Activities that should be carried out as part of the methodology.
4	*Prioritise requirements.*	
5	*Identify manufacturing processes to be considered.*	
6	*Establish criteria.*	
7	*Eliminate candidates not satisfying mandatory PI criteria.*	
8	*Identify component features*	
9	*Identify component properties*	
10	*Identify Basic violations*	
11	*Identify feasible process chains for each candidate*	
12	*Select the most likely process chain for each candidate.*	
13	*Eliminate candidates not satisfying the mandatory PD criteria.*	
14	*Draw a graph of cost vs. utility.*	
15	*Generating or Altering Requirements*	Activities identified in the recordings, which are not part of the methodology but had an effect on the evaluation process. Needed to answer **Q2e)** (see page 90)
16	*Generating or Altering Designs*	
17	*Discussing Requirements*	
18	*Discussing Candidates*	
19	*Eliminating Candidates Outside Screening*	
20	*Discussing the methodology*	Data needed to answer **Q2c)** (see page 90)
21	*Intervention*: Points where the researcher provides assistance beyond that prescribed by his role as an observer or facilitator, as appropriate.	Data needed to answer **Q2d)** (see page 90)

The verbal protocol was developed specifically to provide answers to the research questions relevant to the audio data. It therefore had to identify four things[1]:

1) Which stages of the methodology were carried out (**Q2a), Q2b)**);
2) Any comments about the methodology made by the participants (**Q2c)**);
3) Any interventions made by the facilitator to help the participants (**Q2d), Q3f**); and

[1] Refer to pages 89 to 92 for descriptions of the research questions.

3) Any interventions made by the facilitator to help the participants (**Q2d), Q3f**); and

4) Any activities carried out by the participants that were not a part of the methodology (**Q2e**).

These four categories provided a starting point for the verbal protocol, and the content of each category was refined as the verbal protocol was applied to each recording, until every segment had been accounted for. Once these answers had been established, they were presented to the participants for member checking, so they could raise any objections.

6.2 Results

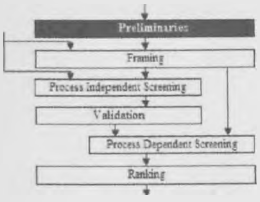
This section presents the results of each experiment, and is therefore divided into three corresponding parts. Each part provides a qualitative account of the events that took place in the experiment, as well as summarising the quantitative data gathered through documentation, interview and observation. This section is only concerned with *process* results: details of the content of the scenario and documentation for each experiment are given in Appendix Four. Only the results of analysis are presented here: supporting evidence for the qualitative accounts is referenced through footnotes.

The division of Screening into process independent and process dependent stages (described in Section 4.1.2) was only introduced in response to feedback during Experiment 2 (see Section 6.2.2). Therefore, Experiments 1 and 2 present an ordering of activities that places Validation before Framing, and has all Screening occurring immediately prior to Ranking. This is a valid implementation of the methodology, obeying the precedence constraints given in Chapter 5 (see Figure 23, page 90), but shows how the implementation of the methodology evolved in response to these experiments.

6.2.1 Design Experiment One: Disposable Pen

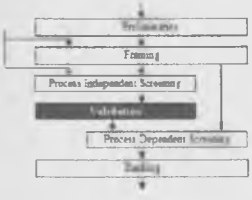
The purpose of this experiment was to find out whether the methodology could be applied at all. A simple, artificial scenario was used so that any problems encountered were more likely to be inherent to the methodology, rather than the complexity of the scenario. The scenario used seven requirements, two manufacturing processes and five designs, each with just one component representing new designs for the barrel of a disposable pen. Pictures and descriptions of the candidate designs, as well as documentation from each stage of the methodology, can be found in Appendix A4.1.

Preliminaries



Given the information presented directly to the participants, most of the preliminary activities had already been carried out. The only preliminary activity required from the participants was the classification of requirements as either process dependent or process independent[1].

Validation – 1st Iteration



The participants worked through Validation, but made two errors. Firstly, they struggled to understand the definition of "feature", and therefore did not define *any* features, despite the presence of holes, bosses and ribs on some of the designs[2]. Secondly, they did not refer to the PRIMAs provided, instead relying on their own knowledge to fill in the compatibility matrix[3]. They accepted *every* candidate as feasible for injection moulding, despite the presence of enclosed hollows and sudden section changes that, according to the PRIMAs, are not suitable for injection moulding. There was also some confusion about the nature of the surface finish property: the participants defined one candidate as having a surface finish of "ribbed", rather than a numerical value. All the correct activities were carried out, but the participants came to several erroneous conclusions about features, properties and which candidates were feasible.

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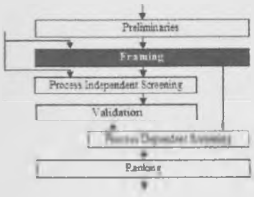
[1] See Figure 24 (page 122): 35:00-40:00,

[2] See Figure 24: (Activity 8 (Identify Features) does not occur) and Table (page 121) (in the first iteration, document 6 is incomplete, as it only contains "basic component" for each design). Given the flexibility allowed by the Compatibility Test described in Chapter 4, the participants were entitled to define no features, if they felt this was appropriate. The fact that Activity 8 did not occur suggests that the lack of features in the documentation was an error, and not the result of careful consideration.

[3] See Appendix A5.1. Transcript One shows the process the participants went through in identifying violations, and Transcript Two shows point where they acknowledge that this was incorrect.

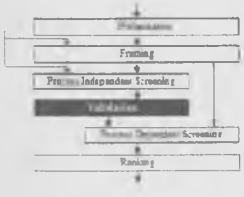
Framing – 1st Iteration



Although the participants attempted the framing process[1] they did not manage to define any criteria[2]. The participants did not understand what was meant by a criterion, and declared that they were not able to proceed, so the experiment came to a halt[3].

The failures of this first iteration stemmed from participants misunderstanding the concepts used by the methodology (specifically: features, surface finish and criteria), and failing to use the decision support provided. In the second iteration, therefore, the researcher acted as a *facilitator* rather than an observer, being able to provide clarification, answer questions, and step in to correct misconceptions. Such activities were no longer treated as interventions, but as a part of the methodology's implementation. This did not mean carrying out tasks on the participants' behalf, but providing *process* assistance, by walking them through each activity, and eliciting *content* from them. As the only preliminary activity had been carried out correctly, the second iteration began from the Validation stage.

Validation – 2nd Iteration



With clarification from the facilitator, the participants were able to understand what was meant by a feature, and this time identified features and properties consistent with the meaning used by the methodology. At the facilitator's prompting, the participants referred to the PRIMAs when filling in the compatibility matrix, and this time eliminated three of the candidates, owing to large step changes (impossible to create through continuous extrusion, and presenting the problem of differential cooling in injection moulding) or internal hollows (impossible to extrude or injection mould). Of the two surviving candidates, one was recommended for extrusion (due to concerns over differential cooling in injection moulding), and the other (the textured grip) for injection moulding (as the textured section meant it

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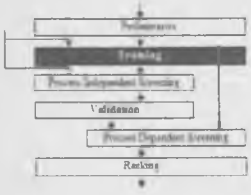
[1] See Figure 24 (page 122): Activity 6 (Establish Criteria) occurs in two segments, 02:35:00-02:45:00

[2] See Table 18 (page 121): the document 3 is empty in the first iteration.

[3] See Appendix A5.1 Transcript Three, for the point where the experiment terminates.

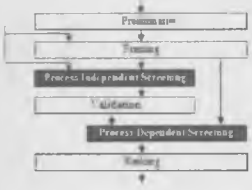
would be impossible for continuous extrusion). As there was only one feasible process chain in each case, there was no need to determine which was most likely[1].

Framing – 2nd Iteration



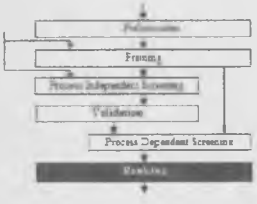
With the facilitator's clarifications, the participants were able to understand the meaning and purpose of criteria, and establish them for each of the requirements[2].

Screening



The two surviving candidates were screened against the process independent and process dependent criteria simultaneously. One candidate, the triangular barrel, was eliminated as it could not be made to satisfy the constraints on both internal and external diameters.

Ranking



With only one candidate surviving screening, this stage could have been omitted, but in order to test the Ranking stage, utilities and costs were estimated for both candidates that survived Validation. The larger size of the triangular barrel meant that it was more expensive due to the material costs, and also saw it penalised against the optional criteria for fitting into a shirt pocket or pencil case. The textured grip design therefore pareto dominated the triangular design, and was the logical choice, even if the triangular barrel had not been eliminated in screening.

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[1] See Figure 25 (page 123): Activity 12 (Select Most Likely Process Chain for Each Candidate) does not occur.

[2] See Figure 25: Activity 6 (Establish Criteria) occupies 30 segments, compared to just two in the first iteration. Also, see Table 18 (page 121): this time, document 7 is complete.

Documentation

Table 18: Status of documents gathered in Experiment 1

DOCUMENT	STATUS	
	1st Iteration	2nd Iteration
1. A list of process dependent requirements, with priorities and classifications.	✓	✓
2. A list of processes under consideration;	✓	✓
3. A list of criteria with classifications.	○	✓
4. A list of candidates under consideration;	✓	✓
5. A list of the components making up each candidate;	✓	✓
6. A list of the features associated with each component;	◉	✓
7. A list of the properties associated with each feature;	◉	✓
8. A compatibility matrix for each component comparing its properties against the capabilities of the available processes.	×	✓
9. A list of process chains for each component	×	✓
10. A list of the recommended process chain for each component	×	✓
11. A list of feasible candidates	×	✓
12. An elimination matrix comparing the candidates against the mandatory criteria.[1]	○	✓
13. A graph of cost vs. utility	○	✓

✓=Complete, × = Incorrect, ◉= Incomplete, ○ = Empty

Feedback Questionnaire

Table 19: Results from questionnaires for the first iteration of Experiment 1

	1st Iteration				2nd Iteration			
PARTICIPANT / ACTIVITY	A	B	C	D	A	B	C	D
Classify requirements as process dependent or process independent.	✓	✓	✓	✓	N/A			
Prioritise Requirements	N/A							
Identify manufacturing processes to be considered.								
Establish criteria.	×	×	×	×		✓	✓	✓
Identify component features	✓	×	✓	✓		✓	✓	✓
Identify component properties	✓	×	✓	✓		✓	✓	✓
Identify Basic violations	✓	×	✓	✓		✓	✓	✓
Identify feasible process chains for each candidate.	✓	✓	✓	✓		✓	✓	✓
Select the most likely process chain for each candidate.	✓	✓	✓	✓		✓	✓	✓
Eliminate candidates not satisfying the mandatory criteria.	×	×	×	×		✓	✓	✓
Draw a graph of cost vs. utility.	×	×	×	×		✓	✓	✓

Observation

Figure 24 (page 122) and Figure 25 (page 123) provide graphs of the protocol analyses for the first and second iterations of Experiment 1. These indicate the main activity (referenced by its Activity Number from Table 17) occurring in each five-minute segment of the recording.

[1] As Screening had not been divided into PI and PD stages at this point, the documentation gathered only reflects a single screening stage.

Figure 24: Protocol analysis for the 1st Iteration of Experiment 1

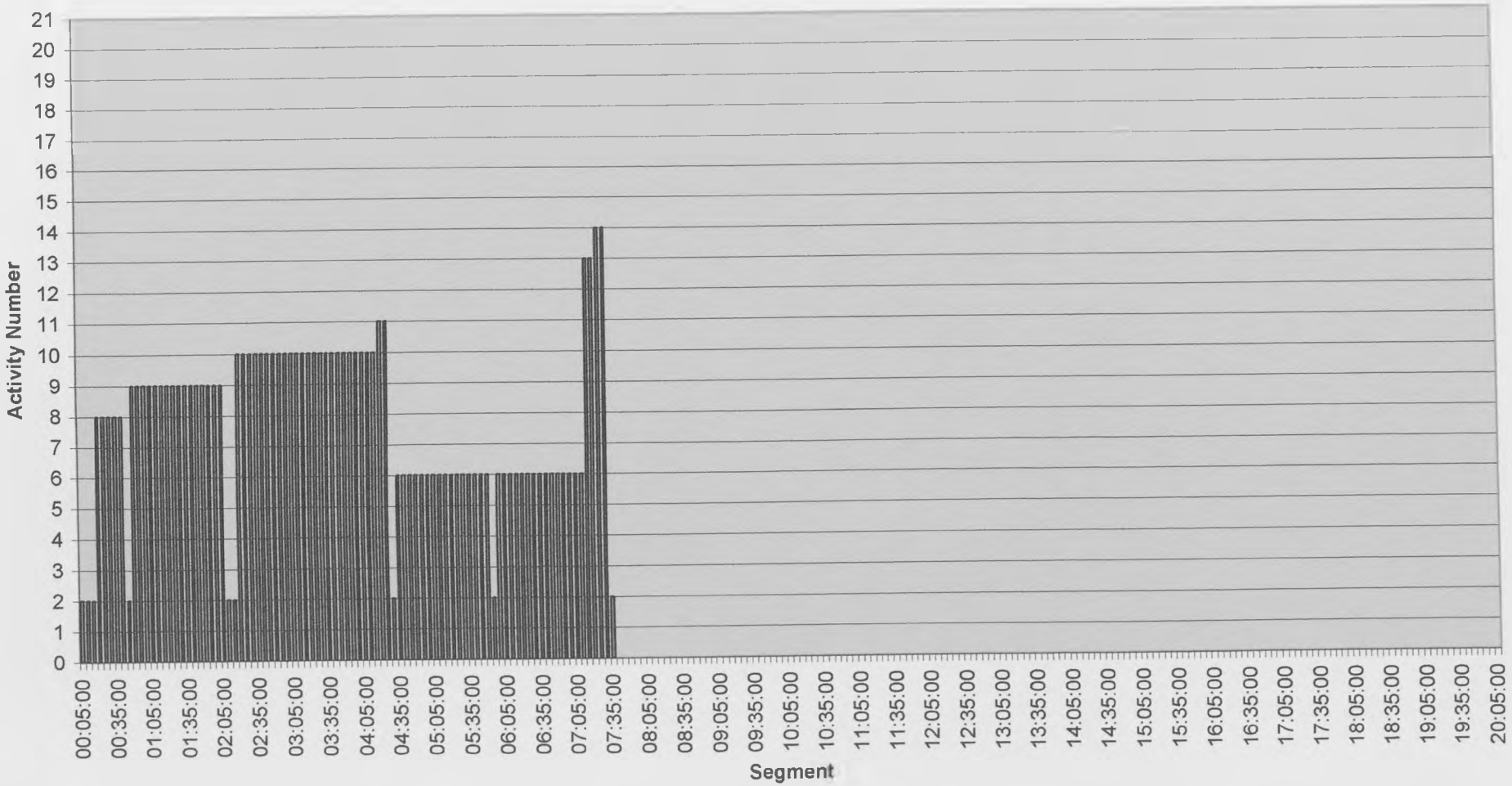
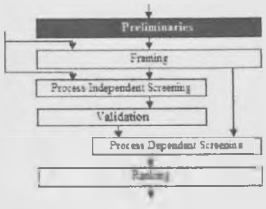


Figure 25: Protocol analysis for the 2nd Iteration of Experiment 1

6.2.2 Design Experiment Two: Rollerball Deodorant

Where Experiment 1 was designed to be simple, this experiment was intended to eliminate some of the factors highlighted in Chapter 5 (see Table 9, page 94), by using more complex designs and requirements. These were drawn from a student project carried out at the University of Leeds in collaboration with a local manufacturer of personal hygiene products. Because they have been developed independently of the experiment, they avoid the possible biases that might be introduced (even subconsciously) by the researcher. This time, the scenario used 22 requirements, three available processes, and six candidates (each of four or five components), representing new designs for a rollerball deodorant applicator. Pictures and descriptions of the candidates, as well as the documentation from each stage, can be found in Appendix 4.2.

Preliminaries



Like Experiment 1, most of the Preliminaries had been done for the participants, and were included in the handout. However, once Framing began[1], the participants began to feel that the requirements presented were not sufficiently developed for Framing to take place[2]. It was decided that they should develop more acceptable requirements that they could use in Framing[3].

This also meant going back to the Preliminaries, to prioritise the new requirements and classify them as process independent or process dependent[4]. In terms of the experiment, this is not a problem, as the requirements were provided by the participants, not the researcher, but it does highlight that the methodology is dependent on a suitable set of requirements existing.

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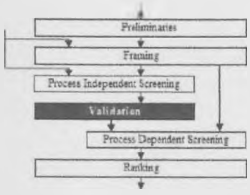
[1] See Figure 26 (page 128): 08:40:00-10:20:00 for the initial attempt at Framing.

[2] See Appendix A5.2, Transcripts One to Three.

[3] See Figure 26: 11:45:00-13:55:00

[4] These activities were carried out for each requirement as it was generated, and therefore do not occupy enough space in each segment to show up in Figure 26. However, as Table 20 (page 127) indicates, this information was entered onto the support software for the new requirements.

Validation



In order to identify features and properties, the participants looked at each candidate in turn – but did not assign information to them all[1]. Features and Properties were assigned for candidates 1, 4 and 6[2]. While identifying properties for Candidate 4, the participants suggested breaking it down into a greater number of simpler components, for ease of manufacture, and this variant was treated as a new candidate, Candidate 4a[3]. However, the participants refused to validate Candidates 2, 3 and 5, on the basis that they would not satisfy the requirements specification[4], effectively carrying out some Screening activities *before* Validation. They investigated ways of amending Candidate 5[5], but eventually decided that it was impossible. Although this contradicted the methodology presented to them, the participants argued that there was no point in analysing designs that they already knew were going to be eliminated.

Thereafter, compatibility matrices were constructed for Candidates 1, 4, 4a and 6[6]. All four were found to be feasible, and each component had only one feasible process chain[7].

---

[1] See Table 20 (page 127): Candidates 2, 3 and 5 do not appear in any of the documents related to Validation, even though every design should have been validated, as Process Independent Screening had not yet been introduced.

[2] See Figure 26 (page 128): activities 8 and 9 occur for Candidate 1 (00:30:00-01:05:00), Candidate 4 (02:45:00-04:40:00, including Candidate 4a) and Candidate 6 (05:40:00-06:05:00).

[3] See Figure 26: Activity 16 (generating or altering designs) occurs at 03:00:00-04:10:00, in the middle of validating candidate 4.

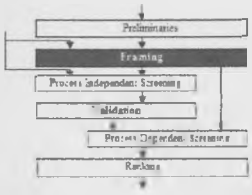
[4] See Figure 26. Validation activities (Activities 8 through 12) occur from 00:30:00-08:25:00, but candidates were eliminated (Activity 20) in the 02:10:00 (Candidate 2), 02:35:00 (Candidate 3) and 05:20:00 (Candidate5) segments.

[5] SeeFigure 26: alterations to the candidate (Activity 16) occur in the five segments immediately prior to Candidate Five's elimination (04:50:00-05:15:00).

[6] See Figure 26: identifying violations and identifying feasible process chains (Activities 10 and 11) take place from 07:15:00-08:25:00.

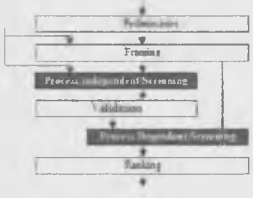
[7] See Figure 26: Activity 12 (Select Most Likely Process Chain for Each Candidate) does not occur.

Framing



As noted under Preliminaries, the participants were not happy with the requirements specified, and generated a new set of requirements. Once the new requirements had been developed, Framing proceeded without difficulty. Eleven requirements were deemed nonessential for the given decision, and 29 criteria were established to represent the remaining 25.

Screening



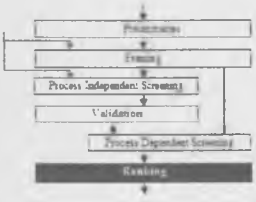
Given that some candidates had been eliminated prior to Framing, screening had effectively been divided into two stages - one pre-Validation, and one post-Validation. Comments from the participants indicate that they felt this was a better way of approaching screening than having a single stage post-Validation[1]. Furthermore, given that Validation had preceded Framing, where new requirements had been developed, the eliminated candidates had *not* been compared with the new requirements. Therefore, the facilitator suggested that *all* the candidates should be screened against the new requirements. He also suggested that Screening against process independent requirements (which could occur prior to Validation) and against process dependent requirements (which could not) should take place separately[2], simulating the proposed change to the methodology. Candidates 2, 3 and 5 were still eliminated. Candidates 4 and 4a were slightly above the cost requirement (with estimated costs of 65 and 68 pence, respectively). Given the inherent uncertainty in estimating costs, it was decided that Candidate 4 should be retained for Ranking, as it was close to the cost constraint. As Candidate 4a was introduced to reduce costs, and not to improve on Candidate 4's performance, it was eliminated.

---

[1] See Appendix 5, Transcripts Four to Nine.

[2] See Figure 26 (page 128), Activities 7 and 13 (Screening against PI and PD criteria, respectively) both occur (at 17:30:00-18:00:00 and 18:00:00-18:10:00, respectively), and take place sequentially.

Ranking



The utilities calculated for the three surviving candidates were identical, so the only way to separate them was on the basis of cost. As Candidate 6 had the lowest estimated cost, it was recommended for further development.

Documentation

Table 20: Status of documents gathered in Experiment 2

DOCUMENT	STATE
1. A list of process dependent requirements with priorities and classifications.	✓
2. A list of processes under consideration;	✓
3. A list of criteria, with classifications.	✓
4. An elimination matrix comparing the candidates against the mandatory PI criteria.	✓
5. A list of candidates under consideration;	✓
6. A list of the components making up each candidate;	✓
7. A list of the features associated with each component;	◉
8. A list of the properties associated with each feature;	◉
9. A compatibility matrix for each component comparing its properties against the capabilities of the available processes.	◉
10. A list of process chains for each component	◉
11. A list of the recommended process chain for each component	◉
12. A list of feasible candidates	◉
13. An elimination matrix comparing the candidates against the mandatory PD criteria.	✓
14. A graph of cost vs. utility	✓

✓=Complete, × = Incorrect, ◉= Incomplete, ○ = Empty

Feedback Questionnaire

Table 21: Results from questionnaires for Experiment 2

ACTIVITY \ PARTICIPANT	A	B	C	D
Classify requirements as process dependent or process independent.[1]	N/A			
Prioritise Requirements				
Identify manufacturing processes to be considered.				
Establish criteria.	✓	✓	✓	✓
Identify component features	✓	✓	✓	✓
Identify component properties	✓	✓	✓	✓
Identify violations	✓	✓	✓	✓
Identify feasible process chains for each candidate.	✓	✓	✓	✓
Select the most likely process chain for each candidate.[14]				
Eliminate candidates not satisfying the mandatory criteria.	✓	✓	✓	✓
Draw a graph of cost vs. utility.	✓	✓	✓	✓

Observation

Figure 26 (page 128) provides a graph of the protocol analysis for Experiment 2.

[1] None of the participants provided feedback for these two stages: the relevant parts of the questionnaires were left blank.

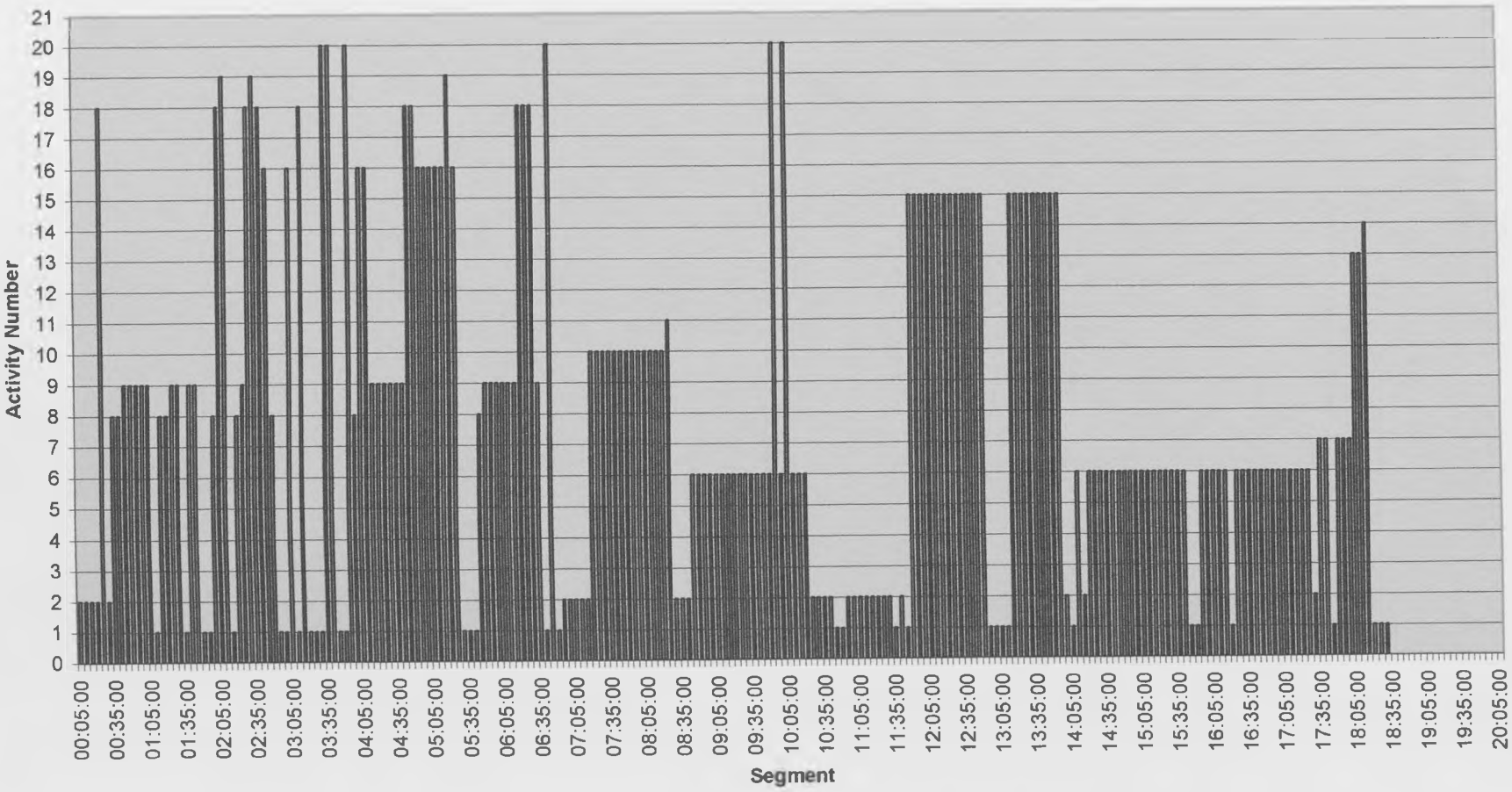


Figure 26: Protocol analysis for Experiment 2

6.2.3 Design Experiment Three: Shaving Gel Dispenser

The purpose of this experiment was to determine whether the methodology could still be applied when activities were divided between two collaborating teams (a design team and a manufacturing team). Experiment 2 had already demonstrated that the methodology *could* be applied to a complex evaluation, and had suggested the separation of Process Dependent and Process Independent Screening, reflected in the methodology in Chapter 4. This experiment was an opportunity to test the methodology in another complex scenario, to verify that the outcome of Experiment 2 was not just a one-off.

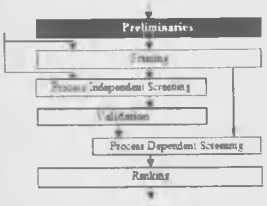
The participants were divided into two pairs, with one pair taking responsibility for design-related activities and the other for manufacturing-related activities, as shown in Table 22. Some activities were common to both teams, and sessions were arranged so that the teams could brief each other on the outcomes of their activities. The teams were presented with a scenario, based on a student project (the design of a pump-actuated dispenser for low-foam shaving gel).

Table 22: Division of activities between design and manufacturing teams in Experiment 3

ACTIVITY	Design Team	Manufacturing Team
Generating new designs	✓	
Generating requirements	✓	
Classify requirements as process dependent or process independent.	✓	✓
Prioritise Requirements	✓	
Identify manufacturing processes to be considered.		✓
Establish criteria.	✓	
Classify criteria as PI or PD.	✓	
Eliminate candidates not satisfying mandatory PI criteria.	✓	
Identify component features		✓
Identify component properties		✓
Identify Basic violations		✓
Identify feasible process chains for each candidate.		✓
Select the most likely process chain for each candidate.		✓
Eliminate candidates not satisfying the mandatory PD criteria.	✓	✓
Draw a graph of cost vs. utility.	✓	✓

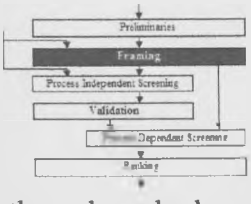
The designers were given a set of five candidate designs to evaluate, but developed the requirements themselves, and were allowed to generate new designs of their own. Pictures and definitions of the candidates can be found in Appendix 4.3. The manufacturers were presented with an initial set of five available processes, representing the manufacturing capabilities at an existing plant.

Preliminaries



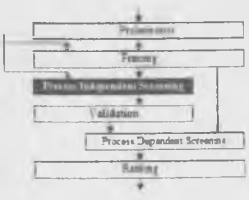
This time preliminaries were divided into three stages. Firstly, there were the *design preliminaries*, where the design participants examined the scenario[1], began to develop the requirements specification, and prioritise the requirements[2]. 24 requirements were generated in all. Next were the *manufacturing preliminaries*, where the manufacturing participants discussed the processes that would be considered in this case. They decided that attention should focus on injection moulding, blow moulding and continuous extrusion, as the other processes were not suitable for the required production rate. Finally, both design and manufacturing participants came together to review the requirements and available processes, and to classify the requirements as either process dependent or process independent. The manufacturing participants were also able to answer questions posed by the designers, on issues such as how the products would be assembled and shipped, and how this should be taken into account.

Framing



As the participants generated the requirements this time, the problems encountered in the previous study were avoided, and framing proceeded without difficulty[3]. However, once Process Independent Screening began, the participants realised that they had omitted hygiene considerations, and went back to amend the requirements and re-frame the criteria (see Process Independent Screening, below). All of the requirements were deemed essential, and a total of 40 criteria were established to represent them.

Process Independent Screening



Once Framing was complete, the participants began to compare the designs against the mandatory process independent criteria that they had established. Candidate 1 was eliminated

[1] Requirements were generated *before* the designers were allowed to see any of the designs.

[2] See Figure 27 (page 135), 00:00:00-01:35:00. Unlike Experiment 2, requirements were not prioritised as they were generated, but assigned priorities later on (see Figure 27: Activity 4 (Prioritise Requirements) occurs at 02:15:00-02:30:00).

[3] See Figure 27 (page 135), 03:15:00-06:25:00.

because it did not provide space for a legislative label. The participants redesigned it to allow for this, and the new candidate (1v2) was accepted[1]. Similarly, Candidate 3 was rejected because of the size it would need to be in order to hold the necessary volume of fluid exceeded the limits on height and diameter. The participants made significant changes to the design to account for this, and the revised candidate (3v2) was accepted[2]. Candidate 4 was eliminated because it could not access the entire product stored inside[3]. Candidate 5 however, raised a new concern – hygiene – which the participants realised they had left out of the requirements specification. They therefore went back to amend the requirements and criteria to reflect this[4], and screened the earlier designs against the new criterion. Candidate 5 was eliminated on the grounds of this new requirement.

In the course of studying Candidate 5, the participants suggested four new designs of their own. Two (Candidates 6 and 7) were variants of the simple bottle redesigns, working with the existing dispenser mechanism (from Candidates 1 and 2). The other two (Candidates 8 and 9) were more unusual versions of the pump actuated dispenser concept, requiring a new mechanism design. These designs were screened[5]. Only candidate eight was eliminated, due to its susceptibility to damage in transit. Thus, six candidates (1v2, 2, 3v2, 6, 7 and 8), survived to Validation – although only one of these (Candidate 2) was one of the original designs.

---

[1] See Figure 27 (page 135), 06:25:00-07:20:00; Activities 7 and 16 (Screening against PI Criteria and Generating or Altering Designs, respectively) both occur.

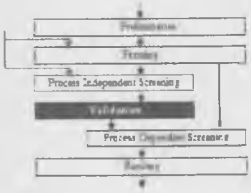
[2] See Figure 27, 07:25:00-08:00:00; again, activites 7 and 16 both occur.

[3] See Figure 27, 07:55:00-08:05:00. The participants initially identify the problem (Activity 7), then try to propose a solution (Activity 16), but are unable to find one, and eliminate the design.

[4] See Figure 27, 08:35:00-08:55:00: these segments show a mixture of Activity 6 (Establishing Criteria) and Activity 15 (Generating or Altering Requirements) as the participants try to generate the new requirement and repeat the framing stage for it.

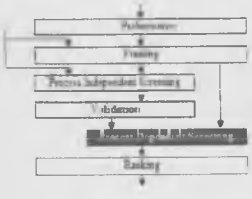
[5] The process is slightly convoluted: see Figure 27, 08:05:00-09:15:00; the participants begin screening the design (Activity 7), then, deciding it is unhygienic, discuss other designs, and generate four new candidates (Candidates 6 and 7, Activity 16), before returning to the discussion of the hygiene requirement (Activity 17); they screen two of the new candidates (Activity 7) against the existing criteria before redefining the requirements, then return to screen the other new candidates, before eliminating candidate five, and comparing the existing designs against the new hygiene criterion.

Validation



As the manufacturing participants were responsible for Validation, they had not been privy to the discussions during Framing or Process Independent Screening, and had not seen the designs before identifying features and properties. Unlike Experiment 2, they decided to identify features for *all* the candidates, before going back to identify their properties[1]. At both stages, there was some debate about how complete the features and properties needed to be. Eventually, both participants agreed that there was no need to include features or properties that they already knew could be done – for example, those that were common to the existing dispenser design[2]. Rather, the purpose of identifying features and properties was to flag up those they weren't sure could be achieved, or knew to be infeasible, so that they could investigate them in more detail, and provide feedback to the designers. They began to refer to the PRIMAs as they were identifying properties, so that properties they felt confident about could be left out[3]. Once the features and properties had been assigned to all the candidates, the compatibility matrices were constructed, and the properties compared against the information in the PRIMAs[4]. Only Candidate 9 was eliminated as infeasible. Once again, each of the surviving designs had just one feasible process chain per component, so there was no need to identify the most likely process chain in each case[5].

Process Dependent Screening



The remaining five candidates were subject to Process Dependent Screening, based on the processes identified in Validation[6]: all the designs passed, except Candidate 3v2. As it introduced many new injection-moulded components, there

[1] See Figure 27 (page 135): identifying features (activity 8) only occurs from 09:20:00 to 10:10:00, while identifying properties (activity 9) only occurs from 10:10:00 to 11:20:00.

[2] See Appendix A5.3, Transcripts One and Two.

[3] See Appendix A5.3, Transcripts Three and Four.

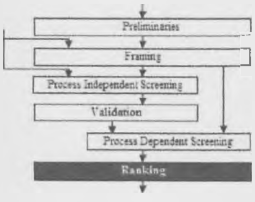
[4] See Figure 27: Activity 10 (Identifying Violations) occurs from 11:25:00 to 11:50:00; and Activity 11 (Identifying feasible process chains) occurs from 11:50:00 to 11:55:00.

[5] See Figure 27: Activity 12 (Selecting the most likely process chain for each candidate) does not occur.

[6] See Figure 27: Activity 13 (Eliminate Candidates not satisfying the mandatory PD criteria) occurs from 12:20:00 to 12:35:00

were queries about whether there would be sufficient capacity to manufacture 50,000 units per annum, and this was highlighted as a possible violation. In the event, this candidate was eliminated anyway, as its estimated cost was 17p over the 30p maximum cost criterion.

Ranking



Prior to Ranking, it was still necessary to assign weights to the optional criteria – one of the stages of SMART - which the designers had not had time to do during the Framing stage, where it would normally occur[1]. A graph of estimated cost against utility was constructed[2], but unlike the previous two case studies, this time there was no clear favourite. All four designs had similar performances, so according to the principle of the flat maximum, it would probably make little difference which was chosen. Candidates 1v2 and 6 were pareto dominant, but the level of uncertainty in estimating both cost and utility means that all four were almost indistinguishable. The participants decided to recommend both Candidates 1v2 and 6 for further development, as subsequent investigation might highlight the differences between them.

Documentation

Table 23: Status of documents gathered for Experiment 3

DOCUMENT	STATE
1. A list of requirements with priorities and classifications.	✓
2. A list of processes under consideration.	✓
3. A list of criteria, with classifications.	✓
4. An elimination matrix comparing the candidates against the mandatory PI criteria.	✓
5. A list of candidates under consideration.	✓
6. A list of the components making up each candidate.	✓
7. A list of the features associated with each component.	✓
8. A list of the properties associated with each feature.	✓
9. A compatibility matrix for each component comparing its properties against the capabilities of the available processes.	✓
10. A list of process chains for each component.	✓
11. A list of the recommended process chain for each component.	✓
12. A list of feasible candidates.	✓
13. An elimination matrix comparing the candidates against the mandatory PD criteria.	✓
14. A graph of cost vs. utility.	✓

✓=Complete, × = Incorrect, ◘= Incomplete, ○ = Empty

[1] See Figure 27 (page 135): Activity 6 (Establishing Criteria) occurs from 12:35:00 to 12:45:00

[2] See Figure 27: Activity 14 (Ranking) occurs from 12:45:00 to 13:10:00.

Feedback Questionnaire

Table 24: Results from questionnaires for Experiment 3

ACTIVITY \ PARTICIPANTS	D1	D2	M1	M2
Classify requirements as process dependent or process independent.	✓	✓	✓	✓
Prioritise requirements.	✓	✓		
Identify manufacturing processes to be considered.			✓	✓
Establish criteria.	✓	✓		
Classify criteria as PI or PD.	✓	✓		
Eliminate candidates not satisfying mandatory PI criteria.	✓	✓		
Identify component features.			✓	✓
Identify component properties.			✓	✓
Identify Basic Violations.			✓	✓
Identify violations due to precedence.			✓	✓
Identify feasible process chains for each candidate.			✓	✓
Select the most likely process chain for each candidate.			✓	✓
Eliminate candidates not satisfying the mandatory PD criteria.	✓	✓	✓	✓
Draw a graph of cost vs. utility.	✓	✓	✓	✓

Observation

Figure 27 (page 135) provides a graph of the protocol analysis for Experiment 3.

6.3 Discussion

This section offers answers to the research questions posed in Chapter 5, based on the data gathered across the three experiments. This section discusses each set of sub-questions in turn, and is therefore divided into two parts. The first considers the answers to **Q2)** and its sub-questions: whether the methodology was actually followed and the changes necessary to implement it. The second considers the answers to **Q3)** and its sub-questions, considering whether or not the methodology satisfied the desiderata. Each section looks at the sub-questions first, and then provides an answer to the overall question in that section.

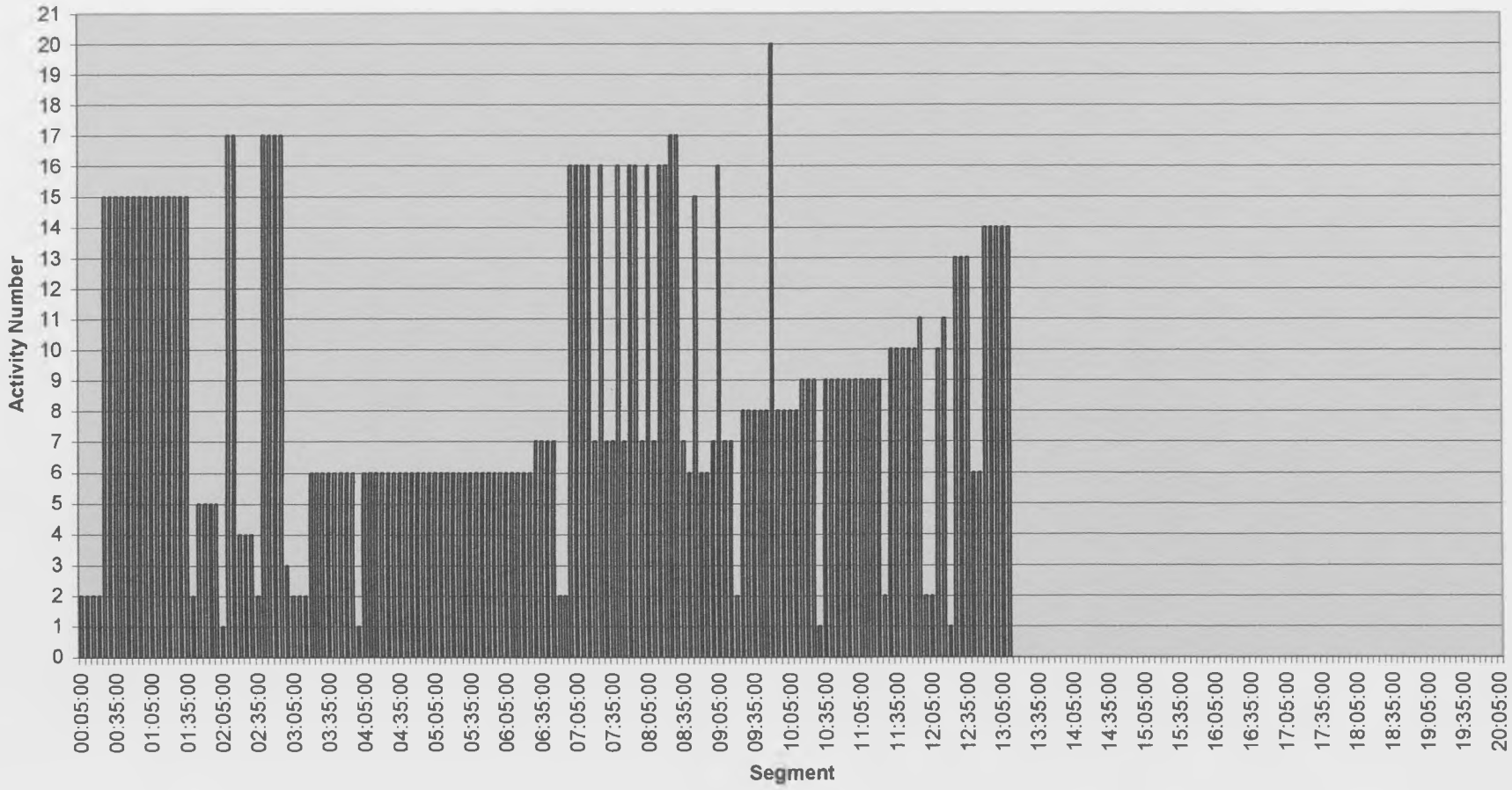


Figure 27: Protocol analysis for Experiment 3

6.3.1 Feasibility of the Methodology

The first issue to consider is whether the methodology as described was actually used to evaluate the designs in each of the experiments.

Q2a) *Were the participants able to work through all the stages of the methodology?*

Table 25 shows the results of triangulation from each design experiment.

Table 25: Results of triangulation for the design experiments

ACTIVITY	Experiment 1: 1st Iteration	Experiment 1: 2nd Iteration	Experiment 2	Experiment 3
Classify requirements as Process dependent or Process independent.	✓	N/A		✓
Prioritise requirements	N/A			✓
Identify manufacturing processes to be considered.				✓
Establish criteria.	⊙	✓	✓	✓
Eliminate candidates not satisfying the mandatory PI criteria.	N/A		✓	✓
Identify component features	×	✓	✓	✓
Identify component properties	×	✓	✓	✓
Identify violations	×	✓	✓	✓
Identify feasible process chains for each candidate.	×	✓	✓	✓
Select the most likely process chain for each candidate.	×	✓	✓	✓
Eliminate candidates not satisfying the mandatory PD criteria.	○	✓	✓	✓
Draw a graph of cost vs. utility.	○	✓	✓	✓

✓=Completed correctly, × = Completed incorrectly, ⊙= Not completed, ○ = Not attempted

Once the process was facilitated – from the second iteration of Experiment 1 onwards – the participants completed every stage. However, without the guidance of a facilitator the participants struggled with the concepts of features, properties and criteria, and also failed to use the Design for Manufacture guidance provided by the PRIMAs. The results of the subsequent experiments suggest that this was an implementation issue, rather than a flaw in the methodology. Without some element of control over the process, the participants' misinterpretations and failure to follow the prescribed procedure were not corrected. Therefore, the first iteration of Experiment 1 does not reflect an application of the methodology as described in Chapter 4. Subsequently, once the participants were working through the methodology as described, under the guidance of the facilitator, they were able to work through all stages of the methodology.

By eliminating candidates prior to Validation – and therefore prior to Framing – in Experiment 2, the participants broke the precedence constraints (see Figure 23, page 90). However, as Table 25 shows, they completed every activity, and this reordering occurred because they refused to follow the prescribed order, not because they were unable to. This is therefore treated as an objection (see **Q2c)**, below), rather than a breakdown of the methodology.

Q2b) *If not, where does the application break down, and for what reason?*

This is closely linked to the answer to the previous question. The methodology only broke down on the first iteration of Experiment 1, and, as shown in Table 25, this took place at the Framing stage (establishing criteria). Until that point, every activity had been attempted (even if they were not carried out correctly), whereas no subsequent stages took place[41]. The reason given for this was that the participants could not understand the decision analytic terminology, and so could not understand the tasks they were being asked to carry out. Once the facilitator was able to explain the activities to them in terms they were familiar with, they were able to carry out the framing stage without further difficulties. This suggests that care must be taken when introducing a new methodology, to explain it in terms the users are familiar with.

Q2c) *Did the participants object to any stages of the methodology?*

Across the three experiments, there are a total of seven segments (see the protocol analyses, Figures 24 to 27) where the participants pass comment on the methodology. These are summarised in Table 26. Five of the comments from the questionnaires could be interpreted as objections, all coming from the first iteration of Experiment 1. These are summarised in Table 27. However, these comments relate to the breakdown of the first iteration (the failure to complete feature identification and establishing criteria). This happened because the participants could not understand what they were being asked to do, not because they refused to do it. As demonstrated in Table 25, these problems were solved by providing a facilitator, so they do not need to be considered objections. Of the six segments identified in Table 26, the comment from Experiment 3 was an observation, rather than an objection, and the comments from Experiment 2 all refer to the same objection. Therefore, across the three

[41] See Appendix A5.1, which highlights the point where the application breaks down.

experiments, the participants only raised one objection to the methodology, although it was repeated at different stages.

Table 26: Comments about the methodology identified during observation.

Experiment	Segment	Transcript	Topic	Activity
2	03:30:00-03:40:00	A4.2, Four	The desire to screen candidates *before* validation.	Identifying Features
	03:50:00-03:55:00	A4.2, Five		Identifying Features
	06:40:00-06:45:00	A4.2, Six		Identifying Properties
	09:50:00-09:55:00	A4.2, Eight		Establishing Criteria
	10:00:00-10:05:00	A4.2, Nine		Establishing Criteria
3	09:45:00-09:50:00	A4.3, Two	The desire to leave out features and properties that are already known to be feasible.	Identifying Features

Table 27: Comments from the questionnaires that could be interpreted as objections

Experiment	Activity	Comment
Experiment 1: 1st Iteration	Identify Features	**C:** No clear definition of "features" **D:** Not completed in its entirety. Some ambiguity over "features" and "properties"
	Establish Criteria	**A:** Unable to distinguish between what was a criteria [*sic*] and an attribute also how criteria linked to req't. Was it of product, process or both. **C:** Incomplete examples and description of this process **D:** Difficulty in defining criteria and hence attributes.

The participants objected to validating designs that they believed were unacceptable, and actively refused to do so, eliminating them prior to formal Screening. This violates the precedence constraints of the methodology (see Figure 23, page 90) and undermines the rigour of decision analysis by Screening before Framing, but it is a reasonable objection. Experiments 2 and 3 show that the time and effort required for Validation is generally greater than that needed for PI Screening (see Table 28). In both cases, the mean effort required per candidate is much greater in Validation than in PI screening. This may vary with the number and complexity of designs and criteria, but it demonstrates that there are good reasons for allowing participants to screen candidates prior to Validation. This issue was resolved by introducing the PI Screening stage into the methodology, but leaving the participants free to arrange the stages as they saw fit.

Table 28: Comparison of segments given to Screening and Validation activities in Experiments 2 and 3

Activity	Statistic	Experiment 1	Experiment 2
PI Screening	Total Segments	5	14
	Candidates Screened	7	11
	Mean Segments per candidate	0.7	1.3
Validation	Total Segments	46	30
	Candidates Validated	4	6
	Mean Segments per candidate	11.5	5

Q2d) *Did the participants require any additional help or advice in order to apply the methodology?*

The only source of additional assistance available to the participants was the researcher, who acted as an observer in the first iteration of Experiment 1, and as a facilitator thereafter. Assistance given beyond these roles was recorded in the verbal protocol as *interventions*. The protocol analyses (see Figures 24 to 27) only indicate three interventions, all occurring in the first iteration of Experiment 1, which are summarised in Table 29. All three are concerned with clarifying the definitions of process dependent, process independent, features, properties and criteria. The participants' comments summarised in Table 27 highlight a similar need for clarification. This is consistent with the reason established above for the failures of the first iteration in Experiment 1: the participants misunderstood the concepts of features, properties and criteria. In the subsequent experiments - where the researcher was present as a facilitator and not as an observer and such interactions were an accepted part of the implementation – no interventions were identified. This again highlights the need for a facilitator, to ensure that the users of the methodology understand what is being asked of them, and follow the methodology as it was intended.

Table 29: Interventions noted during the design experiments

Experiment	Segment	Activity	Description
1,1	00:30:00-00:35:00	Classify Requirements	Responds to request for clarification about the difference between PI and PD Requirements.
	01:10:00-01:15:00	Identify Properties	Observer responds to request for clarification about the definition of a feature, and the difference between features and properties.
	02:10:00-02:35:00	Establishing Criteria	Responds to repeated requests for clarification of the meaning of a criterion.

Q2e) *Did the participants carry out any activities not considered by the methodology?*

The verbal protocol identifies five activities that take place, but are not part of the methodology itself – their occurrences in the design experiments are summarised in Table 30. Of these, four (discussing and generating/altering designs or requirements) are standard activities from the *specification* and *synthesis* stages of the design loop, on which the methodology is based. It is not surprising, therefore, that they should take place (especially in Experiment 3, where this was encouraged), but this does highlight the iterative nature of the design process, which the methodology must consider. Feedback from each stage of the methodology can lead to requirements or designs being rethought. The only activity taking place that should not have occurs in Experiment 2: the elimination of candidates without actual screening. This was caused by the

participants' unwillingness to validate designs they believed to be unsatisfactory, and was addressed by the introduction of Process Independent Screening prior to Validation (see the discussion of **Q2c)**, page 137).

Table 30: Activities identified through protocol analysis that are not part of the methodology

Activity	Number of Segments			
	Experiment 1		Experiment 2	Experiment 3
	1st Iteration	2nd Iteration		
Generating or Altering Requirements	0	0	22	16
Generating or Altering Designs	0	0	10	12
Discussing Requirements	0	0	0	8
Discussing Candidates	0	0	10	0
Eliminating Candidates Outside Screening	0	0	3	0

Q2) *Can the methodology be used to evaluate designs in practice?*

In Experiments 1 and 2, the participants did not follow the methodology as it had been described to them. However, with the introduction of a facilitator, and the introduction of PI Screening prior to Validation – which the methodology in Chapter 4 allows – the participants were able to work through the methodology correctly in each case. Accordingly, it is reasonable to conclude that – under laboratory conditions, at least – the methodology *can* be used to evaluate designs. The next question is whether its use still satisfies the desiderata.

6.3.2 Practical Coherence of the Methodology

Having established that the participants *were* able to use the methodology, the next question is whether these evaluations satisfied the desiderata in practice – which is, after all, the purpose of the methodology.

Q3a) *Were any of the criteria used in the evaluation* **not** *related to a requirement from the requirements specification?*

For all three experiments, every criterion used could be traced back to a requirement from the requirements specification, as indicated by the documents in Appendix Four (See Appendix Four: Tables 48, 56, and 64 on pages 218, 228 and 240, respectively).

Q3b) Were any *essential* requirements not represented by the criteria?

The only requirements not represented by criteria during these experiments were from Experiment 2 (see Appendix A4.2, Table 57, on page 230), and these were all deemed *nonessential*. Therefore, no *essential* requirements were omitted from any of the experiments.

Q3c) *Were any of the designs surviving to Ranking expected to violate the requirements specification?*

Each candidate surviving to the ranking stage of each experiment, had been compared with every criterion, which – as the answer to **Q3a)** and **Q3b)** indicate – covered every requirement that *could* be considered in the given decision. Every design about which serious doubts were raised was eliminated during one of the Screening phases. Candidate 4 in Experiment 2 is the only exception to this, and this was only permitted to Ranking under a caveat, and because of the uncertainty about its cost estimate. The designers were aware of the risks involved.

Q3d) *Were any designs with known manufacturing flaws permitted through Validation?*

Process chains were specified for every candidate. The only time an error occurred was in the first iteration of Experiment 1, where the participants did not use the information provided by the PRIMAs and therefore had incorrect compatibility matrices. Even here, the process chains identified and the candidates carried forwards were consistent with the (incorrect) judgements made.

Q3e) *Did the criteria used to evaluate the designs address cost?*

As the documentation gathered indicates (see Appendix Four), every design surviving to Ranking had its cost estimated, and was included on a graph of Cost vs. Utility (see Figures 55, 60 and 65 on pages 219, 232 and 243, respectively). Furthermore, all three experiments featured mandatory limits on cost, reflected in the PD Screening stage (see Figures 54, 59, and 64, on the same pages).

Q3f) *Were the participants able to gather all the information that they needed for the evaluation?*

None of the interventions, or the comments made about the methodology, suggest that there was any lack of information, or that the methodology was demanding judgements from the participants that they were unable to make with the PRIMAs available.

Q3) *Can the methodology satisfy the desiderata when used to evaluate candidate designs in practice?*

In each experiment (except the first iteration of Experiment 1, where the application was not completed), the desiderata were satisfied. Criteria were based only on the requirements specification - which reflected manufacturing cost - and only *nonessential* requirements were omitted. All designs that the participants expected to violate the requirements specification were eliminated, and once the participants were encouraged by the facilitator to use the decision support provided, they did not pass any designs that the PRIMAs indicated would be unmanufacturable. Therefore, the logical coherence of the methodology held when put into practice. The next question is whether this can still hold when applied beyond the controlled environment of the laboratory.

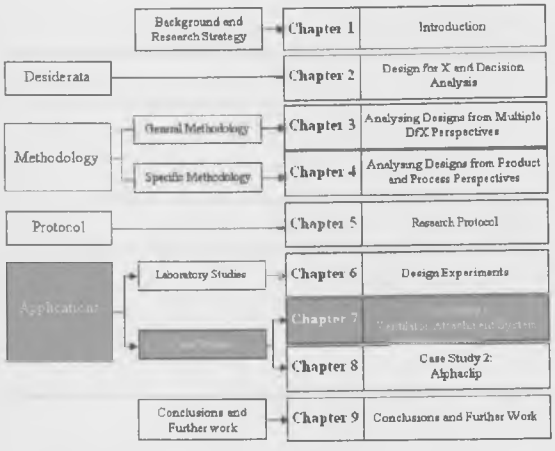
6.4 Summary

The design experiments provide an opportunity to study the methodology in a controlled environment, where data is easy to collect, and internal validity can be ensured. Though they do not have the external validity of the case studies in the following chapter, they have allowed detailed study of the methodology, and have raised several issues. In all three experiments, the participants were able to work through the activities of the methodology, and the desiderata were satisfied. Although this does not prove that the methodology *will* satisfy the desiderata when applied outside the laboratory, it does suggest that it has the potential to.

However, without a facilitator to control the methodology, the participants were not able to follow every activity correctly. This suggests that applying the methodology is not trivial, and special consideration must be given to how the process is controlled and how it is introduced into a design process. This does not necessarily need to be through a facilitator (structured software or additional training might be suitable alternatives), but that approach has been

shown to work, and will be adopted for the case studies. Also, Experiments 2 and 3 highlighted the benefits of flexibility in ordering the Screening and Validation stages. The methodology therefore allows Screening to be separated around Validation, although this does not preclude carrying out all Screening *after* Validation, if that seems more appropriate. With these considerations, it was possible to apply the methodology in each experiment, and this suggests that further study beyond the laboratory is appropriate.

Chapter 7
Case Study 1 - Ventilator Attachment System



Having verified that the methodology can satisfy the desiderata under laboratory conditions, the next step is to move to tests with greater external validity. Before moving on to a commercial case study, the methodology was applied to an undergraduate design project carried out in collaboration with industry. This presented a more realistic scenario for testing the methodology, without the risks of a commercial project: if the project failed, then there was no serious cost to anyone concerned. The project chosen was the design of a system for attaching a ventilator and battery to a wheelchair to improve the mobility of wheelchair-bound patients with breathing difficulties.

This chapter is divided into three sections. **Section 7.1** describes the purpose of this case study, and how it was carried out. **Section 7.2** describes each stage of the methodology, how it was applied to the case in question and presents the documents generated. **Section 7.3** compares the data gathered with the research questions to determine whether the methodology still satisfies the desiderata in this case.

7.1 Purpose and Procedure

This section provides an overview of the case study, its purpose and the way data was gathered. This section is divided into two parts: the first explaining the objectives of the study and the second describing how it was carried out.

7.1.1 Objectives of the Study

This case study builds on the design experiments by providing greater realism, and therefore greater external validity. Table 31 shows how this case study addresses some of the participant, context and scenario factors that limited the external validity of the design experiments. The factors that applied to this case were due to the participants being undergraduates, and not experienced designers.

Table 31: Participant/Context/Scenario factors applying to Case Study 1

Type	Factor	Relevance	Notes
Participant Factors	Not all participants are experienced designers;	●	The participants were undergraduate students, with no industrial experience.
	The participants have no specific expertise in the product they are evaluating;	○	Though the participants had no personal expertise in this area, they had carried out research through literature reviews and interviews with patients and healthcare professionals.
	The participants are not part of a pre-existing design team;		The participants had been working together for six months prior to this case study.
	The participants do not necessarily reflect the constitution of a "typical" design team	●	The participants were undergraduates: none were professional designers.
Context Factors	The participants do not have the rest of the organisation to consult with – to receive clarification or guidance, for example;		In this project, the participants liaised with both customers and the National Health Service Trust throughout the project.
	The participants had no stake in the outcome of the decision they were simulating;	○	Though the participants had no stake in the success or failure of the product itself, they had a stake in making the best choice, to maximise their project marks.
Scenario Factors	The requirements are not necessarily representative of typical design requirements;	○	As this was not a commercial project, its requirements may not be representative of a commercial project's priorities. However, these requirements were developed in conjunction with a real organisation and with real customers.
	The candidates are not necessarily representative of typical design candidates;		The candidate designs were developed independent of the methodology.
	The designers did not generate the candidates that they were evaluating.		The designers had generated the candidates that were being evaluated.

● = Factor applies to this case study;
○ = Factor applies partially to this case study.

These improvements in external validity came at the expense of control compared to the design experiments (see Section 7.1.2). The participants arranged meetings to suit their own agenda, so the researcher was not always present and some activities were carried out in his absence. This meant a reliance on e-mail communication and meeting minutes as well as face-to-face communication. Accordingly, this chapter presents and analyses an account of the case study based on the researcher's experience and the supporting documentation and physical artefacts gathered. The study had two objectives:

1) to determine whether the methodology can be applied beyond the idealised conditions of the laboratory; and

2) to determine whether the methodology can satisfy the desiderata beyond idealised laboratory conditions.

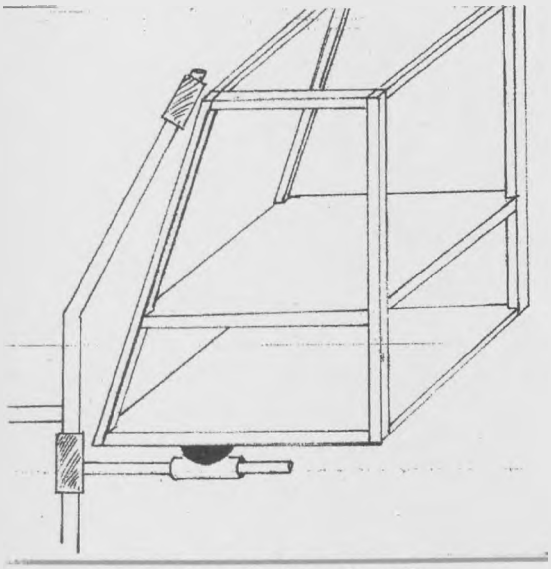
In contrast with the design experiments, which emphasised the process the participants went through, this chapter emphasises the content of the case, which is captured through the documentation. Attention was therefore restricted to whether the case reflected all the stages of the methodology (**Q2a)** and, if appropriate, **Q2b)** (see page 90)) and whether it satisfied the desiderata (**Q3a)** through **Q3e)** (see page 92)).

7.1.2 Procedure

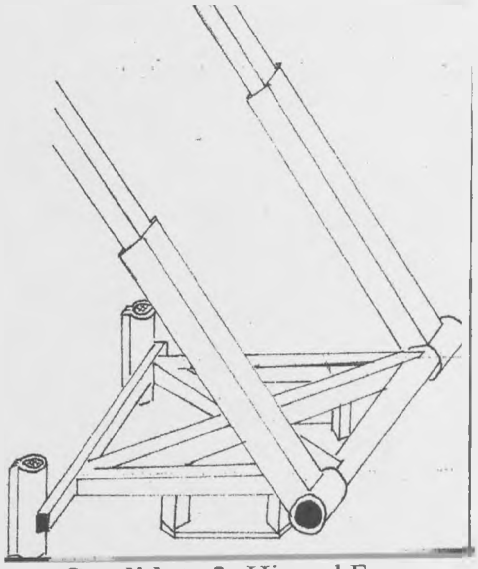
This project began as a National Health Service (NHS) initiative to improve the mobility of wheelchair bound patients with breathing difficulties who need regular use of a ventilator. If such patients could carry the ventilator and its rechargeable battery on their wheelchair, this would dramatically increase the time they could spend away from home. The goal of the student project was therefore to develop a system for carrying a ventilator and battery on a wheelchair.

The participants were responsible for developing a formal requirements specification for the proposed system and generating a design to satisfy it. Requirements were developed through interviews with patients, carers and NHS staff who would be involved with the proposed system. The methodology was applied during the final months of the project, at a point where the designers had developed five candidate designs and had to choose one to develop further. These designs are illustrated in Figure 28.

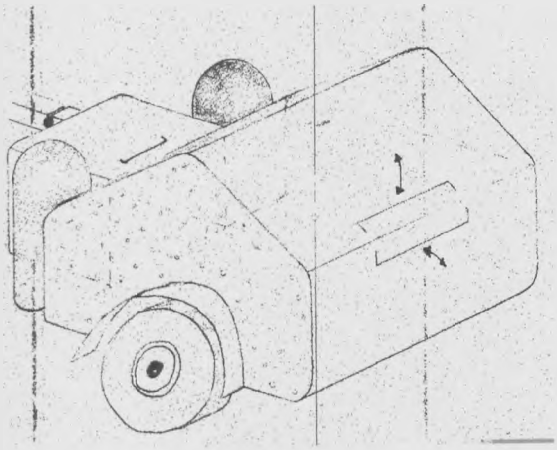
Two issues had to be addressed in this case study that the laboratory cases had not considered. The first was *time pressure*: the participants were working to a project deadline, and also had other commitments (both to the project, and to other aspects of their degree). Therefore, the researcher took responsibility for Validation, which would otherwise have been too time-consuming for the participants to learn and carry out. This case study therefore followed the same pattern as Experiment 3, with the researcher and participants taking on the roles of the manufacturing and design teams, respectively.



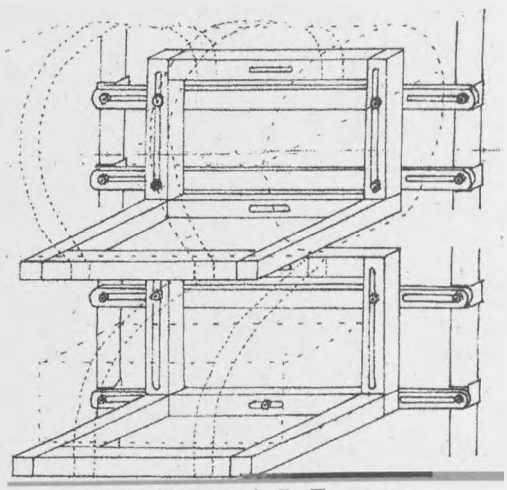
Candidate 1: Standard Frame



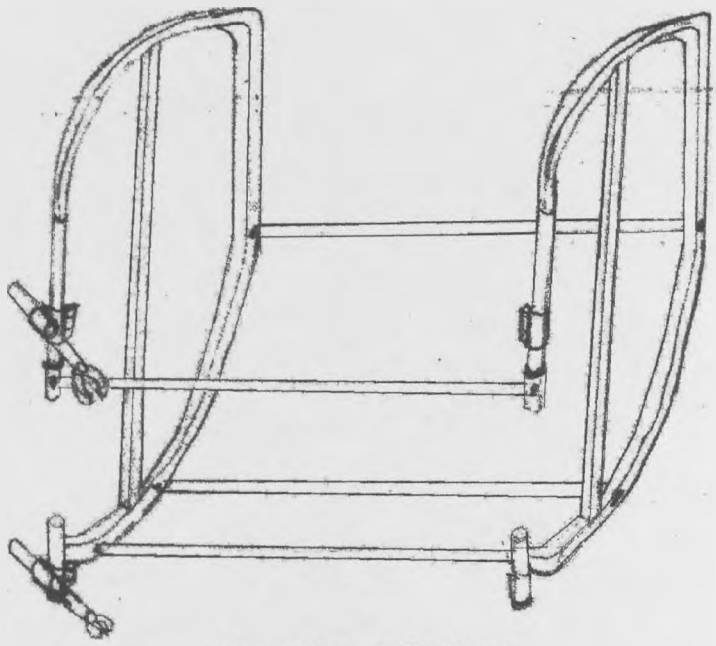
Candidate 2: Hinged Frame



Candidate 3: Trailer



Candidate 4: L-Frames



Candidate 5: D-Frame

Figure 28: The five candidate designs for Case Study 1

The second issue was *assembly*: as all the designs involved multiple components, they required assembly operations. While it was acceptable to omit assembly considerations in the design experiments, the participants here did not have this luxury. They were designing a real product, and assembly had to be taken into account. Lucas DFA (Lucas Engineering Systems, Ltd, 1993) was used to develop variants of each design, which were then analysed using the methodology, alongside the originals, to see if the changes made any difference to their performance. Cost estimates developed using Swift and Booker's (2003) Design Costing Methodology already include both manufacture and assembly costs.

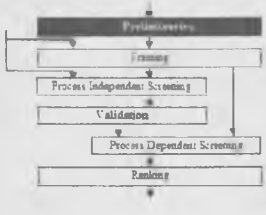
As in the design experiments, the researcher acted as a facilitator, taking the participants through the relevant stages of the methodology. The facilitator entered the participants' information into the support software to generate documentation for analysis, and to verify that it fitted the pattern required by the methodology.

7.2 Results

This section describes the results of each stage of the methodology, as it was applied to this case study. This section is divided into four parts, each describing a major stage of the methodology: Preliminaries and Framing; Process Independent Screening; Validation; and Ranking. As there were no mandatory process dependent criteria, there was no need for Process Dependent Screening, and that stage has therefore been omitted.

7.2.1 Preliminaries and Framing

Preliminaries



The participants had developed a set of 47 requirements and the first step in applying the methodology was to classify and prioritise them. Table 32[1] lists these requirements, with the classification and priority assigned to each one.

[1] A tick in the "PD"column indicates that a requirement or criterion is process depedent. A tick in the "M" column indicates that a requirement or criterion is mandatory.

Table 32: Requirements, classifications and priorities for Case Study 1

No.	Requirement	PD	M
1	The design must attach the ventilator in a location such as to not compromise the structural integrity of the wheelchair, in fatigue or single load deformation.		✓
2	The product attachment points must not induce critical local stress concentrations.		✓
3	Utilising and fixing the product should not require structural alterations to the existing wheelchairs hence negating their proven integrity, warranty and official safety approvals.		✓
4	With the ventilator located in its attachment, the integrated system must remain stable under a normal range of operating conditions.		✓
5	Wheelchair stability performance must not be critically attenuated in a range of adverse weather, physical and dynamic conditions		✓
6	The wheelchair performance and stability must remain safe in traversing up and down a standard 4-inch kerb.		✓
7	The attachment of the ventilator must not induce a unacceptably high force required for the carer to lift the wheelchair front wheels up a standard 4-inch kerb		✓
8	The additional weight of the ventilator and attachment product must not cause an unacceptable decrement in wheelchair speed performance and load carrying capacity.		✓
9	The altered weight distribution of the integrated system due to ventilator attachment must not cause dynamic performance reduction in the loss of traction and control during normal usage.		✓
10	The attachment product must be able to perform all its specified requirements whilst withstanding all applied stresses in single loading and fatigue over a specified lifetime.		✓
11	The attaching device must be able to securely attach to a selection of wheelchairs with a range of attachment site dimensions as specified.		✓
12	The ventilator must be located in the attachment product so as to not induce a significant or inconvenient geometrical change to the wheelchair, preventing increased difficulties in manoeuvring.		
13	The ventilator must be attached in the attachment product in a location so as to not inhibit any previous function of the wheelchair. I.E clearance of front wheel castors.		✓
14	The patients must have access to an alarm to alert others to a potential problem with ventilation.		✓
15	The ventilator pipes must be protected from crushing, occlusion and unnecessary damage		✓
16	Suitable access for easy ventilator charging procedures/attachments must be possible whilst the ventilator is housed in the attachment product.		✓
17	The ventilator pipes must be routed or fixed in a way such as to prevent snagging due to unacceptable protrusion from the wheelchair space.		✓
18	The ventilator pipes must be suitably supported to ensure that no tension force can be induced and hence reacted at the patient attachment point.		✓
19	The product be sufficiently ventilated and have heat transfer properties to not cause heat accumulation to a temperature that may affect ventilator operation, mechanically or in the quality of air transported to the patient.		✓
20	The product must be suitably ventilated and have heat transfer properties to not induce unacceptable humidity conditions during operation in its attachment housing.		✓
21	The location and orientation of the ventilator on the wheelchair must allow sufficient interfacing as specified by any who require it in normal operation.		✓
22	The attachment product must secure the ventilator to the specified criteria whilst maintaining easy and convenient interfacing access for to operator and carer.		✓
23	The attachment housing must be designed to allow piping and wiring to exit the casing whilst the ventilator entrance remaining fully closed.		✓

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Table 32 *continued.*

No.	Requirement	PD	M
24	The ventilator attachment must not inhibit the process of wheelchair loading and unloading onto a motor vehicle via maintaining geometry within functional limits.		✓
25	The addition of the ventilator must not be so as to unbalance the wheelchair when it is raised on or off a vehicle		✓
26	The attachment of the ventilator must not impinge upon any wheelchair transport attachment points upon the chair.		✓
27	The ventilator in its attached position must not be subject to vibration of frequency such as to cause any performance reduction or damage.		✓
28	The Ventilator must be protected from shock loadings transmitted through the wheels and wheelchair structure that could cause damage and affect performance of the ventilator.		✓
29	The product must house the ventilator, protecting it from splash wetting and rain wetting.		✓
30	The product must protect the ventilator from damage via shock loadings due to impact with objects during motion.		✓
31	The ventilator must be constrained in its attachment in an orientation that does not affect its performance.		✓
32	The mounting of the product upon the chair must not encroach on the seated position of the wheelchair user.		✓
33	The location of the mounted product must not cause interaction between the product and locus of the carer legs during gait.		✓
34	The attachment product must not reduce the visibility of the patient at all.		✓
35	Conform to specified simple manufacturing techniques.	✓	✓
36	Product must accommodate the usage of inverters where necessary on specified ventilators.		✓
37	The final integrated design must not contravene any previous ISO standards and regulations for the wheelchair and ventilator operation.		✓
38	Potential of single part replacement in the event of breakage of one component.		✓
39	Must be possible to remove ventilator without disengaging the frame.		✓
40	Must fit both Breas and Nippy model ventilators		✓
41	Removal and location of the ventilator from within the attachment product must be as quick, simple and easy as possible.		
42	Manufacture to be as cheap as possible.	✓	
43	Easy assembly[1]		
44	The attachment product must be styled and aesthetically pleasing as specified by patients and other relevant stakeholders.		
45	The product should allow storage/attachment of specified required equipment such as a battery and spare.		
46	The product should allow storage/attachment of extra equipment required for the patient such as spare oxygen cylinder or a suction unit.		
47	Must allow unrestricted access to ventilator pipes without removing anything but cover.		✓

Classify Requirements

As this was not a commercial project, the emphasis was on functional, rather than economic, performance and the requirements were mostly concerned with the shape and substance of the finished product. Requirement 42 was deemed process dependent, but not considered mandatory: as this was an exploratory design project no absolute cost constraint had been specified. Requirement 35 caused some

[1] Here, "assembly" refers to the process of attaching the system to the wheelchair, rather than the process of assembling the system itself.

debate: whether it was the shape and substance of the design that had to "Conform to the specified simple manufacturing techniques" or the process chain. It was eventually agreed that it should be the latter, and the requirement was deemed process dependent.

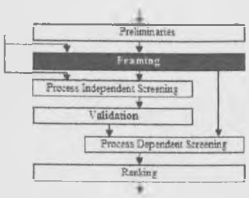
Prioritise Requirements

Requirements 1 through 11 and 13 through 34 refer to attaching the ventilator and battery to the wheelchair without compromising their functions, and to protect them from damage. Without these, the system would be useless, and they were not open to negotiation. Six other requirements were deemed mandatory, but the designers were willing to consider relaxing them if absolutely necessary. Requirements 16, 21, 39 and 47 referred to the patients' ability to use the ventilator for themselves while it was attached to the wheelchair. Failure to satisfy them would not render the system useless, but would make the patient dependent on a carer, regardless of whether they needed one before. Requirements 35 and 38 refer to the practicalities of manufacture and maintenance. The participants wanted to avoid production being dependent on a narrow range of specialist manufacturers and to ensure that a new system was not required every time a component broke. Requirement 14 indicated that the patient should have access to an alarm to alert others if there was a problem with ventilation. This was critical to the patient's safety, but could be satisfied independently of the system's design, by providing a separate alarm.

Identify Manufacturing Processes to be Considered

Requirement 35 immediately limited the set of processes worth considering, as any process chain violating it would automatically be eliminated during Process Dependent Screening. Given the low rates of production (probably no more than 500 systems per annum), the requirement was based on avoiding the need for permanent tooling. The participants were therefore focussing on machining and welding operations that could be performed on stock material, with sand casting acceptable to achieve near-net shape on more complicated components. Tube or section bending was also considered, as a way of reducing the need to weld bends or angles in sections.

Framing



The participants had kept many of the mandatory requirements in mind when generating designs, so that all the designs satisfied them. Therefore, only 20 requirements were considered *essential* to the current decision, and a total of 26 criteria were established to represent them. Table 33 summarises the requirements

that were considered essential, and their associated criteria. Table 34 summarises the requirements deemed *nonessential* and gives the reasoning behind this. Requirements 35 and 42 were considered essential but, because they were already addressed by other stages of the methodology, were *redundant* and are therefore included in Table 34.

Table 33: Criteria established for *essential* requirements in Case Study 1

Requirement	Criterion	PD	M
Utilising and fixing the product should not require structural alterations to the existing wheelchairs hence negating their proven integrity, warranty and official safety approvals.	Design must not require any structural alterations to the wheelchairs.		✓
With the ventilator located in its attachment, the integrated system must remain stable under a normal range of operating conditions. (See stability analysis)	Estimated Critical Tip Angle to be greater than 16 degrees for Remploy		✓
	Estimated Critical Tip Angle to be greater than 16 degrees for Lomax		✓
	Estimated Critical Tip Angle to be greater than 16 degrees for Apollo		✓
The altered weight distribution of the integrated system due to ventilator attachment must not cause dynamic performance reduction in the loss of traction and control during normal usage.	Must not reduce load on rear wheels causing tractive reduction		✓
The attaching device must be able to securely attach to a selection of wheelchairs with a range of attachment site dimensions as specified.	Must be able to fit to Apollo Wheelchair		✓
	Must be able to fit to Lomax Wheelchair		✓
	Must be able to fit to Remploy Wheelchair		✓
The ventilator must be located in the attachment product so as to not induce a significant or inconvenient geometrical change to the wheelchair, preventing increased difficulties in manoeuvring.	Width must be no greater than existing Apollo wheelchair (500mm)		✓
The ventilator must be attached in the attachment product in a location so as to not inhibit any previous function of the wheelchair *i.e.* clearance of front wheel castors.	Must not interfere with essential moving parts of wheelchair.		✓
Suitable access for easy ventilator charging procedures/attachments must be possible whilst the ventilator is housed in the attachment product.	Must allow access to battery charging points without removing anything but cover.		✓
The product must house the ventilator, protecting it from splash wetting and rain wetting.	Must allow for attachment of waterproof cover.		✓
The product must protect the ventilator from damage via shock loadings due to impact with objects during motion.	Must keep ventilator within space envelope of frame		✓
The ventilator must be constrained in its attachment in an orientation that does not affect its performance.	Ventilator Must be kept within 10 degrees of horizontal (on all chairs)		✓
The ventilator in its attached position must not be subject to vibration of frequency such as to cause any performance reduction or damage	Ventilator Must not be subjected to vibration in excess of that experienced by the wheelchair		✓

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Table 33 *continued*

Requirement	Criterion	PD	M
The mounting of the product upon the chair must not encroach on the seated position of the wheelchair user.	Structure (between sides of wheelchair) must be kept more than 10cm from back of wheelchair.		✓
It must be possible to remove ventilator without disengaging the frame.	Must be possible to disengage ventilator without disassembling or removing frame.		✓
The design must be suitable for both Breas and Nippy model ventilators.	Must fit Breas Ventilator		✓
	Must fit Nippy Ventilator		✓
Must allow unrestricted access to ventilator pipes without removing anything but cover.	Must allow unrestricted access to ventilator pipes without removing anything but cover.		✓
Easy assembly	Minimise time for end user attachment.		
Removal and location of the ventilator from within the attachment product must be as quick, simple and easy as possible.	Minimise time for Ventilator disengagement.		
	Minimise time for Battery Disengagement		
The ventilator must be located in the attachment product so as to not induce a significant or inconvenient geometrical change to the wheelchair, preventing increased difficulties in manoeuvring.	Distance from back of chair (manoeuvrability)		
The product should allow storage/attachment of specified required equipment such as a battery and spare.	Includes space for portable oxygen cylinder?		
The product should allow storage/attachment of extra equipment required for the patient such as spare oxygen cylinder or a suction unit.	Includes space for vacuum suction unit?		

Table 34: Nonessential requirements for Case Study 1

Requirement	Justification
The design must attach the ventilator in a location such as to not compromise the structural integrity of the wheelchair, in fatigue or single load deformation.	The participants had identified mounting points that automatically satisfied these requirements, which every design conformed to. Although these were dependent on the overall mass of the system, this could not be calculated accurately for any of the designs at this stage, and the weight of the system was likely to be negligible compared with the weight of the battery and ventilator.
The product attachment points must not induce critical local stress concentrations.	
Wheelchair stability performance must not be critically attenuated in a range of adverse weather, physical and dynamic conditions	
The wheelchair performance and stability must remain safe in traversing up and down a standard 4-inch kerb.	
The attachment of the ventilator must not induce a unacceptably high force required for the carer to lift the wheelchair front wheels up a standard 4-inch kerb	
The additional weight of the ventilator and attachment product must not cause an unacceptable decrement in wheelchair speed performance and load carrying capacity.	
The attachment product must be able to perform all its specified requirements whilst withstanding all applied stresses in single loading and fatigue over a specified lifetime.	
The patients must have access to an alarm to alert others to a potential problem with ventilation.	The participants felt that this was best done by providing the user with a separate alarm; therefore all the solutions satisfied this requirement.

Continues on next page

Table 34 *continued*

Requirement	Justification
The ventilator pipes must be protected from crushing, occlusion and unnecessary damage	The participants had identified the constraints upon the system needed to satisfy these requirements, and had based all of the designs on them.
The ventilator pipes must be routed or fixed in a way such as to prevent snagging due to unacceptable protrusion from the wheelchair space.	
The ventilator pipes must be suitably supported to ensure that no tension force can be induced and hence reacted at the patient attachment point.	
The product be sufficiently ventilated and have heat transfer properties to not cause heat accumulation to a temperature that may affect ventilator operation, mechanically or in the quality of air transported to the patient.	
The product must be suitably ventilated and have heat transfer properties to not induce unacceptable humidity conditions during operation in its attachment housing.	
The location and orientation of the ventilator on the wheelchair must allow sufficient interfacing as specified by any who require it in normal operation.	
The attachment product must secure the ventilator to the specified criteria whilst maintaining easy and convenient interfacing access for to operator and carer.	
The attachment housing must be designed to allow piping and wiring to exit the casing whilst the ventilator entrance remaining fully closed.	
The ventilator attachment must not inhibit the process of wheelchair loading and unloading onto a motor vehicle via maintaining geometry within functional limits.	
The addition of the ventilator must not be so as to unbalance the wheelchair when it is raised on or off a vehicle	The participants had identified mounting points that automatically satisfied these requirements, which every design conformed to. Although these were dependent on the overall mass of the system, this could not be calculated accurately for any of the designs at this stage, and the weight of the system was likely to be negligible compared with the weight of the battery and ventilator.
The attachment of the ventilator must not impinge upon any wheelchair transport attachment points upon the chair.	
The Ventilator must be protected from shock loadings transmitted through the wheels and wheelchair structure that could cause damage and affect performance of the ventilator.	All of the designs featured foam padding for the base of the ventilator to absorb vibrations.

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Table 34 *continued*

Requirement	Justification
The addition of the ventilator must not be so as to unbalance the wheelchair when it is raised on or off a vehicle	The participants had identified mounting points that automatically satisfied these requirements, which every design conformed to. Although these were dependent on the overall mass of the system, this could not be calculated accurately for any of the designs at this stage, and the weight of the system was likely to be negligible compared with the weight of the battery and ventilator.
The attachment of the ventilator must not impinge upon any wheelchair transport attachment points upon the chair.	
The Ventilator must be protected from shock loadings transmitted through the wheels and wheelchair structure that could cause damage and affect performance of the ventilator.	All of the designs featured foam padding for the base of the ventilator to absorb vibrations.
The location of the mounted product must not cause interaction between the product and locus of the carer legs during gait.	The participants had identified mounting points that automatically satisfied these requirements, which every design conformed to. Although these were dependent on the overall mass of the system, this could not be calculated accurately for any of the designs at this stage, and the weight of the system was likely to be negligible compared with the weight of the battery and ventilator.
The attachment product must not reduce the visibility of the patient at all.	
Conform to specified simple manufacturing techniques.	In fact, this decision was considered *essential*, but as it was addressed by the Validation stage (by restricting the processes under consideration to those satisfying this requirement) the requirement became *redundant*.
Product must accommodate the usage of inverters where necessary on specified ventilators.	The participants had identified the constraints upon the system needed to satisfy these requirements, and had based all of the designs on them.
The final integrated design must not contravene any previous ISO standards and regulations for the wheelchair and ventilator operation.	
Potential of single part replacement in the event of breakage of one component.	The designs were not sufficiently detailed to know exactly whether this would be a problem, but there was no reason to believe that any component could not be removed and replaced individually.

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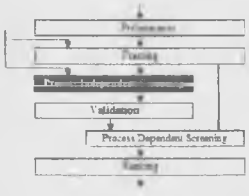
Table 34 *continued*

Requirement	Justification
Manufacture to be as cheap as possible.	This was to be dealt with through the graph of cost vs. utility in ranking, so the requirement was *redundant* and did not be incorporated into the utility measure.
The attachment product must be styled and aesthetically pleasing as specified by patients and other relevant stakeholders.	All of the designs were either hidden from view, or had a canvas cover, which could be adapted to suit the system's aesthetic needs.

7.2.2 Process Independent Screening



As there were no mandatory process dependent criteria, this was the only screening that took place. It was a simple process of applying the mandatory criteria to each of the candidates. The five original designs were screened first, before considering how the changes suggested by DFMA would affect the performance of the variant designs. For many criteria this was straightforward, and consensus among the team members was easily achieved. For example, it was obvious from the descriptions of the candidates whether they required structural alterations to the wheelchairs, and whether they could accept a waterproof cover. Where dimensions were concerned, values were estimated based on the sizes of the ventilators and batteries to be stored, with the "worst case scenario" being assumed. Care had to be taken in eliminating candidates against these criteria, as a candidate failing under "worst case" assumptions might turn out to be acceptable in practice. Nevertheless, it was felt to be important that potential problems were identified and given serious consideration before allowing a design through. One of the participants had been tasked with developing a spreadsheet model for stability and traction and this was used to evaluate performance against criteria related to traction and critical tip angle. Figure 29 shows the elimination matrix developed through this process.

Three candidates were eliminated. Candidate 2, the Hinged Frame, could only fit two of the three wheelchairs. The attachment method of Candidate 3, the Trailer, meant that it would be subject to severe vibrations, and might potentially interfere with the wheels of the wheelchair. Candidate 4, the L-Frame, caused some controversy against the first criterion, as it required the removal of the canvas back of the wheelchair. This could be done by cutting the canvas and re-stitching it once the system had been attached, or by dismantling and then reassembling the wheelchair. Neither required fundamental change to the structure of the chair, and this would only need to be done when the frame was first installed.

Criterion \ Candidate	1. Standard Frame	2. Hinged Frame	3. Trailer	4. L-Frame	5. D-Frame
Design must not require any structural alterations to the wheelchairs.				?	
Critical Tip Angle to be greater than 16 degrees for Remploy					
Critical Tip Angle to be greater than 16 degrees for Lomax	?				?
Critical Tip Angle to be greater than 16 degrees Apollo					
Must not reduce load on rear wheels causing tractive reduction					
Must be able to fit to Apollo Wheelchair					
Must be able to fit to Lomax Wheelchair		X			
Must be able to fit to Remploy Wheelchair					
Width must be no greater than existing Apollo wheelchair (500mm)					
Must not interfere with essential moving parts of wheelchair.			X		
Must allow access to battery charging points without removing anything but cover.					
Must allow for attachment of waterproof cover.					
Must keep ventilator within space envelope of frame				X	
Ventilator Must be kept within 10 degrees of horizontal (on all chairs)	?		X	X	
Ventilator Must not be subjected to vibration in excess of that experienced by the wheelchair			X		
Structure (between sides of wheelchair) must be kept more than 10cm from back of wheelchair.					
Must be possible to disengage ventilator without disassembling or removing frame.					
Must fit Breas Ventilator					
Must fit Nippy Ventilator					
Must allow unrestricted access to ventilator pipes without removing anything but cover.					

Figure 29: Elimination matrix for Process Independent Screening

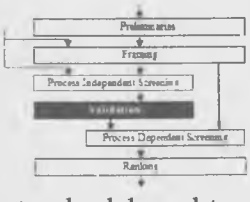
However, some of the participants argued that this was not in keeping with the spirit of the requirement, and that even temporary interference with the wheelchair was unacceptable. They agreed to consider this a *potential* violation, retaining the design, but to keep the issue in mind if Candidate 4 survived to Ranking. In fact, it caused a definite violation, as it did not offer any kind of protection to the back and sides of the ventilator, leaving it vulnerable to impact damage.

Candidates 1 and 5 both caused potential stability problems, according to the stability model, with respective critical tip angles of 13° and 14.5°, for the Lomax

wheelchair. As noted above, this was the worst case scenario, and under these conditions, both candidates were acceptable against the Remploy and Apollo models. The participants decided to note both as potential violations. Also, the sloped upper section of Candidate One meant that the frame would attach at a slight angle on the Lomax wheelchair, although the participants felt reasonably sure that this could be kept to less than ten degrees through careful detail design. Again, a potential violation was noted.

The alterations suggested by DFA analysis consisted of combining or eliminating parts, seeking pareto improvements by getting the same function at lower cost. None of the suggested alterations changed the functional performance of the designs, except that the reduced material usage meant that the variants were lighter, slightly improving their stability. However, given that the weight of the frame was expected to be small compared to that of the ventilator and battery, the change in weight was expected to have a negligible effect. Therefore, the variants were expected to have identical performance to the original designs against these criteria and the participants chose to proceed with Candidates 1 and 5, and their variants.

7.2.3 Validation



The designs being considered in this case were more complex than those in the design experiments: between the two surviving designs and their variants, there were a total of 93 components. However, many of these components were standard bought out parts, or lengths of metal cut from stock, that did not need validation. Furthermore, many components were duplicated within a design, and only needed to be validated once, rather than once per instance. This left a total of seven components to be validated from the original designs, with a further six from the variants. Although the variants reduced the number of components overall, they moved away from standard, cut lengths towards more complicated parts that required other manufacturing approaches.

Rather than present every detail of the 13 components validated, each stage of Validation is illustrated for just one component: part of the attachment mechanism from the original Standard Frame (Candidate 2). This component is called the *fixed disc*, and is welded to the base of the frame. The sleeve is attached to an arm that clamps to the wheelchair, and the *sleeve disc* is fitted to the boss on the sleeve and welded in place. The boss on the sleeve can then be used to locate the sleeve in the fixed disc, and a bolt is passed through the hole in the sleeve disc and the slot in the fixed disc, attaching the sleeve and arm (and thereby the wheelchair) to the frame.

The slot in the fixed disc means that the arm and sleeve can be rotated to any angle, allowing fits to all three wheelchairs. Figure 30 illustrates this arrangement.

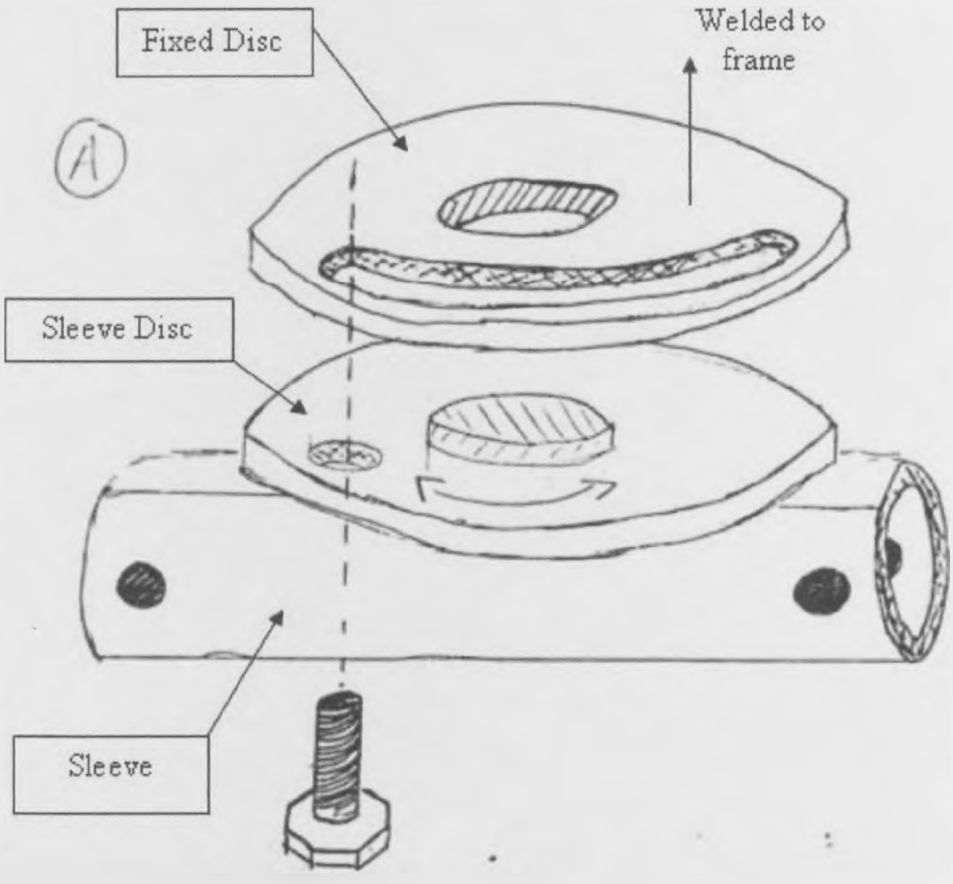


Figure 30: Attachment assembly for the Standard Frame design.

Identify Features

Given that the designs existed only as rough sketches, without specific dimensions (and in some cases without exact shapes defined), features and properties could only be assigned approximately. Nevertheless, it was possible to use the data available to build up a set of features and properties for each design based on what was known at the time of the decision. For the fixed disc, there are two obvious features (see Figure 31): the **locating hole** through the centre of the disc, and the **slot** through which the bolt used to attach the sleeve disc is fastened.

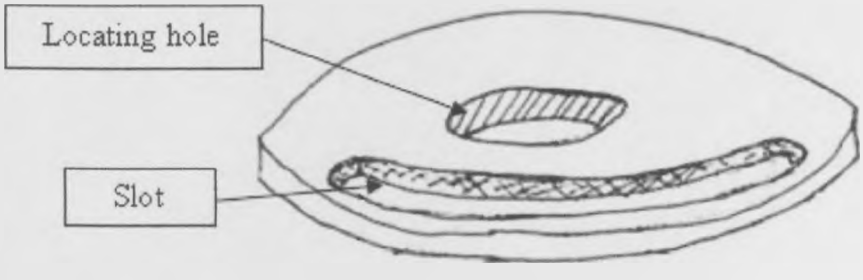


Figure 31: Features for the fixed disc component

Identify Properties

The participants expected to make the fixed disc from either aluminium or stainless steel. Although exact dimensions had not been established, many could be narrowed down to estimated ranges (for example, the disc was unlikely to be under 10mm in diameter, or larger than 300mm in diameter). It has to be remembered that the purpose of these properties is not to prove that the components *are* manufacturable, only to identify whether there is any reason at this stage to believe that they are not. Finally, it was known that a tolerance would have to be specified on the locating hole. To line the bolt up with the slot, this had to be narrow enough to fit the boss on the sleeve without "slop", but loose enough for the sleeve to rotate. The participants had estimated that a tolerance of ±0.01mm would be suitable.

Identify Violations

Figure 32 shows the compatibility matrix constructed for the fixed disc component. Bending and welding were clearly not appropriate for the part's shape, so only sand casting and machining (lathe, milling machine, and drill) were considered. The compatibility matrix was populated by the researcher, based on the information from three handbooks (Swift and Booker, 2003; Bralla, 1999; and Boothroyd *et al.* 2002). Drilling was clearly unable to satisfy the shape of the basic component, as it can only create holes. To maintain core rigidity, sand casting can only manage holes greater than 6mm in diameter and no more than 6 diameters deep. The locating hole was expected to be over 10mm diameter, but this was only an estimate, so a note was taken in case the part was carried forward to detail design No estimate of the hole's depth had been given: the sketch – see Figure 30 – shows it as a through hole, although it does not have to be. The eventual depth would be based on the strength required from the component, and would be established in detail design. Therefore, a new dimension property, "Depth", was defined for the locating hole, even though its value was not known, so that a conditional constraint could be recorded. The tolerance on the diameter raised a number of issues. Sand casting could not achieve the tolerance, while milling and drilling could only achieve it up to very limited diameters. Whereas a diameter greater than 6mm was considered almost certain, a diameter of 1.5mm or 4mm seemed very unlikely. Finally, the lathe and drill were unable to produce the slot: the lathe because it can only work axisymmetric shapes and the drill because it can only manage circular holes.

Fixed Disc

Feature	Property	Description	Candidate Processes			
			Sand Cast	Lathe	Mill	Drill
Basic Component	Material	Aluminium or Stainless Steel				
	Shape	Circular Disc	1			X
	Dimension	**Diameter:** 40mm to 130mm (estimated)				
Locating Hole	Shape	Circle	2			
	Dimension	**Diameter:** 10mm to 30mm (estimated)	3			
	Tolerance	**On Diameter:** +/- 0.01mm (estimated - light press)	X		4	5
	Dimension	**Depth:** Not specified.	6			
Slot	Shape	See sketch.	2	X		X
	Dimension	**Width:** 5mm to 10mm (estimated)				

1= Draft Angle of 3° recommended
2 = Draft Angle of 5° recommended
3 =Must be greater than 6mm
4 = Achievable for diameters up to around 4mm
5 = Achievable for diameters up to around 1.5mm
6 = Must be less than 6 times its diameter.

Figure 32: Compatibility matrix for the fixed disc component.

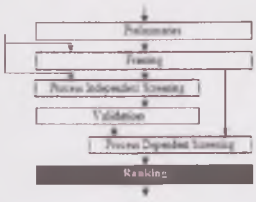
Identify Process Chains for Each Candidate & Eliminate Infeasible Candidates

Based on the compatibility matrix, there were two process chains that could make the fixed disc: milling the part from stock and finishing the location hole on the lathe; or sand casting followed by finishing the location hole on the lathe. Costs for each process chain using aluminium and stainless steel were estimated using Swift and Booker's (2003) Design Costing Methodology, using the data shown in Table 35. Sand casting then turning was expected to be the cheaper of the two, and was therefore the approach used to estimate the overall cost of the candidate. Both designs and their variants were accepted as feasible, and were passed on to Ranking (in the absence of any criteria for Process Dependent Screening), with suggested process chains for cost estimates.

Table 35: Design Costing Methodology comparison for sand casting vs. manual machining

Material	Primary Process	Estimated Cost
Aluminium	Sand Casting	£1.15
	Manual machining	£1.69
Stainless Steel	Sand Casting	£1.68
	Manual machining	£2.66

7.2.4 Ranking and Final Choice



Costs were estimated for each candidate, using Swift and Booker's Design Costing Methodology. Costs for many of the basic components had already been calculated during Validation, although assembly costs and costs for components which only had one feasible process chain also had to be considered. The cost of bought-out parts was a particular problem: while they could be identified, it was difficult to know whether they were on the same scale as the estimated costs. As a relative measure, the costs did not need to be exact: to be comparable, they would have to be. The Design Costing Methodology was used, as it was the best information available, but estimated cost and the cost of bought-out parts were analysed separately, so that the participants could be aware of the two different scales. Also, costs had to be estimated separately for the designs in aluminium and in stainless steel; and also for the variant of each design, as the suggested changes had a serious compact on the cost. Table 36 summarises the cost breakdowns for each candidate.

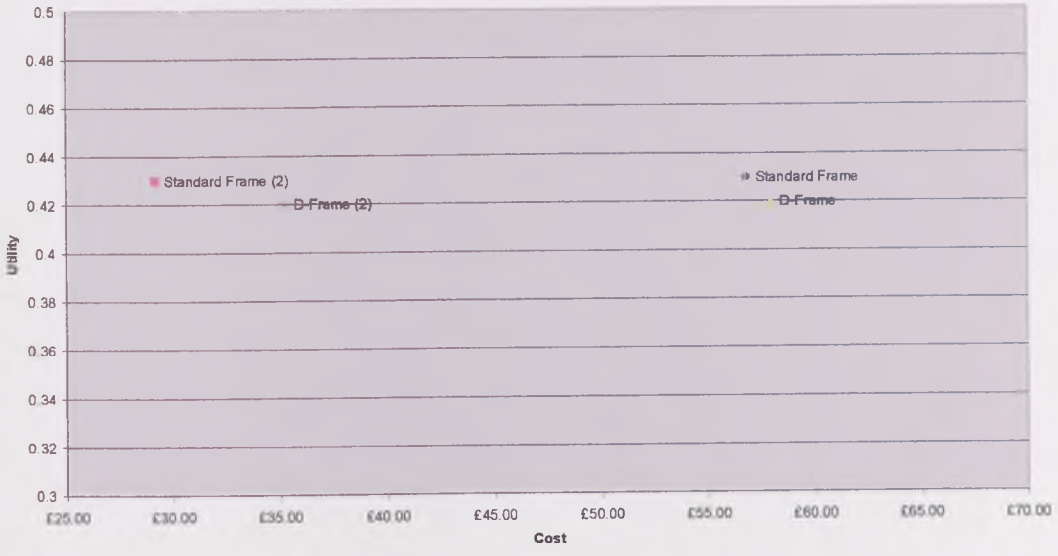
Table 36: Cost Breakdowns for the variants of each candidate.

Candidate	Bought Out Parts	Ass'y	Manufacture		Material		Total	
			Al	St. Steel	Al	St. Steel	Al.	St. Steel
Standard Frame	£8.12	£0.68	£8.97	£16.96	£39.91	£99.05	£57.68	£124.81
Standard Frame (2)	£8.06	£0.31	£1.69	£3.04	£19.11	£47.01	£29.17	£58.42
D-Frame	£8.12	£0.50	£2.48	£5.52	£46.81	£116.18	£57.91	£130.32
D-Frame (2)	£8.12	£0.37	£2.24	£3.36	£24.51	£60.83	£35.24	£72.68

NB: the suffix (2) indicates the revised version of a design

The next step was to use the optional criteria established in Framing to generate a utility for each candidate. Again, the changes suggested through DFA analysis did not impact these criteria – only cost changed, as shown in Table 36, above.

As in Process Dependent Screening, values were estimated by team agreement. Once the overall utility for each candidate had been calculated, it was plotted on a graph against cost, as shown in Figure 33 for aluminium and Figure 34 for stainless steel. The choice of material, in fact, does not make any difference to the relative positions of the designs, and can therefore be left out of the present decision.



NB: the suffix (2) indicates the revised version of a design

Figure 33: Comparison of Cost vs. Utility for the designs in aluminium

NB: the suffix (2) indicates the revised version of a design

Figure 34: Comparison of Cost vs. Utility for the designs in stainless steel

The revised versions of the designs show a pareto improvement over the originals and are therefore the preferred choice. Both designs are close together in estimated cost and estimated utility. Given the inherent uncertainty in these values, the two designs can be considered roughly equal. However, as the revised version of the standard frame pareto dominated the revised D-frame, it seemed to be the more promising design, and the participants decided to take it on for further development.

7.3 Discussion

This section discusses the research questions in the context of this case study. It is divided into two parts, the first considering the answers to each of the relevant research questions, and the second discussing the main conclusions drawn from this case study.

7.3.1 Feasibility and Practical Coherence of the Methodology

This section considers the subset of research questions that are relevant to the case studies, as discussed in Section 7.1.1.

Q2a) *Were the participants able to work through all the stages of the methodology?*

Table 37 summarises the status of each document gathered from the support software. Every document is complete, apart from Document 13, which is empty, and Document 9, which was incomplete. This suggests that every stage apart from Process Dependent Screening took place, which supports the account given in Section 7.2.

However, these three documents do not suggest a failure in applying the methodology. As Table 34 (page 153) indicates, the only process dependent requirements were deemed *redundant* because they were automatically addressed by the methodology through Validation and Ranking (see Framing, in Section 7.2.1). Therefore, one would expect there to be no process dependent criteria, and no need for Process Dependent Screening. Similarly, Document 9 indicated that not every component was compared with every process. However, as in the example given in Section 7.2.3, processes were left out only where they were clearly not suitable for making the component, and would never be chosen. There was no need to carry out an analysis when the answer was already obvious. As Document 9 was left incomplete and Process Dependent Screening omitted for acceptable reasons, this suggests that the methodology was applied correctly.

Table 37: Documents gathered from Case Study 1

DOCUMENT	STATE
A list of process dependent requirements with classifications and priorities.	✓
A list of processes under consideration;	✓
A list of criteria with classifications.	✓
An elimination matrix comparing the candidates against the mandatory PI criteria.	✓
A list of candidates under consideration;	✓
A list of the components making up each candidate;	✓
A list of the features associated with each component;	✓
A list of the properties associated with each feature;	✓
A compatibility matrix for each component comparing its properties against the capabilities of the available processes.	⊙[1]
A list of process chains for each component	✓
A list of the recommended process chain for each component	✓
A list of feasible candidates	✓
An elimination matrix comparing the candidates against the mandatory PD criteria.	○[2]
A graph of cost vs. utility	✓

✓=Complete, × = Incorrect, ⊙= Incomplete, ○ = Empty

Q3a) *Were any of the criteria used in the evaluation* **not** *related to a requirement from the requirements specification?*

Table 33 (page 152) shows the criteria used for Screening and Ranking in this case study: every criterion can be traced back to a requirement.

Q3b) *Were any* essential *requirements not represented by the criteria?*

Table 32 (page 149) provides a full list of the requirements used in the project. Every requirement in this table should either have been allocated a set of one or more criteria, or deemed *nonessential.* Table 33 shows the criteria used for Screening and Ranking: every requirement in this table is represented by at least one criterion. Table 34 (page 153) lists the requirements that were deemed nonessential – and therefore did not need criteria for this decision – and provides justification for this choice. Between them, Table 33 and Table 34 account for every requirement in Table 32.

Q3c) *Were any of the designs surviving to Ranking expected to violate the requirements specification?*

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[1] The feasibility matrices do not compare every candidate against every process.

[2] No Process Dependent criteria were established, it was expected that this document would be empty.

As Figure 29 (page 157) shows, both the designs that survived to Ranking caused potential violations in Process Independent Screening, particularly with regard to the stability of the Lomax wheelchair. Section 7.2.2 shows that the participants *did* consider eliminating the designs, but because the violations only occurred under Worst Case Scenario conditions, the participants decided to let them through. This was not a mistake, or an oversight – the designers were aware of the potential problem, and made an informed choice about whether to accept or eliminate these candidates. This was a calculated risk, rather than a known violation of the requirements specification.

Q3d) *Were any designs with known manufacturing flaws permitted through Validation?*

Both the designs that survived Process Independent Screening also survived Validation. For every component in these designs, some combination of the available processes could be found that satisfied all the identified properties.

Q3e) *Did the criteria used to evaluate the designs address cost?*

As Table 33 indicates, the criteria applied to this decision did not include an explicit cost criterion. However, as Table 34 shows, criteria for the cost requirement were deemed *redundant*, as minimising cost (in line with Requirement 42) would automatically be considered in Ranking, by plotting cost against utility. If ranking had been based on utility alone, the requirement would have been nonredundant and a cost criterion included.

7.3.2 Conclusions

The purpose of this case study was to identify whether the methodology described in Chapters 3 and 4 is able to satisfy the desiderata in a practical case. As section 7.3.2 shows, the answers to the research questions posed for this case study indicate that the methodology was followed and *did* satisfy the desiderata. The final choice was based on the requirements specification, and not on a preference imposed by the methodology or the DfX tools provided. At the same time, the designers were able to ensure that the available information on manufacturing and cost were incorporated into the decision in a rigorous and systematic manner. This has taken the methodology beyond the idealised circumstances of the laboratory, and shown it working in practice, under time pressure, dealing with more complex designs than those considered in the laboratory. Most importantly, this has shown that the methodology can satisfy the desiderata when applied to a real design scenario, and not one specifically developed for testing the methodology. It has also

demonstrated that the methodology can be used in conjunction with an existing DfA method, and illustrates how DfX approaches that support synthesis would work with the methodology.

The issue of uncertainty was raised, highlighting the importance of conditional constraints in Validation. Without exact dimensions, it was difficult to say whether a given process would be suitable for a given component, as the estimated properties might change later on. In Figure 32, for example, it was highlighted that the locating hole needed a diameter greater than 6mm, even though the estimated diameter was 10mm to 30mm. It was important that this requirement was highlighted, as the participants needed to be aware that there was a manufacturing implication of changing the estimated diameter in detail design.

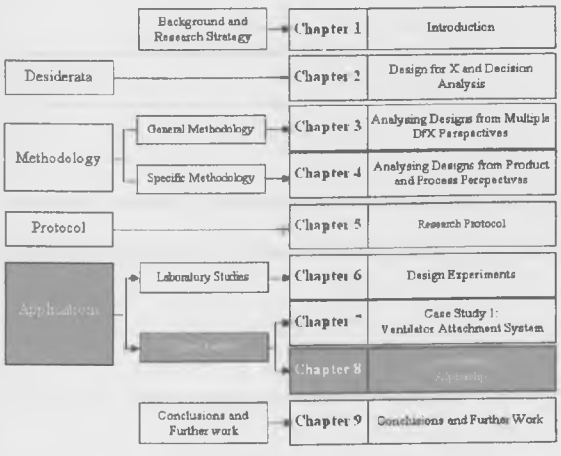
Related to uncertainty are difficulties in cost estimation. Without exact details of the designs, the costs estimated were very approximate, and difficult to compare with known costs, such as those of bought-out parts. It is open to debate whether a very approximate cost estimate is better or worse than none at all, but this is a decision support issue, and beyond the scope of this thesis. If designers really have no reliable way of differentiating the costs of designs then the cost requirement should be considered nonessential and left out of the decision.

Finally, there is the trade-off between effort and rigour. It was not necessary to compare every component against every process as some were clearly not appropriate, and the outcome of analysis was already known. Some corners can be cut without undermining the rigour of the methodology, but how one knows which can be cut safely is an open question.

7.4 Summary

This case study has demonstrated that the methodology can be applied and is able to satisfy the desiderata beyond the controlled environment of the laboratory. Again, the benefits of carrying out Screening activities prior to Validation have been demonstrated, as three designs (and their associated DFA revisions) were eliminated prior to Validation. Given the complexity of the candidates, this greatly reduced the effort that would otherwise have been needed for Validation. Applying the methodology to a real case has also highlighted some new issues for consideration in future work: how uncertainty and the trade-off between effort and rigour should be managed. This suggests that the final stage of the study is appropriate: applying the methodology to a commercial project.

Chapter 8
Case Study 2 - Alphaclip



The final stage of this research project was to establish whether the methodology can satisfy the desiderata in a commercial design project. The project selected for this purpose was the design of a "branded paperclip" whose shape would represent letters or logos that could be used to reinforce brand identity when sending out mail shots. Unlike the previous case study, this was a commercial product intended for sale, and the participants were professionals. The company initiating the project were investing in the proposed product, in the hope of capturing new markets. The risks in this application were therefore greater. Slowing down the design process or making the wrong choices would cost money.

This chapter is divided into three sections. **Section 8.1** describes the purpose of this case study and how it was conducted. **Section 8.2** describes each stage of the methodology, and how it was applied to the case in question. **Section 8.3** compares the data gathered with the research questions to determine whether the methodology still satisfies the desiderata in this case.

8.1 Purpose and Procedure

This section provides an overview of the case study, its purpose, and the way data was gathered. This section is divided into two parts, the first explaining the objectives of the study and the second describing how it was carried out.

8.1.1 Objectives of the Study

This case study builds on the previous chapter by providing complete realism, and therefore greater external validity. While care must be taken in generalising from a single case, this chapter demonstrates that the methodology was able to satisfy the desiderata in a real design project. The participants were all professionals in their roles: a marketing representative from Involution Ltd,

and two design engineers from the Keyworth Institute at the University of Leeds. The researcher acted as a third designer, assisting with research and helping to generate requirements and designs. Requirements were elicited from the marketing representative and the designs were two concepts he brought to the project, which were fleshed out by the designers. Table 38 shows how this case study addressed the participant, context and scenario factors that limited the external validity of the previous studies.

Table 38: Mitigation of Participant/Context/Scenario factors Case Study 2

Type	Factor	Mitigation	Notes
Participant Factors	Not all participants are experienced designers;		Although only two of the participants were experienced designers, all four were experienced professionals in their roles.
	The participants have no specific expertise in the product they are evaluating;	●	None of the participants had designed paperclips in the past.
	The participants are not part of a pre-existing design team;	○	Both the designers and the manufacturing consultant had worked together in the past. Only the marketer, who was contracting their services, was new to the team.
	The participants do not necessarily reflect the constitution of a "typical" design team;		While not all of the participants were experienced designers, cross-functional teams are common in industry, and all were experienced professionals in their roles.
Context Factors	The participants do not have the rest of the organisation to consult with – to receive clarification or guidance, for example;		In this case, organisations were involved, and directly available for consultation.
	The participants had no stake in the outcome of the decision they were simulating;		While only the Involution representative had a financial stake in the project's outcome the designers and manufacturing consultant had a professional interest in being involved with a successful product.
Scenario Factors	The requirements are not necessarily representative of typical design requirements;		Requirements were specified for a real product to be developed, manufactured and sold.
	The candidates are not necessarily representative of typical design candidates;		Designs were generated for a real product to be developed, manufactured and sold.
	The designers did not generate the candidates that they were evaluating.		In this case, the designers *had* generated the candidates that were being evaluated.

● = Factor applies to this case study;
○ = Factor applies partially to this case study.

As with the previous case study, moving beyond the laboratory context made data collection difficult. The researcher was not present at every meeting, and some activities were carried out in his absence. Again, this meant reliance on e-mail and meeting minutes, as well as chance conversations that were difficult to record. Like Chapter 7, this chapter provides an account of the case study based on the researcher's experience and the supporting documentation and physical artefacts gathered from the study. The researcher entered information gathered from the study into the support software, so that formal documentation could be gathered. Again, the emphasis is on the content of the study, rather than its process. The purpose of the study is to find out whether the methodology is able to satisfy the desiderata in a real design project. It therefore has two objectives:

1) to determine whether the methodology can be applied in a real design project; and
2) to determine whether the methodology can satisfy the desiderata in a real design project.

8.1.2 Procedure

This project was initiated by Involution Promotional Wear Ltd (www.involution.co.uk), which specialises in producing branded clothing, adding company logos to existing items (such as t-shirts, pens, or mugs). The company hoped to enter a new market by developing a branded paperclip - nicknamed the Alphaclip – that would be shaped like a letter or a simple symbol (such as a square or spiral). This would provide a new way for companies such as banks and solicitors to reinforce their brand identity when sending out mail shots. Plastic paperclips with printed logos on are already available, but these are all a standard shape: only the print varies. The Alphaclip's eye-catching shape would separate it from the competition, but it would still be a paperclip and had to function correctly, as well as being available at a competitive price. Rather than generate over 26 designs before establishing the feasibility of the concept, attention focussed initially on just four letters, and two symbols. The range could be expanded if these were successful.

Involution provided two initial concepts that they wanted to develop further, and choose between: thin letters formed from metal wire (see Figure 35); and "chunky" letters formed from injection-moulded plastic (see Figure 36). Each option was a family of designs, one for each character, rather than a

single component. However, as each Alphaclip would be an individual component, assembly issues did not need to be considered. The methodology was applied to determine which design was most suitable for further development. The researcher acted as part of the design team, providing his own input into the project, as well as entering the information generated into the support software. As in the previous case study, this was an opportunity to gather documents for analysis and verify that the information generated in this case fitted the pattern required by the methodology.

Figure 35: Example sketch for the wire Alphaclip design

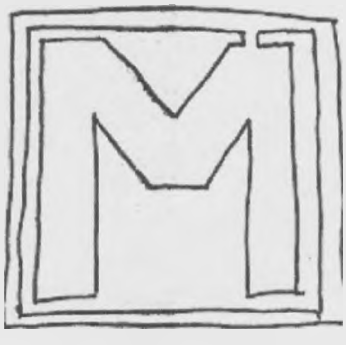


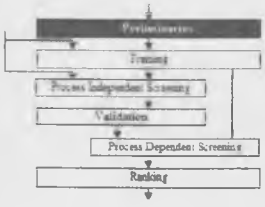
Figure 36: Example sketch for the plastic Alphaclip design.

8.2 Results

This section describes the results of each stage of the methodology as it was applied to this case study. This section is divided into four parts, each describing a major stage of the methodology: Preliminaries and framing; Process Independent Screening; Validation; and Process Dependent Screening. The results of Process Dependent Screening suggested that *none* of the designs were acceptable, and a decision was taken to abandon the project, rather than proceed to Ranking. The full rationale for this decision is given in Section 8.2.4.

8.2.1 Preliminaries and Framing

Preliminaries



The designers agreed a set of 16 requirements with the Involution representative: these are summarised in Table 39, with the classifications and priorities assigned to them.

Table 39 : Requirements for Case Study 2.

No.	Requirement	PD	M
1	The Alphaclip will cost less than 1p each, including material and manufacturing costs.	✓	✓
2	The Alphaclip will be suitable for manufacture in batches of 100,000 to 1,000,000 plus.	✓	✓
3	The Alphaclip should be visually appealing (as determined by Involution)		✓
4	The Alphaclip will be initially available as a range of six characters: S, A, I, M, a square and a spiral.		✓
5	The Alphaclip design should be extensible to cover all letters of the alphabet.		✓
6	The Alphaclip mechanism should be immediately intuitive to use.		✓
7	The Alphaclip will have no sharp edges or points that might cause users to injure themselves.		✓
8	The Alphaclip will have the look and feel of a metal.		✓
9	The Alphaclip will be made from non-toxic material.		✓
10	The Alphaclip will be able to fasten 12 sheets of paper securely together, without suffering permanent deformation.		✓
11	The Alphaclip should not require more effort to use than an existing paperclip.		✓
12	The Alphaclip will be able to fasten 2 sheets of paper securely together, without coming loose.		
13	The Alphaclip should not damage the papers it is used to fasten.		
14	The Alphaclip will not present a choking hazard if swallowed by a child.		
15	Alphaclips should not tangle when stored loose together.		
16	The Alphaclip will fit in a space envelope of 25mm × 25mm × 1.5mm		

Classify requirements

Cost was extremely important in this project. The purpose of the Alphaclip was to generate profit, unlike the system in the previous case study. Involution could invest in other projects, and unless the Alphaclip sold at a reasonable profit margin, then other projects would provide a better return on investment. Although it is difficult to be exact when developing revenue projections, Involution felt that the Alphaclip needed to cost less than 1p each to be viable. This cost estimate was for production and material only – the cost of shipping, handling and packaging had already been taken into account. The cost

requirement (Requirement 1) was therefore process dependent, as was the feasible rate of production (Requirement 2). The remaining requirements are dependent on either shape (requirements 3 through 7, and 14 through 16), material (requirements 8 and 9) or – for those requirements concerned with stiffness – a combination of both (Requirements 10 through 13). These were therefore process dependent.

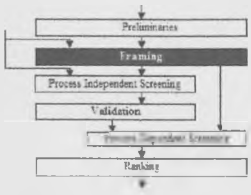
Prioritise Requirements

Requirements 1 through 4 were integral to the Alphaclip's purpose. Its cost and sale quantities would make the project profitable, while its shape and aesthetics would distinguish it from the competition. Requirement 5 was less important, and though it was considered mandatory, it could be relaxed if (and only if) it was proving difficult to satisfy. The remaining requirements (6 through 16) were all related to the Alphaclip's ability to function like a normal paperclip. There were safety issues – the risk of injury, and the need for a non-toxic material were considered critical. The need to avoid choking hazards for a child was considered serious, but optional, as the designs were not intended for use by children. Requirement 8 was to counteract the perception that plastic paperclips (in the event that the plastic design was chosen) are a cheap, low quality alternative to gem paperclips. Involution were willing to relax it, as they might still be able to sell the Alphaclip on its novelty value, but only if absolutely necessary. The size constraint was a target, rather than an absolute limit. Similarly, the risk of damage to the clipped papers was considered optional, as existing metal paperclips are prone to damaging the papers that they clip. Finally, preventing the Alphaclips tangling (making them more convenient to retrieve from their packaging), was considered optional, as it was expected to be very difficult to achieve.

Identify manufacturing processes to be considered.

Production of the Alphaclip would be outsourced, giving a great deal of freedom in the processes that *could* be used. However, the designers quickly limited attention to just two processes: wire-forming for the slim, wire design and injection moulding for the plastic design. They argued that these were the only realistic choices for each design, given the production quantity, material and the basic shapes being considered.

Framing



Given the incomplete state of the candidate designs, only five of the requirements were considered *essential* to the current decision, and none of these were *controllable* in their current form. Table 40 summarises the requirements that were considered essential, and the surrogate criteria that were developed to represent them. Table 41 summarises the requirements deemed *nonessential* and explains the reasoning behind this. As Table 40 shows, none of the optional requirements were deemed essential, so Ranking would be impossible. If only one design survived Screening, this would not be an issue. Instead, it was agreed that if both designs survived to Ranking, the one with the lowest predicted unit cost would be accepted. If both unit costs were too close to separate them, then it would be considered too early to take the decision, and both designs would be developed further. To help with evaluation, manufacturing professionals would be consulted. An injection-moulding consultant was brought in to discuss the plastic design, and sketches of the wire design were sent to a local wire-forming company for feedback and cost estimates.

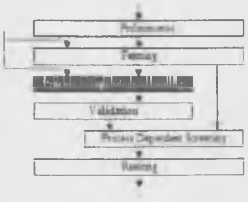
Table 40: Criteria for *essential* requirements for Case Study 2

Requirement	Criterion	PD	M
The Alphaclip will cost less than 1p each, including material and manufacturing costs.	Agreement from the manufacturing consultant that the design is feasible at less than 1p, including material and manufacturing costs.	✓	✓
The Alphaclip will be suitable for manufacture in batches of 100,000 to 1,000,000 plus.	This already being accounted for in the choice of processes. It doesn't need any further representation.	✓	✓
The Alphaclip will have no sharp edges or points that might cause users to injure themselves.	Team agreement that none of the letters have sharp edges or points that might cause users to injure themselves.		✓
The Alphaclip will have the look and feel of a metal.	Agreement from the manufacturing consultant that the design will have the look and feel of a metal.		✓
The Alphaclip will be made from non-toxic material.	Agreement from the manufacturing consultant that the material used in the design will be non-toxic.		✓

Table 41: Nonessential requirements for Case Study 2

Requirement	Justification
The Alphaclip should be visually appealing (as determined by Involution)	Exact designs were not available, so a final judgement on their visual appeal would need to be left until a more detailed stage. Involution had already indicated that they were happy either of the two approaches (wire or chunky lettering), so there is nothing at this stage to distinguish between designs.
The Alphaclip will be initially available as a range of six characters: S, A, I, M, a square and a spiral.	A full alphabet had been sketched out for both concepts, along with sketches for the square and spiral. Therefore, both designs, in principle could cover the required shapes.
The Alphaclip design should be extensible to cover all letters of the alphabet.	
The Alphaclip mechanism should be immediately intuitive to use.	Both concepts worked exactly like a normal paperclip
The Alphaclip will be able to fasten 12 sheets of paper securely together, without suffering permanent deformation.	These requirements depend upon details that have not yet been determined for either design. Given the current information, there is no reason to think that either design will violate these requirements.
The Alphaclip should not require more effort to use than an existing paperclip.	
The Alphaclip will be able to fasten 2 sheets of paper securely together, without coming loose.	
The Alphaclip should not damage the papers it is used to fasten.	
The Alphaclip will not present a choking hazard if swallowed by a child.	
Alphaclips should not tangle when stored loose together.	
The Alphaclip will fit in a space envelope of 25mm × 25mm × 1.5mm	

8.2.2 Process Independent Screening



There are three mandatory Process Independent Criteria, which are used for Process Independent Screening. Figure 37 shows the elimination matrix constructed for this purpose. For the first criterion, the team agreed that the wire-formed letters were certain to pass, as the wire itself would be rounded. Only the ends of the wire would be remotely sharp, and were no more likely to cut the user than a gem paperclip. The sketches for the plastic design show it having a square frame, and several sharp angles. However, the plastic was expected to be too soft to cause cuts, and the frame could be made circular, or given corner radii.

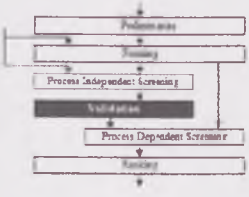
The remaining criteria called for the agreement of the manufacturing consultant. The wire design was passed immediately, as it would be made in stainless steel. When it came to the plastic design, the injection-moulding consultant confirmed that plastic compounds were available that could provide a metallic-finish, without a need for post-processing operations such as coating.

He also confirmed that this compound was not toxic. Therefore, the plastic design was also passed against these two criteria and both designs were carried forward for validation.

Criterion \ Candidate	Wire Formed Letters	Plastic Letters
Team agreement that none of the letters have sharp edges or points that might cause users to injure themselves.		
Agreement from the manufacturing consultant that the design will have the look and feel of a metal.		
Agreement from the manufacturing consultant that the material used in the design will be non-toxic.		

Figure 37: Elimination matrix for Process Independent Screening

8.2.3 Validation

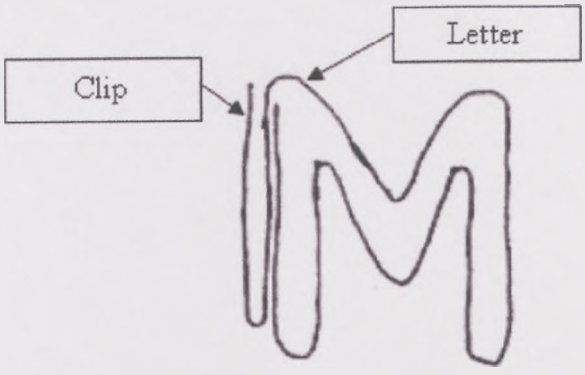


Although each Alphaclip would be a single component, Validation was complicated by the fact that each design represented a *family* of parts. Each character was therefore treated as a separate component. Although only six characters would be developed in detail, to verify that the designs could be extended to the full alphabet, all the letters of the alphabet were validated. As only shape varies from character to character, the results for each character were very similar. Each stage of Validation will therefore be illustrated for just one character – the letter M - for each design.

Identify Features

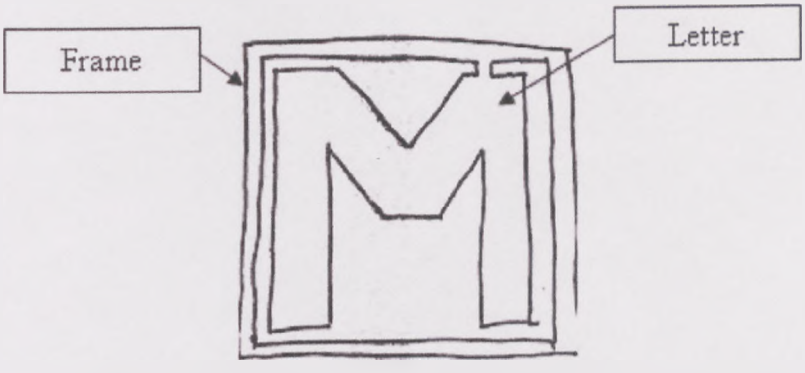
As with the previous case study, the candidates existed only as approximate sketches, so features and properties could only be established approximately. This stage assessed the designs based on the available information, to make sure there were no serious problems before developing either in greater detail.

Features were difficult to identify: the holes and bosses that have been present in every previous case are not so easy to define here. For the wire-formed designs, the component was treated as a ***clip*** (the basic component), with a ***letter*** attached (see Figure 38). Similarly, the plastic design can be treated as a ***frame*** (the basic component) which pushes the paper against the letter, and the ***letter*** itself (see Figure 39). In both cases, it is only the letter that changes across each member of the family.



Original Image ©Involution Ltd. 2004

Figure 38: Features for the wire Alphaclip design



Original Image ©Involution Ltd. 2004

Figure 39: Features for the plastic Alphaclip design.

Identify Properties

The materials for the designs are known (stainless steel for the wire design, a metallic polycarbonate compound for the plastic design). Because there are no assembly relationships, no surface finishes or tolerances need to be specified. Shape is difficult to capture, and best represented by reference to the sketches. Although specific dimensions are not known, general values can be estimated based on the maximum space envelope for the Alphaclip (25mm × 25mm × 1.5mm). It had to be kept in mind that these were just estimates, so any manufacturing implications of changing these values had to be recorded for future reference.

Identify Violations

As processes had already been nominated for each design, the purpose of this stage was only to check that the design as described *could* be made by the given process. The compatibility matrices were populated by the researcher, based on information from four handbooks (Swift and Booker, 2003; Bralla,

1999; Boothroyd *et al.*, 2002; Bryce, 1997) and the designers' discussion with the manufacturing consultants.

Figure 40 shows the compatibility matrix for the wire-formed design. This was straightforward, as the design was essentially the same as a gem paper clip with longer wire and additional turns. With CNC wire-forming (the most likely way of implementing this) a great deal of precision can be achieved, and making parts of that size is not difficult.

Feature	Property	Description	Candidate Process
			Wire-forming
Basic Component (Clip)	Material	Stainless Steel	
	Shape	See sketches	
	Dimension	**Length:** 25mm	
	Dimension	**Breadth:** 5mm	
	Dimension	**Wire Diameter:** 1.5mm	
Letter	Shape	See sketches.	
	Dimension	**Length:** 25mm	
	Dimension	**Breadth:** 20mm	
	Dimension	**Wire Diameter:** 1.5mm	

Figure 40: Compatibility matrix for the wire "M" design

Figure 41 shows the compatibility matrix for the plastic design: this had several issues that would need to be kept in mind in detail design if it was to be acceptable. First, there was a need for a draft angle on the part, to reduce the risk of damaging it when ejected from the die. This would only need to be slight (around ½° should suffice) and would not affect the function of the part.

Feature	Property	Description	Candidate Process
			Injection Moulding
Basic Component (Frame)	Material	Metallic Polycarbonate Compound	
	Shape	See sketches	**1, 2, 3, 4**
	Dimension	**Length:** 25mm	
	Dimension	**Breadth:** 25mm	
	Dimension	**Thickness:** 1.5mm	
Letter	Shape	See sketches	**1, 2, 4**
	Dimension	**Length:** 20mm	
	Dimension	**Breadth:** 20mm	
	Dimension	**Thickness:** 1.5mm	

1 = Subject to a draft angle of ½°
2 = Witness mark from ejector pins, gates, and parting line are unavoidable, but can be positioned to suit the design.
3 = Risk of knit lines on frame opposite plastic entry point.
4 = Corners should be rounded, rather than right-angled, with outer radius 1.5 the nominal wall thickness, and inner radius of half the nominal wall thickness, to encourage uniform wall-thickness.

Figure 41: Compatibility matrix for Plastic "M" design

Several defects are unavoidable in injection moulding. Witness marks left by the ejector pins, gates and parting line are inevitable, and all the designers can do is specify where they should be avoided. They will not interfere with the function of the part, but may reduce its aesthetic appeal. The back of the part are obvious places for them, where they will not be immediately obvious when the Alphaclip is in use. The worst place would be on the front of the letter, where the user's attention would focus. Knit lines would occur in the frame, where the plastic that has had to run around its outline recombines. This would introduce a weakness in the frame, though not in the part of the frame that is under stress, so it was not expected to interfere with the Alphaclip's function. However, like witness marks, visible knit lines could reduce the aesthetic appeal of the design. These could only be eliminated by creating a "break" at the bottom of the frame, so the plastic does not recombine at all. This might make the part more difficult to use, as the two "legs" that replace the frame would not necessarily line up with each other – although this, in turn could be avoided by using only one "leg" for the frame. Knit lines were also a risk for several characters (e.g. B, D, O, Q).

The most serious issue was the need for uniform wall thickness, or at least, a very gradual change in wall thickness, to minimise differential cooling. Sharp angles also had to be avoided, making the edges rounded, so the angular design shown in Figure 36 (page 171) would not be practical. A particular problem was the narrow interface between frame and letter, where there was a risk that the plastic would cool, creating a blockage and preventing the letter cavity filling properly. Additional heating at this point could help to avoid the problem, but would inevitably increase the cost of tooling and the energy needed for production. These problems could be overcome, so the plastic design was still feasible, but it was unlikely to resemble the initial concept sketches.

Feasibility, Process Chains and Re-Evaluation

Both designs were feasible (subject to the identified constraints on the plastic design being obeyed in detail design), but only the wire-form design would match the initial sketches. This was not a problem – after all, the shapes of the designs had not been finalised – but it did highlight some issues that could be kept in mind for subsequent stages of design. It also meant revisiting Process Independent Screening for the plastic design, to see if the limitations and suggested alterations contradicted any mandatory criteria. None of the

alterations changed the material of the design, and the inclusion of corner radii reduced the number of sharp edges; therefore the design was still acceptable. One other issue was raised: the aesthetic requirement had been deemed nonessential, because Involution had passed both concepts in principle. It could not be taken for granted that they would approve the alterations to the plastic design. After discussion with the designers, the Involution representative agreed that the letter, not the frame, was important aesthetically, so any changes to the frame were acceptable. Equally, he had no problem with rounding edges on the frame and letters, as there was no aesthetic need to make them angular. He was not keen on visible witness marks, or knit lines, but felt they were not a problem if they kept out of sight or did not stand out in particular. As only one process was considered for each design, process chains were not an issue, and both candidates were passed on for Process Dependent Screening.

8.2.4 Process Dependent Screening

The only process dependent criterion was agreement from the manufacturing consultants that the designs could be made for less than 1p per unit. While exact costs were impossible to establish this early in design, all that was necessary was an indication of whether the target cost of under 1p per unit was realistic. As long as the part could be made for approximately a penny, then more accurate cost estimates could be established once the designs had been developed in further detail.

For the wire-formed design, the process used would be computer-controlled, so no specialist tooling would be required, but a separate program would need to be written for each character. This would require a one-off fixed cost for the programming of each character, but thereafter there would only be the cost of producing each batch to consider. However, the quotes obtained suggested that at the expected levels of production (between 3500 and 35,000 of each character per annum) they would charge around 11p per unit. This was far beyond what was economically feasible for Involution.

For the plastic design, material costs would be extremely low, no more than 0.1p per unit but tooling costs would be extremely high, as each character would require a separate die. Each die might cost several thousand pounds, requiring production rates into the hundreds of thousands for each character just to get die costs below 1p per unit. Setup and running costs would need to be included on top of that. The manufacturing consultant suggested that this problem could be reduced by using a multi-cavity die, which might produce as many as 32 units in a single cycle. However, this would require a hot-runner

system, to ensure that all the cavities received molten plastic: the cost of running this alone would come to more than 1p per unit. In his opinion, it was not possible to produce parts at such low volumes at the target cost.

Figure 42 shows the elimination matrix for Process Dependent Screening: both designs were eliminated. Wire forming was definitely unacceptable, due to the high cost per unit, regardless of the level of variety or production. Only injection moulding had any chance of producing the Alphaclip at less than 1p per unit, and this would be impossible with a multi-cavity die. The only way of keeping tooling costs at an acceptable level would be to use a single cavity die, and massively increase production of each character.

Criterion \ Candidate	Wire Formed Letters	Plastic Letters
Agreement from the manufacturing consultant that the design is feasible at less than 1p, including material and manufacturing costs.	X	X

Figure 42: Elimination matrix for Process Dependent Screening

Involution therefore had three options: abandon the project, relax the cost requirement or increase expected production. As a new product, Involution were not sure what levels of demand for the Alphaclip would be, but they wanted to begin seeing a Return on Investment within three years. Expecting demand for any given character to exceed 100,000 units per annum was just too risky. Relaxing the cost requirement would immediately cut into profits: anything more than 1p per unit and the money would be better invested elsewhere. The designers suggested that Involution could injection mould a smaller range of Alphaclip designs, and then customise them by printing logos or letters on them using in-house capabilities. At 1,000,000 Alphaclips this could cut die costs to under a penny, although handling costs would increase. The Involution representative was not keen on this idea, as variety set the Alphaclip apart. Going for a single design, or very limited range of designs would mean that the Alphaclip would be no different to existing plastic paperclips with printed logos. Other companies already had a strong hold on this market, and it would be difficult for Involution, as newcomers, to break in without considerable investment. The variety requirement could not be relaxed. In light of this, Involution decided that the Alphaclip was not feasible, and the project was cancelled.

8.3 Discussion

This section discusses the research questions in the context of this case study. It is divided into two parts, the first considering the answers to each of

the relevant research questions, and the second discussing the main conclusions drawn from this case study.

8.3.1 Feasibility and Practical Coherence of the Methodology

This section discusses the subset of research questions that are relevant to this case study.

Q2a) *Were the participants able to work through all the stages of the methodology?*

Table 42 summarises the status of the documents gathered from the supporting software. Every document is complete, except for Document 9, which is incomplete, and Document 14, which is empty. This suggests that every stage apart from Ranking took place, which supports the account given in Section 8.2.

Table 42: Documents gathered from Case Study 2

	DOCUMENT	STATE
1	A list of requirements with priorities and classifications.	✓
2.	A list of processes under consideration;	✓
3.	A list of criteria with classifications.	✓
4.	An elimination matrix comparing the candidates against the mandatory PI criteria.	✓
5.	A list of candidates under consideration;	✓
6.	A list of the components making up each candidate;	✓
7.	A list of the features associated with each component;	✓
8.	A list of the properties associated with each feature;	✓
9.	A compatibility matrix for each component comparing its properties against the capabilities of the available processes.	⊙[1]
10.	A list of process chains for each component	✓
11.	A list of the recommended process chain for each component	✓
12.	A list of feasible candidates	✓
13.	An elimination matrix comparing the candidates against the mandatory PD criteria.	✓
14	A graph of cost vs. utility	○[2]

✓=Complete, × = Incorrect, ⊙= Incomplete, ○ = Empty

The contents of documents 6, 10 and 11 were trivial: each candidate only comprised one component, and only one process was ever considered for each design. As in the previous case study, Document 9 was technically incomplete, as each candidate was only compared against a single process. However, this was for the same reason: it was obvious that each process under consideration was only suitable for one of the two designs. That wire-forming could not produce the plastic design, and that injection-moulding could not produce a metal wire design, were obvious without the need for analysis. Document 14 is empty, because all the designs had been eliminated in Process Dependent

[1] The compatibility matrix for each candidate only considered one of the two processes.

[2] As none of the designs survived Process Dependent Screening, there was no opportunity for Ranking.

Screening (see Figure 42, page 181). As this was in line with the methodology, and not an error, it suggests that the methodology was applied correctly.

Q3a) *Were any of the criteria used in the evaluation* **not** *related to a requirement from the requirements specification?*

Table 40 (page 174) shows the criteria used for Screening in this case study: every criterion can be traced back to a requirement. However, there was a serious issue with the optional criteria established for Ranking purposes: none of the optional requirements were essential for this decision, so no optional criteria could be derived. As both designs were eliminated in Process Dependent Screening, this never became in issue. Section 8.2.1 indicates that if Ranking had taken place, it would have been based purely on choosing the design with the lowest estimated cost. However, this was not derived directly from a requirement.

Three comments can be made on this subject. Firstly, in the absence of any *essential* optional requirements, some way was needed for choosing between the designs. If all analysis suggests that the designs are indistinguishable, then a rational decision-maker would be indifferent between them, so using an alternative approach to the decision would be acceptable. In these circumstances, even random selection – by tossing a coin, for example – would be acceptable, as the decision-maker has no better way of making the choice. Secondly, it could be argued that choosing the design with the lowest estimated cost would maximise the chance of satisfying the only cost based requirement – that the Alphaclip should cost less than 1p per unit. Thirdly, one could argue that minimising cost is desirable, as – all else being equal – lower cost would mean greater profit for Involution. This would suggest that there *should* have been an optional requirement to minimise cost, in addition to the mandatory requirement for a maximum cost of 1p per unit. However, given that this criterion was only introduced in the absence of any other way of distinguishing between designs, it does not suggest a flaw in the methodology.

Q3b) *Were any* essential *requirements not represented by the criteria?*

Table 39 (page 172) provides a full list of the requirements used in the project. Every requirement in this table should have been either allocated a set of one or more criteria, or deemed *nonessential.* Table 40 (page 174) shows the criteria used for Screening and Ranking: every requirement in this table is

represented by at least one criterion. Table 41 (page 175) lists the requirements that were deemed nonessential – and therefore did not need criteria for this decision – and provides justification for this choice. Between them, Table 40 and Table 41 account for every requirement in Table 39.

Q3c) *Were any of the designs surviving to Ranking expected to violate the requirements specification?*

As none of the designs survived to Ranking, this question is redundant.

Q3d) *Were any designs with known manufacturing flaws permitted through Validation?*

Both designs survived Validation, although the plastic design required some alterations to be suitable for injection moulding. There was no known reason that either design should be impossible to manufacture by the process proposed for it. Neither of the manufacturing consultants felt that the designs were infeasible for the given processes – only that they couldn't be achieved at the desired price.

Q3e) *Did the criteria used to evaluate the designs address cost?*

As Table 40 (page 174) shows, a mandatory cost criterion was included to reflect the cost requirement specified in Table 39 (page 172). Figure 42 (page 181) shows that both Designs were evaluated (and eliminated) against this criterion. As suggested under **Q3a)**, a case could be made that the requirements specification should have been updated to include a preference for minimising costs, but this is strictly beyond the scope of the methodology.

8.3.2 Conclusions

The purpose of this case study was to identify whether the methodology described in Chapters 3 and 4 is able to satisfy the desiderata in practice. It builds on the previous case study, by applying the methodology to a commercial project. As section 8.3.2 shows, the answers to the research questions posed for this case study indicate that the methodology *did* satisfy the desiderata. However, the final choice was not one of the candidate designs, but the decision to terminate the project entirely. Nevertheless, this decision was still based on the intentions and requirements set out by Involution, and not on a preference imposed by the methodology, the designers or the manufacturing consultant. The decision was explored in a structured and rigorous manner.

Although this technically seems like a failure, Involution benefited from establishing early on that the requirements for variety and low cost were mutually exclusive, and that the project should be cancelled, rather than discovering this once a full design had been established.

It is worth noting, however, that given that only one process was being considered for each candidate design, the Process Dependent Screening could have taken place before Validation. While it was useful from a research perspective that the project went as far as it did, time could have been saved by looking at cost issues first. Of course, it is easy to say these things in hindsight: it is inevitable that if one already *knew* which criteria would eliminate a design, one would check against those first, so that it would not need to be considered further. But then, if one knew that the design was going to be eliminated, one wouldn't consider it in the first place. This does suggest that there may be some merit in thinking carefully about the order in which activities are carried out, and the methodology is flexible enough to allow cost to be considered first. However, there would need to be a basis for deciding in advance which order stages would be carried out in.

Unlike the previous case study, uncertainty about the details of the designs did not present a problem. It was possible to highlight general manufacturing issues that might pose a problem, even before the exact shape of the designs had been established. A number of constraints were highlighted that the designers would need to keep in mind if they had developed the designs further. Even general cost estimates were possible, although the fact that the estimated costs were so far beyond the cost criterion made the decision quite straightforward. Had they been very close to the cost constraint, then the decision would have been much more difficult, and the methodology would not have been able to assist. The Involution representative would have had to consider how certain they were about the estimates, how critical the cost requirement was, and whether they were prepared to risk developing the design further to get more accurate cost estimates before making a firm decision. As ever, the structured approach provided by decision analysis helps the process of thinking through a decision, but responsibility still lies with the human decision-maker.

8.4 Summary

This chapter has demonstrated the application of the methodology to a commercial design project, with simpler designs than the previous case study,

but with new risks involved. This study has demonstrated that in reality, the options available in a design decision often go beyond the alternatives under consideration: in this case, the chosen option was cancelling the project. The ordering of Screening and Validation was again an issue. Because only one process was considered for each candidate, cost estimates could have been made prior to Validation. Of course, if both candidates had satisfied the constraint, and one had proved infeasible, the reverse complaint would be raised. This suggests that there are benefits in a flexible ordering of Screening and Validation activities, though how users can identify the best arrangement for their context is an open question.

This case study has demonstrated that the methodology can be applied and is able to satisfy the desiderata in a commercial project. This does not mean that the methodology is suitable to all design decisions, only that there exists, in the real world, a class of decisions for which the methodology is appropriate. Further work is necessary to determine what the extent and characteristics of this class is, but this case study suggests that this further work *is* appropriate.

Chapter 9
Conclusions and Further Work

This Chapter reviews the findings of this thesis, and expands upon them, considering their implications and directions for future research. This chapter is divided into three sections. **Section 9.1** reviews the work carried out in this thesis, and discusses new questions that this worked has raised but not answered. **Section 9.2** highlights the contributions this thesis has made, and discusses the value of this research. **Section 9.3** discusses the limitations of this research, and the future work needed to build on this thesis to develop tools and techniques that can support design practice.

9.1 Summary Discussion

This section reviews the outcomes of the work carried out in this thesis, drawing together discussion from previous chapters, and is divided into two parts. The first reviews the previous chapters, and highlights the main points raised in each one. The second highlights new questions that this work has raised, but which have not yet been answered.

9.1.1 Recapitulation

The focus of this thesis has been on clarifying and answering the overarching research question posed in Chapter 1:

"Can decision analysis incorporate Design for Manufacture information in design evaluation without imposing a preference structure on the decision?"

To do this, the thesis has had to:

1) set out ***desiderata*** providing a formal definition of what it means to *"incorporate Design for Manufacture information in design evaluation without imposing a preference structure on the decision"*. This was the focus of Chapter 2.

2) set out a ***methodology*** for using decision analysis in this way. This was the focus of Chapters 3 and 4, with Chapter 3 considering the evaluation of designs against multiple virtues and lifephases, while Chapter 4 considered the specific case of product and process design.

3) provide a ***protocol*** for evaluating applications of this ***methodology*** against the ***desiderata***. This was the focus of Chapter 5; and

4) Apply the ***methodology*** to see if it could satisfy the ***desiderata*** in practice. This was the focus of Chapters 6 to 8, with Chapter 6 examining three design experiments, Chapter 7 an application to a student project, and Chapter 8 providing an application to a commercial design project.

Chapter 2 reviewed the literature on Design for X tools and decision analysis. It examined the support provided by DfX tools and demonstrated that they provide decision support, helping designers understand the implications of their choices. DfX techniques addressing virtues, and those addressing lifephases, provide different kinds of support, but each tends to address only a single virtue or lifephase.

The review also considered decision analysis techniques and some complicating issues in their use, particularly Arrow's Impossibility Theorem, and their implications for assessing trade-offs between multiple virtues and lifephases. Game Theory provides one way around Arrow's Impossibility Theorem, and has been adopted by some researchers as a basis for concurrent engineering. However, this thesis has argued that it is not a suitable basis for design decision-making, as it does not relate to the overall needs of the design. A decision-conferencing approach is more appropriate – building a shared model of the decision, and using disagreements to explore the problem, rather than trying to resolve them mathematically. This review also demonstrated that the mathematics of decision analysis is less important than the systematic process it provides for evaluating alternatives. These findings formed the basis of the ***desiderata*** which guided the rest of this thesis, and the methodology derived in the following chapters.

Chapter 3 showed that a logical relationship exists between the support provided by DfX and the main tools of decision analysis. $DfX_{lifephase}$ techniques can be incorporated through the decision tree and DfX_{virtue} techniques through the MCDM algorithm. It presented a methodology for exploiting this relationship and demonstrated that this methodology can satisfy the desiderata logically. ***Chapter 4*** built on this, by showing how the methodology derived in Chapter 3 could be applied to the specific case of integrated product and process design without violating the desiderata. It also proposed specific methods for using DfM techniques in Validation, although other implementations will also be valid.

Satisfying the desiderata logically is one thing, but if the methodology is to provide real benefits, it must satisfy them when put into practice. ***Chapter 5*** discussed how applications of the methodology could be evaluated, and the difficulties this presented. The main issues were *internal* and *external* validity – the

nature of the methodology meant that it was impossible to provide full *external* validity. In a single thesis it would be impossible to test the methodology against a sufficiently large sample representative of the full population of all possible design decisions. Instead, the aim has been the more modest objective of providing a single application to a real design decision, demonstrating that the methodology *can* work in practice, and is worthy of the further investigation needed to provide external validity. In a real case, *internal* and *construct* validity are more difficult to ensure, and to address this ***Chapter 6*** provided three applications of the methodology in a laboratory context. Here, the applications could be studied in more depth, and difficulties could be investigated before applying it to any real cases. In all three cases, it proved possible to apply the methodology, although the importance of facilitating the process was highlighted. These experiments also suggested that there are benefits to allowing a flexible ordering of Validation and Screening activities.

Chapter 7 demonstrated that the methodology could be applied and satisfy the desiderata beyond the controlled environment of the laboratory. This also raised new questions of how uncertainty should be managed in Screening and Validation, and how the trade-off between rigour and effort should be managed.

Chapter 8 applied the methodology to a commercial design decision, and demonstrated that the methodology could be applied and satisfy the desiderata in practice. The methodology provided a structured basis for investigating the problem, and it was concluded that three critical requirements were mutually exclusive, and the project was abandoned. This demonstrated that the candidate designs are not the only alternatives in a design decision. Strategic options may also be available, though how these should be dealt with is an open question: this thesis restricts its attention to evaluating designs. As Ranking was not necessary in this application, one cannot say whether it would have worked in this case. However, Ranking presented no problems in the previous applications, and the feasibility of using MCDM algorithms in engineering design has been, and continues to be, addressed by other researchers. That the methodology *can* be used in practice to satisfy the desiderata suggests that some class of design decisions exists for which the methodology will satisfy the desiderata. Defining the exact limitations of this class, or whether better implementations of the methodology are possible is beyond the scope of this thesis.

9.1.2 New Questions

As well as answering its core research question, this thesis has also raised a number of new questions that need to be addressed. These questions are distinct from the limitations of the study, defined by its scope in Chapter 1. While it is important to remember which issues this thesis has deliberately left unaddressed (covered in

Section 9.3.1), the emphasis here is on additional questions that have been raised in the course of the study.

1. *Which MCDM algorithms are most appropriate to different design decisions?*

Chapter 2 dealt with the relationship between decision analysis and Design for X techniques, and highlighted the fact that the best approach to decision-making is *adaptive*: choosing a decision analysis technique to suit the context of the decision being taken. However, this thesis has not addressed the question of *when* different techniques are most appropriate, or what range of decision contexts exist in engineering design. SMART was adopted as the only decision analysis algorithm for testing, but that does not imply that SMART is the most appropriate choice generally, or even the best for the given circumstances. This thesis has restricted its attention to demonstrating that DfX can be used in conjunction with the basic principles of decision analysis: any MCDM algorithm could be used. There would therefore be value in developing a taxonomy of design decisions so that available decision analysis techniques could be matched to the decisions they were most appropriate to. This would help design researchers select appropriate methods to underpin their work, and industrial decision-makers to focus on the most appropriate techniques for their decisions.

2. *How should requirements be defined and managed?*

This thesis has presupposed that the requirements specification, which it has defined as the rational basis for all design decisions, is both complete and correct. Without a suitable underlying specification, there is no way of making rational design decisions, as the designers cannot know what they are working towards. One of the benefits of decision analysis is that it helps to make decisions and the judgements underpinning them explicit, but this cannot be of any real help if there is no overall goal to structure the decision around. This emphasises the importance of having a suitable requirements specification, but offers no guidance on how to develop one. Therefore, there is a need for research on how requirements can best be developed, especially given their tendency to evolve over a project. This is, in part, the domain of DfX_{virtue} techniques, which prompt designers on important factors they should be incorporating into their decisions.

3. How should uncertainty be dealt with in Screening?

The design experiments raised the issue of how uncertainty could be incorporated into Screening. As yet, there has been no work in this area, leaving the decision-makers to say whether they are confident enough to accept the design against a given criterion, or so uncertain that they will reject it. However, a design passed with uncertainty against every criterion cannot be considered equal to a design that is considered certain to pass every criterion. As yet, no method exists for reflecting this, though it might be incorporated by adding additional Ranking criteria to penalise uncertain designs.

4. How should criteria be derived from requirements?

This thesis has not provided any formal way of establishing criteria from a set of requirements. There is the question of how criteria and performance measures for an *incomplete* design can be derived from its requirements specification, though this may depend upon the MCDM algorithm adopted. This is an issue for decision-based design, and design evaluation in general, rather than being specific to concurrent engineering or Design for X. However, it is an area which DfX_{virtue} techniques may again play a part in, by helping designers to understand what aspects of designs at different stages of their development can be related to requirements, and therefore can be used as the basis for criteria.

5. Can features and properties be formally represented?

There is also the question of whether greater formality could be brought into the Validation stage, through a formal taxonomy of features and properties, and a more formal method for comparing them against process capabilities. Properties such as shape are particularly difficult to capture and communicate when a design is incomplete. There are many taxonomies of features, and whether a single accepted taxonomy will emerge, or whether different taxonomies will be more appropriate to different contexts remains to be seen. Can a single taxonomy ever hope to be appropriate for every stage of design? This raises the question of how an appropriate taxonomy of features can be chosen, and what difference this makes to Validation of designs in this methodology.

6. How should Screening and Validation activities be ordered?

The design experiments and the final case study suggest that there are benefits to dividing Screening into Process Dependent and Process Independent stages. The methodology presented here was flexible enough to allow this, but could guidance be provided? What happens when multiple lifephases are involved? Even without considering DfX, there may still be benefits to applying criteria in the most efficient order, but *how* this order should be determined is an open question.

7. How should the methodology be integrated into an existing Product Development Process?

Finally, there is the practical question of how this methodology would fit into an organisation's existing product development process. As the methodology is based on the structure of decision analysis, rather than a specific algorithm, it is theoretically compatible with any process where alternatives are compared against criteria. It should therefore be compatible with the stage-gate process often adopted in product development (Agouridas and Steenson, 2004). However, Design Experiment 1 showed that following the methodology is not trivial – even under artificially simple laboratory conditions - and that problems can arise if it is not facilitated properly. While this is true of any process, there is the question of how well this would integrate with existing product development practice. Would a facilitator be necessary whenever the methodology was applied, or would design teams be able to manage the process for themselves, with appropriate training? Would structuring software – perhaps a more advanced version of the support software described in Appendix Two – be necessary? Any tool or technique adopted in an organisation requires the support of those who will be using it if it is going to be used correctly. Would designers be willing to take the time and effort to work through the structured process, especially when under pressure to deliver a product to market quickly? The answers to these questions may well vary from organisation to organisation, but they are issues that must be considered when implementing the methodology.

These are all questions that this research has raised, but not answered. Along with the limitations of this study, they provide a guide to the future directions that research on this subject could take.

9.2 Research Value

Engineering – even design – is an applied, not an abstract, discipline. To be of value, research in this area must offer benefits to practitioners, and not just solve interesting hypothetical problems. Demonstrating such value is not trivial and even well-established techniques are open to criticism. This thesis has not introduced a new tool that can be transferred to industry, but has opened the way to develop such a tool. This section highlights the contributions made by this research and the value in pursuing it further, and is divided into two corresponding parts.

9.2.1 Research Contribution

This thesis has demonstrated that decision analysis provides a way of incorporating Design for Manufacture information in a design decision without imposing a preference structure. In doing this, the thesis has:

1) Characterised the relationship between decision analysis and Design for X (see Section 3.2);
2) Embodied this relationship as a general methodology for incorporating Design for X information in design decisions (see Section 3.3); and in a specific methodology for integrated product and process design; (See Section 4.1); and
3) Demonstrated that the latter methodology is feasible for real design decisions, and that the characterised relationship therefore holds in practice (see Chapters 5 to 8).

In answering its overarching research question, this thesis has also made three supplementary contributions. It has:

1) Demonstrated that the current approach for applying decision analysis to concurrent engineering (Game Theory) is unsatisfactory (see Section 2.3.2);
2) Drawn together literature from decision analysis and concurrent engineering to propose a set of desirable characteristics for incorporating DfX information in design decisions; (see Section 2.4); and
3) Demonstrated that the methodology embodying the characterised relationship between decision analysis and DfX can provide the specified characteristics in practice (see Chapters 5 to 8).

Demonstrating the relationship between Design for X and decision analysis has opened a new avenue for research in both decision-based design and concurrent engineering. As well as showing a way of relating DfX tools to one another, this could be developed into a framework for future DfX tools, based on decision analysis principles. Most DfX tools are developed from the bottom up, based on data about the lifephase or virtue they represent. This research suggests that decision analysis could provide a top down approach to developing DfX tools, by providing common underlying principles for the way data about a lifephase or virtue are used. Developing such principles would require further research, but this thesis has provided the first step along this path.

9.2.2 Value of the Contribution

Before moving on to look at the future work required to build on this thesis, it is worth examining what benefits there are in taking this work further. To have value, a design methodology must improve the design process – either by leading to products with a better match between physical and intentional natures, or by reducing the resources needed for product development. To be worth researching, new approaches to design must offer benefits that are not already available from existing approaches. This section discusses the value in developing DfX tools based on decision analysis: what does this offer that decision analysis or DfX cannot when used alone?

The purpose of concurrent engineering is to avoid late changes to a design. This research is only beneficial insofar as combining DfX and decision analysis will do this better than using one of them alone, or an alternative method. By itself decision analysis depends upon having (as far as possible) complete and correct information. DfX guidance – whether provided by a tool or a person – addresses this need, helping to make sure that problems can be identified as soon as possible. Without DfX information, decision analysis cannot ensure that *all* the important virtues and lifephases have been considered or that information about them is not mere supposition by the designers. The strength of decision analysis is its rigour and structure, ensuring that *all* the important issues raised are considered and making judgements explicit for discussion and, if necessary, fruitful disagreement. It provides an overall structure that individual DfX lack, helping to manage information, making it less likely that errors will get through, and relating information to the product's purpose. Without this, there is no guarantee that DfX information will be used correctly; decision analysis encourages rigorous, systematic evaluation. However, without a systematic way of relating DfX to decision analysis, that rigour is lost – there is no guarantee that important DfX information won't be

left out or misrepresented. By providing a coherent way of relating DfX and decision analysis, the value of both can be combined to permit rigorous and systematic evaluation of designs as they are developed. This allows proactive application of DfX, helping designers manage the competing demands of today's complex markets, and catch and correct as many problems as possible at the earliest possible opportunity.

This suggests that there is value in pursuing this research direction. Individually, research on DfX and decision analysis, though necessary, cannot provide the full benefits of using the two together – at least in theory. Whether these hypothesized benefits hold in practice can only be determined by developing this research further.

9.3 Future Work

This section expands upon the findings of this research, and discusses how they can be developed in future research projects. It is divided into two parts. The first part discusses the limitations of the investigation carried out in this thesis: the areas that it does not consider, and remain to be addressed. The second part discusses how future studies can address these limitations and build on the research presented here.

9.3.1 Limitations of the Study

This thesis has taken the first steps in answering the question that initiated this research, but as described in Chapter 1, practical constraints have meant limiting its scope. The limitations of this study must be recognised, as these provide the basis for future work to expand on that presented here. This thesis has shown that this approach to integrating product and process design *can* work, and is therefore worthy of further investigation to see if it provides a full solution to the initial research problem.

This work has three important limitations, related to the three directions of generalisation identified in Chapter 5 (see page 98: Other DfX, Other Decisions, and Other Users) that need to be kept in mind:

1) This thesis has only addressed the use of Design for Manufacture information in design decisions. While this illustrates the general principle, it does not prove that other DfX can be addressed in the same way. It suggests that this *might* be possible, but further validation with other techniques would be necessary.

2) In a similar vein, the methodology has only been tested for embodiment decisions (a stage where layout and shapes issues are being considered, but exact dimensions have not been defined). While this proved that the methodology *can* be applied to embodiment decisions, it does not prove that it will be suitable for other types of decision, or even to all embodiment decisions. Again, further investigation is needed to identify which factors (if any) affect the methodology's applicability to a given decision.

3) The success or failure of any given application of a methodology depends upon the individuals who apply it. The fact that the methodology worked with one group of individuals does not necessarily mean that it will work for every group who apply it. It would take many applications by different groups to prove that the methodology was suitable for most groups. Nor is it as simple as the methodology being inherently good or bad – it may be more applicable to some groups than to others, and this thesis has not investigated which factors (if any) affect its applicability to a given group.

This thesis has shown that circumstances exist under which this method can be applied successfully, but has not shown exactly what the limit of those circumstances are. That is what future work needs to establish.

9.3.2 Directions for Future Research

This thesis has demonstrated the feasibility of using decision analysis to integrate product and process design. However, this is only the first step in the larger task of finding a way to integrate *all* virtues and lifephases in design evaluation.

This means testing the theoretical validity of using decision analysis in this way, and also testing its practical benefits. As a set of principles, a methodology cannot be tested directly – it can only be tested through the methods derived from those principles. However, the methodology gives rise to a whole family of methods, for different DfX, different decisions and different MCDM algorithms, some of which may be more successful than others. Each method must be tested individually, but by establishing which methods derived from the methodology are successful and which (if any) are not, one can begin to identify the methodology's limits. It may be that the methodology is only suitable for a limited range of decisions, or for a limited set of lifephases and virtues. If this range is very limited then the methodology is not worth pursuing – but exactly how broad this range needs to be is difficult to determine. To test the methodology this way, the research design presented in this

thesis must be extended in the three directions identified in Chapter 5 (see page 98: other DfX, other decisions, and other users). Each has its own set of tasks.

Other DfX

There are many possible combinations of DfX, and establishing a comprehensive list of virtues and lifephases would be difficult, and perhaps impossible. Accordingly, research should be carried out to establish a list of virtues and lifephases that are important to industrial practitioners. While not definitive – and possibly subject to change over time – it would provide a focus for the proposed research. Each virtue or lifephase could be tested in turn, through the following tasks:

1) Repeating Chapters 4 to 8 of this thesis for the given virtue or lifephase. This would create a new DfX tool based on decision analysis, and demonstrate the feasibility of the methodology beyond IPPD.
2) If the new tool was shown to be valid, the next step would be to combine it with the existing methodology for IPPD, and test this combination through applications. If successful, the new combined methodology could be combined and tested with subsequent DfX tools developed through Task 1, gradually building up an overall methodology.

If an important virtue or lifephase could *not* be successfully incorporated into the methodology, then this would immediately call the value of this approach into question. While research might continue to develop a tool combining several DfX, for practitioners who were not concerned with the intractable virtue or lifephase, it would mean that decision analysis could not be used to combine *all* virtues and lifephases.

Other Decisions

Whether decision analysis can be used to incorporate all virtues and lifephases is critical to this line of research: whether it can apply to all decisions is not. Nevertheless, from a practical point of view it is important to understand the limits of where this approach can be applied. This means carrying out two tasks:

1) It is necessary to investigate the kind of decisions being taken in product development, and how they can be categorised. This would help to identify *when* different MCDM algorithms were appropriate, but most importantly, it would help to identify different decisions against which the methodologies developed should be validated.

2) The methodology needs to be applied to different identified classes of decision, to see which it is suitable for. This would mean repeating the research design of this thesis for each class of decision: developing specific approaches for each decision (e.g. concept selection, parameter selection) and then applying them.

Of course, this interacts with the range of DfX being used. It may be that different DfX are more, or less, appropriate for certain classes of decision. The most thorough approach would be to test each DfX tool against each decision as soon as it was combined into the methodology (Task 2 under Other DfX, above). The least effort would be to wait until every virtue and lifephase identified as important had been combined, and then test against the range of decision. Which approach is adopted would depend on practicality, a decision that would need to be taken as each new DfX tool was developed: whether it was better to develop more DfX, or test the range of decisions this was appropriate to.

Other Users

The final direction for this research is to test more applications of the derived methodologies to different decisions. Whereas the other two directions test the limits of where the methodology *can* be applied (which DfX, which decisions) this is about determining whether the methodology has demonstrable value. This cannot be done through logic or simulation: it means applying the methodology to actual cases and evaluating its benefits. No version of the methodology should be permitted to this stage without first demonstrating that the given DfX *can* be applied to the given decision. By investigating a given version of the methodology over a range of cases one can evaluate whether it is generally able to satisfy the desiderata, whether there are any problems in its implementation, and whether any important considerations have been omitted from the desiderata. In the absence of repeatable experiments, it is only through repeated successful applications that the methodology can be accepted as beneficial. Such testing can take place as soon as a version of the methodology has

survived Task 1 under Other Decisions (above), repeatedly applying the same methodology to the same class of decision to test its value.

This would only be necessary if the given version of the methodology was being seriously considered for practical use in industry. This would be the final step in demonstrating that a given set of virtues and lifephase *could* be combined for a given class of decision using decision analysis.

9.4 Conclusions

This thesis has shown that decision analysis can provide a way of incorporating Design for Manufacture information in a design decision without imposing a preference structure. It has shown that DfX techniques can be related to the main tools of decision analysis: $DfX_{lifephase}$ techniques to the decision tree; DfX_{virtue} techniques to the MCDM algorithm. This relationship provides a way of linking the support provided by DfX to the purpose of a design, incorporating it into a decision without the need to impose a preference structure. This relationship has been embodied in a methodology, and its feasibility in Design for Manufacture demonstrated through a series of design experiments and two case studies.

Further work could help to guide the ordering of Validation and Screening stages, and identify which MCDM algorithms are appropriate to different classes of decision. To fully determine whether decision analysis can be used to relate multiple DfX, it is necessary to develop and test methodologies for other DfX, Combinations of DfX and other classes of decision. Once any given methodology has been shown to be viable for a given combination of DfX in a given decision, its practical benefits must be demonstrated over repeated case studies. Such a research project would be long term, but this thesis has taken the first step towards determining whether decision analysis can resolve conflicts in a structured and systematic manner.

Appendices

Appendix 1: Arrow's Impossibility Theorem

In his seminal book *Social Choice and Individual Values*[1], Arrow (1973) proposed two axioms for preference relationships, and five conditions for a "Social Welfare Function" necessary for capturing the actual preferences of the group members (Arrow, 1973) as follows:

AXIOM 1: For all x and y, either xRy or yRx. (This is known as connectedness, and implies that there must be some preference relationship – even if it is indifference – between every pair of alternatives).

AXIOM 2: For all x, y, and z, xRy and yRz implies xRz. (This is known as transitivity, and means that preferences cannot be cyclic).

CONDITION 1. ***Unrestricted Domain*** Each individual should be free to order the available alternatives according to their preferences – no preference ordering is automatically disqualified.

CONDITION 2. ***Positive Association of Social and Individual Values***: If one individual gets worse off, and the welfare of all the other individuals in the group remains the same, then the welfare of the group as a whole decreases.

CONDITION 3. ***The Independence of Irrelevant Alternatives:*** The addition of a new alternative should not alter the relative preference over the original alternatives (i.e. if A is preferred to B, then adding a third alternative, C, should not make B preferred to A). This forbids the phenomenon of *rank reversal*, which has already been discussed.

CONDITION 4. ***Citizen's Sovereignty:*** The social welfare function should be based on the preferences of the individuals in the group, and not imposed by some pre-defined code of conduct.

CONDITION 5. ***Non-Dictatorship:*** There should be no member of the group whose preferences automatically dictate the social welfare function, regardless of the preferences of the other group members.

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[1] In his book, Arrow refers to this as his *possibility* theorem, but – confusingly – literature has come to refer to it as his *impossibility* theorem. As the latter terminology is the most common, and the best understood, it has been adopted for this thesis.

The axioms are common sense, and seem reasonable in any decision situation – given any two outcomes, a decision-maker must always prefer one to the other, or be indifferent between them. Equally, cyclic preferences (such as $A \succ B$, $B \succ C$, $C \succ A$), are nonsensical, and cannot be allowed.

Conditions 1, 4, and 5 mean that each individual is free to express their actual preferences, and are not having their preferences enforced on them by some external influence. If these conditions are not satisfied, then there is not really a group decision, as the actual preferences of the group members are not being taken into account.

Condition 2 means that there must be no members of the group that the group as a whole seeks to penalise. This seems reasonable: if no one else gets worse off, then no member of the group can have any reason to object if another member gets better off. In practical situations, individuals may feel slighted if one member's payoff increases, while their own does not. However, this kind of "one-upsmanship" is not a sign of good decision-making: the point of decision analysis is to improve on unaided judgement, not to mimic it.

Condition 3, the Independence of Irrelevant Alternatives, is the most controversial of Arrow's conditions. Nonetheless, while there may be situations in which this "rank reversal" occurs when decision-makers are confronted with new alternatives, it is difficult to think of any situations in which this is actually desirable. Once again, it must be said that the object of decision analysis is to improve on unaided judgement, not to mimic its mistakes.

Thus, these five conditions seem reasonable for group decision-making. However, Arrow's Impossibility Theorem states:

> "If there are at least three alternatives which the members of the society are free to order in any way, then every social welfare function satisfying conditions 2 and 3 and yielding a social ordering satisfying Axioms 1 and 2 must be either imposed, or dictatorial" (Arrow, 1973)

This has serious implications for group decision-making, as it effectively means that groups cannot make a reasonable decision, and this disqualifies any notion of arriving at a group utility function, or somehow aggregating multiple viewpoints within a single MCDM technique. Of course, these conditions were developed for social choices – elections, decisions on how resources should be distributed, etc. – rather than engineering decisions. Scott and Antonsson (1999) argue that AIT does not apply to Engineering Design, as equity between decision-makers is not important and preferences are dictated by a requirements specification. The conditions of unrestricted domain and citizen's sovereignty can therefore be

relaxed, although they do not suggest how a suitable "code of conduct" could be imposed.

However, Franssen (2005) demonstrates that these axioms and conditions apply to *any* attempt to aggregate multiple preferences – even the preferences of a single decision-maker over multiple criteria. Therefore, AIT applies to *any* MCDM algorithm, as much as it applies to any social voting procedure: no algorithm will satisfy all of these desirable conditions. Franssen goes on to point out that:

> "It is important not to be mistaken about what Arrow s theorem tells us with respect to the problem. The theorem does not show that multi-criteria decision-making on the basis of single-criterion preference orders is impossible. What it says is that, for any procedure of a functional form that is used to arrive at a collective or global order, there are specific cases in which it will fail, in the sense of violating at least one of Arrow s five requirements. Accordingly, for any specific procedure applied, one must always be sensitive to the possibility of such failures." (Franssen, 2005)

This supports the argument that decision-making should be *adaptive* (Payne, *et al.* 1993), choosing MCDM algorithms to suit the needs of a given situation, rather than depending on a single "correct" algorithm.

Appendix 2: Software

This appendix describes the supporting software used to gather documentation in the Design Experiments and Case Studies (Chapters 6 to 8). As the software is not an integral part of the methodology, nor intended for anything beyond testing purposes, it has not been described in the body of this thesis. However, for readers interested in how data was stored and documentation obtained, the software is described here. This appendix is divided into two sections: the first defining the reasons for providing software, and the second describing the structure of the software itself.

A2.1 Purpose of the Software

Software is not necessary to implement the methodology, but was introduced to make the methodology easier to apply. It serves two purposes:

1) to reduce the burden on participants, by automating the calculation of costs and utilities, and the construction of elimination and compatibility matrices; and

2) to provide a formal structure for capturing information provided by the participants, so that it could easily be recovered as documentation.

With the software, all that was required of the participants was to provide the judgements used by the methodology. In the Design Experiments, the participants also entered this data into the software: in the Case Studies, it was entered by the researcher. It is important to understand the software was a convenience for testing purposes, and was not intended as an "official" implementation of the methodology. As such, it is not reasonable to draw conclusions about the methodology or its implementation based on the software. Future work may develop more user-friendly software, which would go to greater lengths in enforcing and facilitating the methodology: for the research described here, only a simple application was necessary.

A2.2 Structure of the Software

The software was not a single program, but a Microsoft Access Database, for data entry, and a set of five Microsoft Excel spreadsheets: PI Screening, Validation, PD Screening, Cost Calculator and Score Calculator. The database is used throughout the methodology, whereas each Spreadsheet is specific to one particular

activity. Table 43 shows where in the methodology data is entered into the spreadsheets and into the fields of the database. More specific descriptions of the database and spreadsheets are given below.

Table 43: Database tables and spreadsheets populated at each stage of the methodology

STAGE	ACTIVITY	Database Tables Populated		Spreadsheets Populated
		Table	Fields	
Preparatory Stages		Candidates	Candidate Description	
		Requirements	Description	
Preliminaries	Classify requirements as process dependent or process independent.	Requirements	Process Dependent?	
	Prioritise Requirements	Requirements	Mandatory?	
	Identify manufacturing processes to be considered.	Available Processes	Process	
Framing	Establish criteria. (including Classification)	Criteria	Description Requirement Mandatory? Weight Scoring Function Maximum Minimum Target Process Dependent? Measure of Effectiveness MOE Type Success	
PI Screening	Eliminate candidates not satisfying mandatory PI criteria.	Candidates	Satisfactory?	PI Screening
Validation	Identify component features	Parts	Name Candidate Type	
		Features	Name Description Component	
	Identify component properties	Properties	Property Type Description Feature	
	Identify Basic violations			Validation
	Identify feasible process chains for each candidate.	Process Chains	Component Process Chain Primary Process	
		Parts	Feasible?	
	Select the most likely process chain for each candidate.	Parts	Suggested Primary Process	
		Candidates	Feasible?	
PD Screening	Eliminate candidates not satisfying the mandatory PD criteria.	Candidates	Satisfactory?	PD Screening Cost Calculator
Ranking	Draw a graph of cost vs. utility.	Candidates	Estimated Cost	Cost Calculator Score Calculator

Database

The database was created in Microsoft Access. It uses eight tables, whose fields and structure are shown in Figure 43. The table *criteria* reflects the fact that SMART was used for Ranking, and contains specific information about the measure used for the scoring function (Measure of Effectiveness, MOE Type and Success) and the data used to derive it (Scoring Function (which indicates the type of scoring function used), Minimum, Maximum, Target and Weight). Different data would be needed if other MCDM algorithms – Multi-Attribute Utility or the Analytical Hierarchy Process – were used in place of SMART.

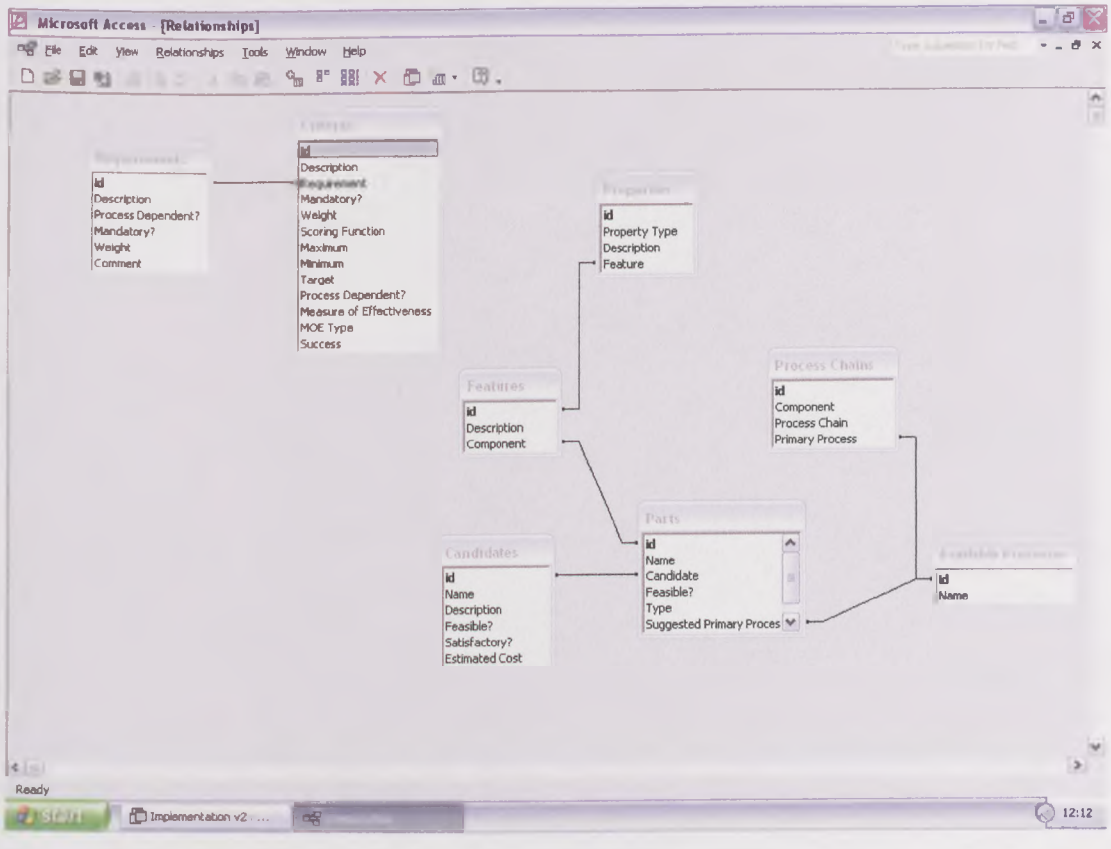


Figure 43: Structure of tables and fields in the Access database

The database provides a structured way of capturing the information generated in the methodology's activities, as shown in Table 43, so that it can be exported to the spreadsheets for analysis. Data was exported from the tables to the spreadsheets using a series of queries, reports and macros. The queries used to draw information from the tables are shown in Figure 44 and Figure 45. Reports based on the given queries (or on the table itself, where no query is shown) were exported to Microsoft Excel format using "output to" macros. This macro translates a report into an Excel spreadsheet, which can then be referenced from the spreadsheets described below.

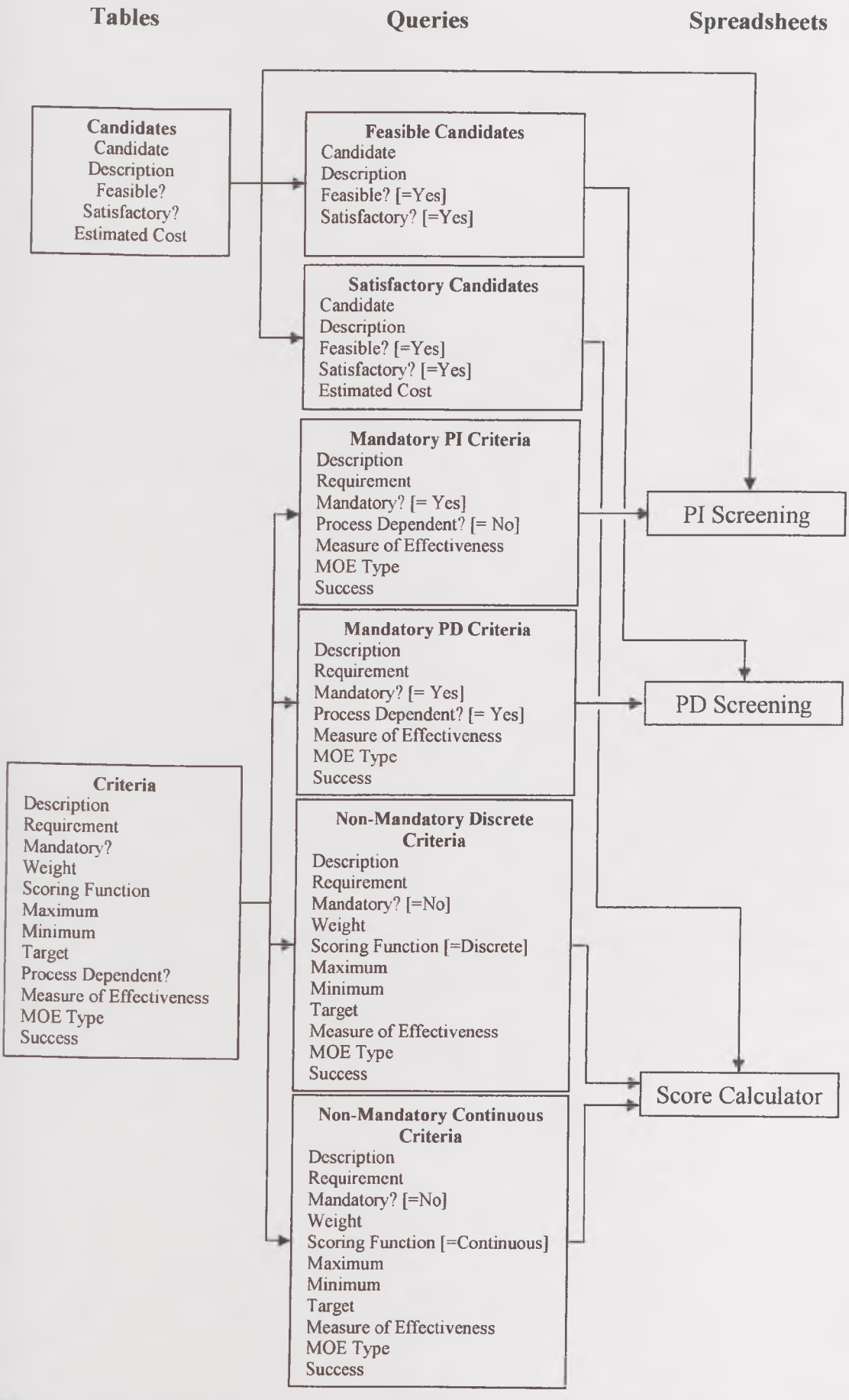


Figure 44: Relationship between the database and the Screening and Scoring spreadsheets

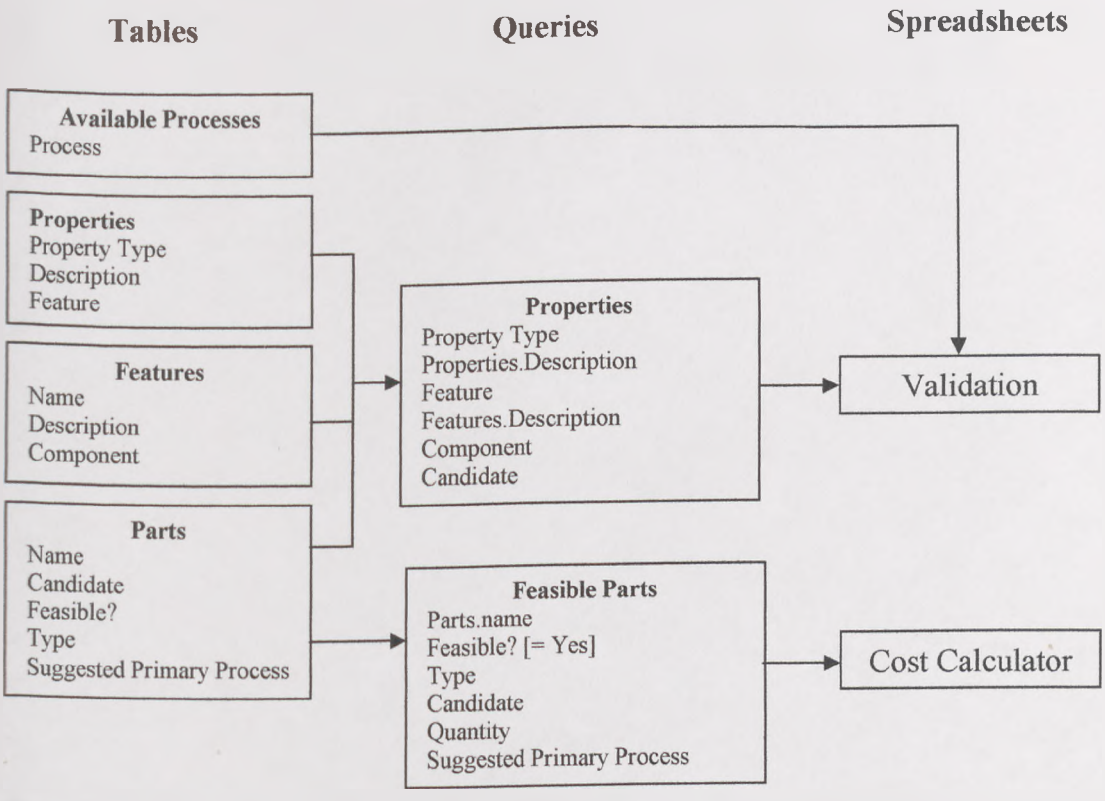


Figure 45: Relationship between the database and the Validation and Cost spreadsheets

Spreadsheets

Where the database provided a way structured of capturing data, the spreadsheets were used for the analytic activities in the methodology. They automatically generate the relevant matrices, based on the information imported from the database (see above), and perform calculations based on additional information provided by the participants.

PI Screening

This spreadsheet constructs an empty elimination matrix, using data on the available candidates and mandatory process independent criteria provided in the database. The participants could then make compare each candidate design against each criterion, and enter the judgement in the appropriate cell. An example elimination matrix in this spreadsheet is shown in Figure 46. The spreadsheet does not automatically work out which candidates are unsatisfactory: that is done by the participants, based on the information they have entered, who can then update the *Candidates* table in the spreadsheet manually in accordance with Table 43.

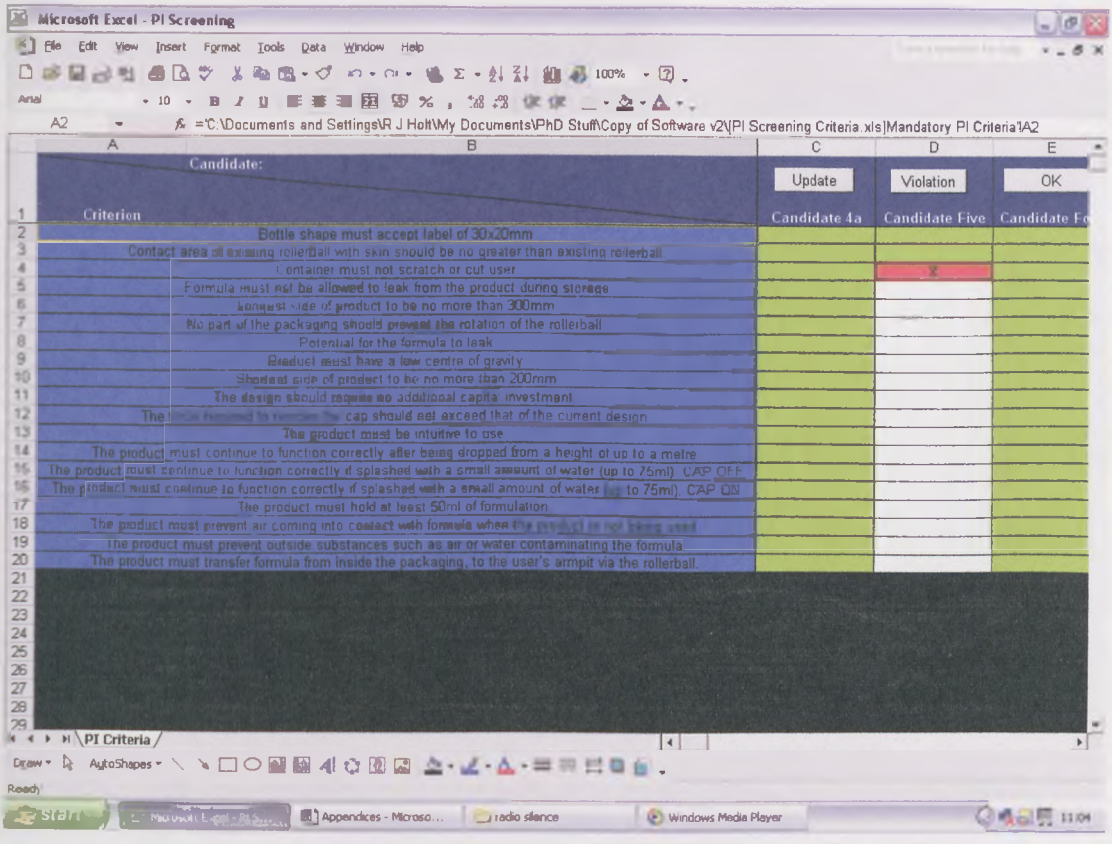


Figure 46: Screenshot of PI Screening spreadsheet

Validation

This matrix constructs a set of compatibility matrices: one for each component of each candidate that has had properties defined. An example is shown in Figure 47: the compatibility matrices follow directly on from one another, with only the candidate and component headings (the two leftmost columns) distinguishing one matrix from the next. As with the compatibility matrix in the previous spreadsheet, participants enter their judgements in the relevant cell, and must determine the feasibility of each component and each candidate for themselves, and enter the results in the Candidate and Parts tables in the database manually.

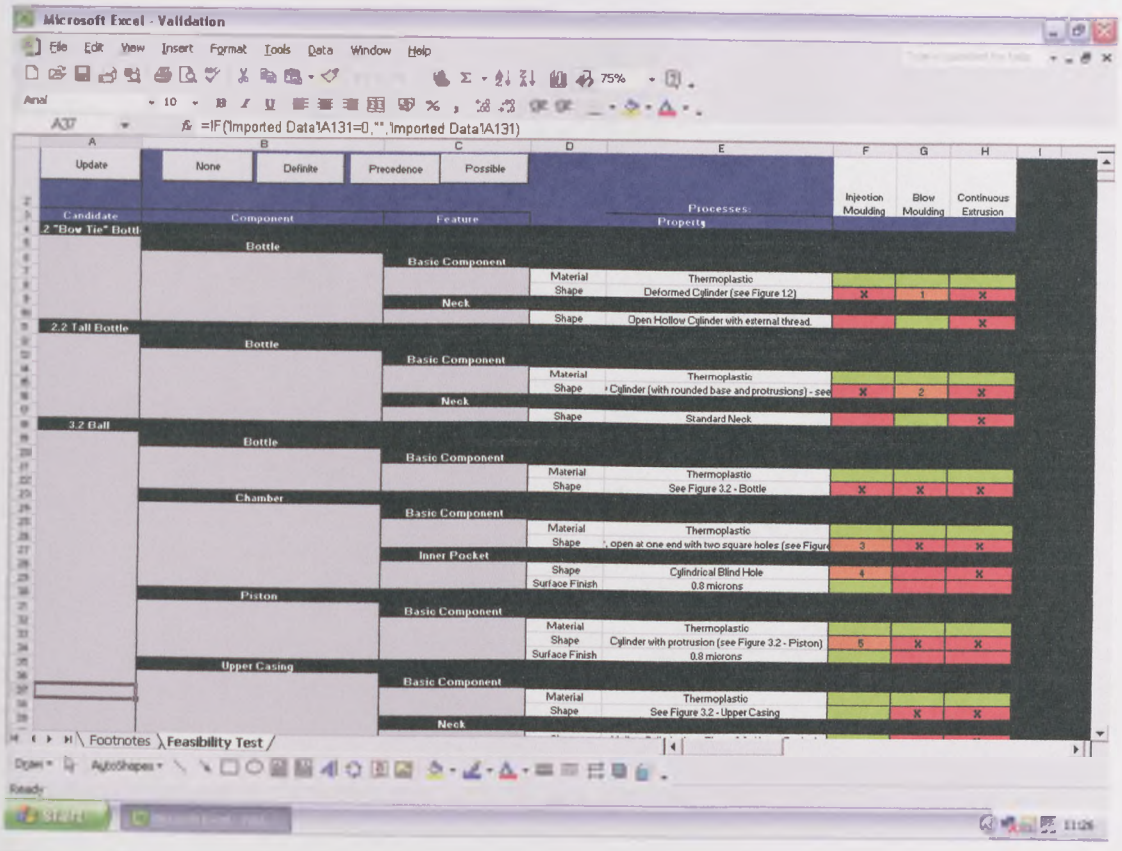


Figure 47: Screenshot of the Validation spreadsheet

PD Screening

This spreadsheet is identical to the PI Screening spreadsheet. It constructs an empty elimination matrix, using data on the available candidates and mandatory process dependent criteria provided in the database. Participants compare each candidate design against each criterion, and enter their judgement in the appropriate cell. An example elimination matrix in this spreadsheet is shown in Figure 48. Like PI Screening, the spreadsheet does not automatically work out which candidates are unsatisfactory: that is done by the participants, based on the information they have entered, who can then update the *Candidates* table in the spreadsheet manually in accordance with Table 43.

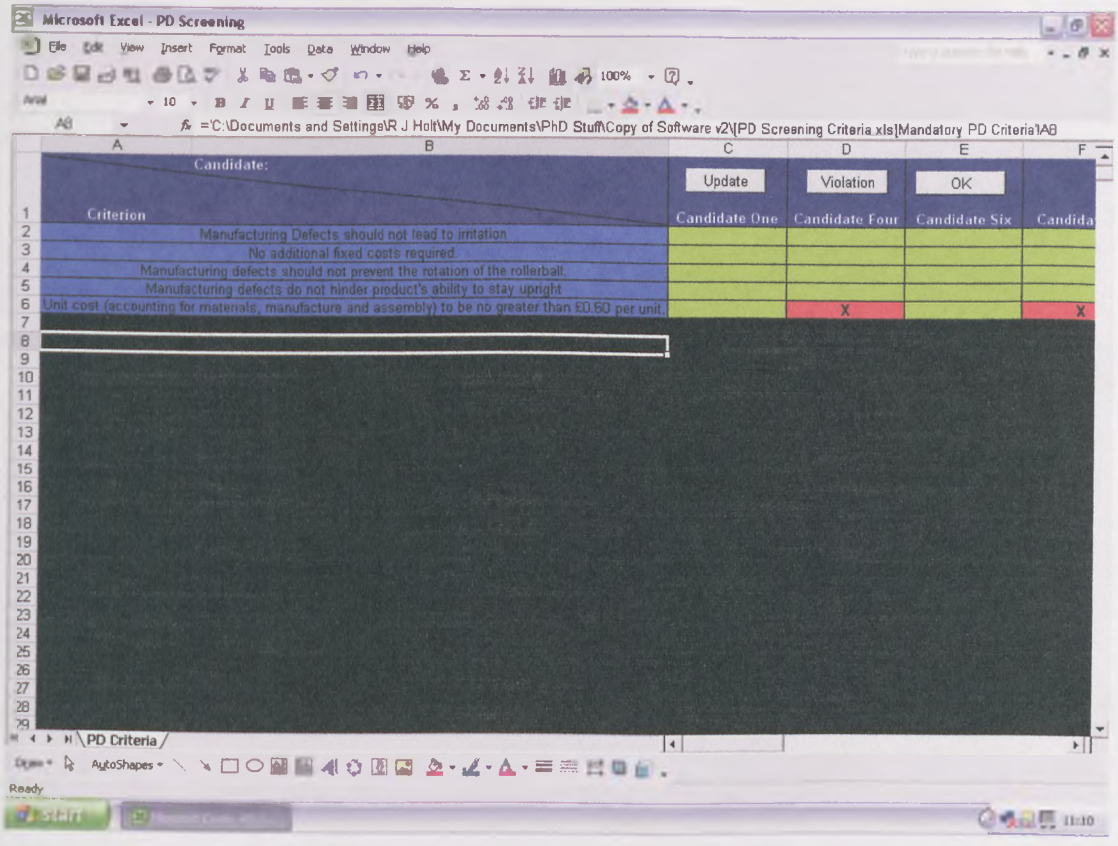


Figure 48: Screenshot of PD Screening spreadsheet

Cost Calculator

This spreadsheet is slightly different from the others, in that it isn't a formal part of the method proposed in Chapter 4. Instead, this is a spreadsheet applying Swift and Booker's (2003) Design Costing Methodology. Information on assemblies, feasible components and their recommended process chains is imported from the database, and the participants enter appropriate coefficients are entered from the Design Costing Methodology manually. The spreadsheet automatically calculates the estimated cost for each assembly and component then aggregates these to calculate the estimated cost for each candidate. Participants can then enter this information into the *Candidates* table manually.

Unlike the other spreadsheets, there is no single point at which this spreadsheet would be used: if there is a mandatory cost constraint, then it may be used prior to Process Dependent Screening, otherwise it will be used at the Ranking stage. It can also be used to compare the costs of different process chains for the same component.

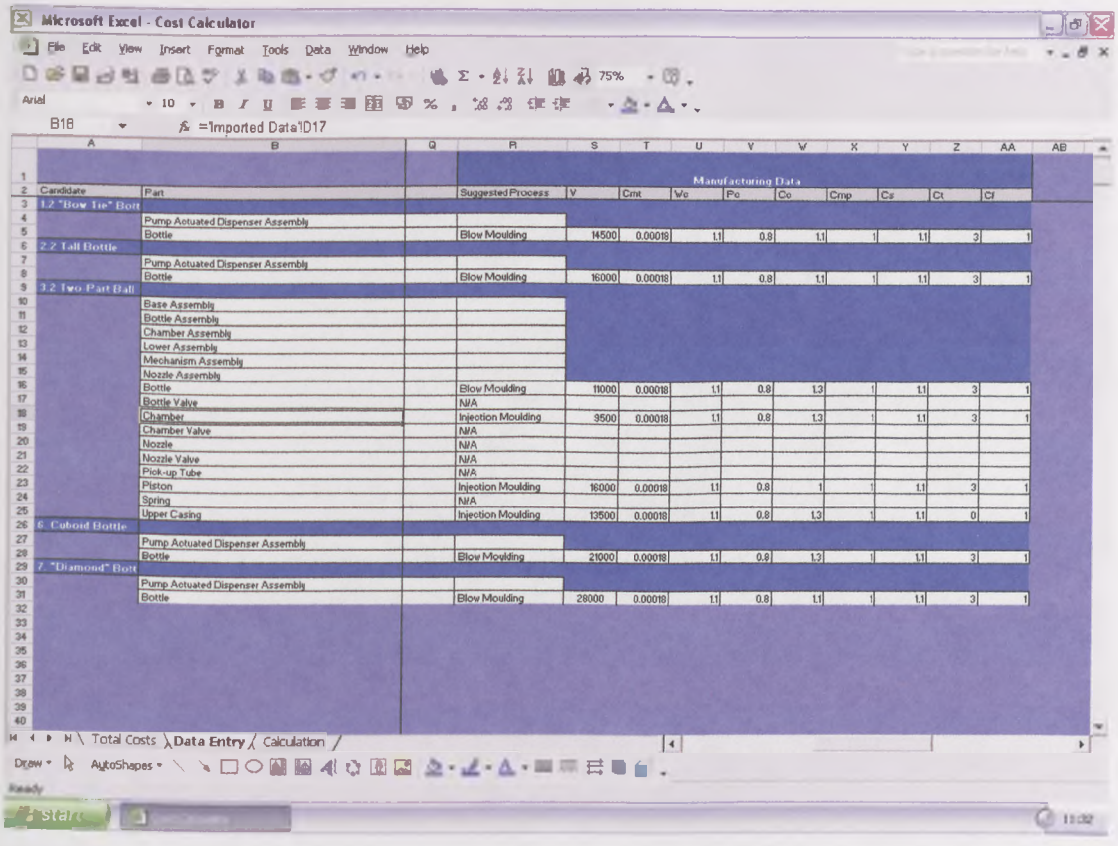


Figure 49: Screenshot of the Cost Calculator spreadsheet

Score Calculator

The final spreadsheet is substantially different from the others. Information on the satisfactory and feasible designs, along with their estimated costs, as well as all the information on non-mandatory criteria and their scoring functions are imported from the database. The criteria are separated across two worksheets – one for *discrete criteria* (where scores are entered directly), and one for *continuous criteria* (where scores are calculated from an attribute value using the scoring function) – and judgements on each are entered separately. The spreadsheet automatically calculates utility from this information, and plots it against cost as a graph, which is the final output of the methodology.

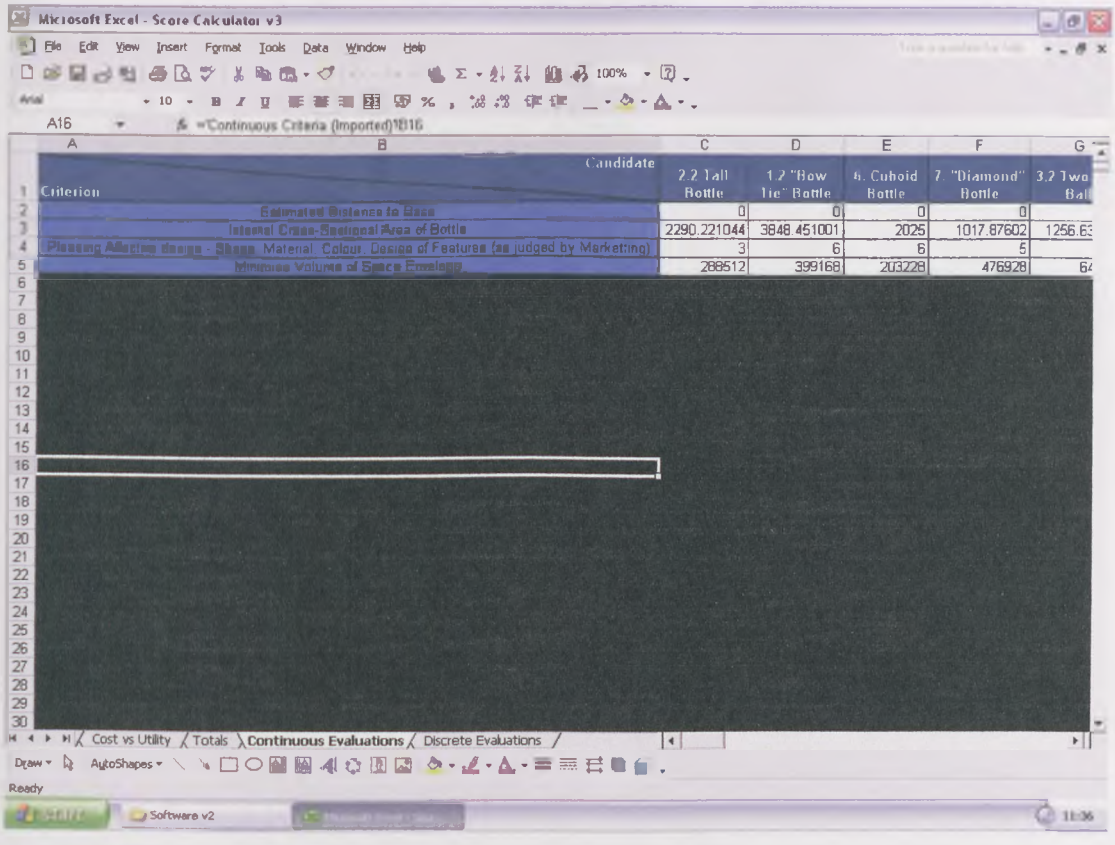


Figure 50: Screenshot of Score Calculator spreadsheet

A2.2.3 Documentation

As well as helping to reduce the burden of calculation on participants, the software was also used to gather formal documentation from each design experiment. Table 44 summarises which sources in the software provide each of the documents gathered. The spreadsheets are able to act as documents in themselves: in the database, the relevant fields are extracted using Reports.

Table 44: Sources of documentation gathered from the software

Document	*Stored As:*	*Source*	*Included Fields*
A list of requirements with priorities and classifications	**Access Report:** Requirements	**Table:** Requirements	Mandatory? Process Dependent? Description
A list of processes under consideration;	**Access Report:** Available Processes	**Table:** Available Processes	Name
A list of criteria with classifications.	**Access Report:** Criteria	**Table:** Criteria	Mandatory? Requirement Process Dependent? Description Measure of Effectiveness MOE Type Success
An elimination matrix comparing the candidates against the mandatory PI criteria.	**Excel Spreadsheet:** "PI Screening"	N/A	N/A
A list of candidates under consideration;	**Access Report:** Properties	**Table:** Parts	Name Type Candidate
A list of the components making up each candidate;			
A list of the features associated with each component;		**Table:** Features	Description Component
A list of the properties associated with each feature;		**Table:** Properties	Property Type Description Feature
A compatibility matrix for each component comparing its properties against the capabilities of the available processes.	**Excel Spreadsheet:** Validation	N/A	N/A
A list of process chains for each component	**Access Report:** Process Chains	**Table:** Process Chains	Component Process Chain Primary Process
A list of the recommended process chain for each component	**Access Report:** Feasible Components	**Query:** Feasible Components on **Table:** Parts	[Feasible? = Yes] [Type = Component] Candidate Name Suggested Primary Process
A list of feasible candidates	**Access Report:** Feasible Candidates	**Query:** Feasible Candidates on **Table:** Candidates	[Feasible? = Yes] Candidate
An elimination matrix comparing the candidates against the mandatory PD criteria.	**Excel Spreadsheet:** PD Screening	N/A	N/A
A graph of cost vs. utility	**Excel Spreadsheet:** Score Calculator	N/A	N/A

Appendix 3: Questionnaire

ACTIVITY	Was this activity completed?	Please use this space to make any additional comments you have about each activities
Classify requirements as process dependent or process independent.	Yes ☐ No ☐	
Prioritise requirements	Yes ☐ No ☐	
Identify manufacturing processes to be considered.	Yes ☐ No ☐	
Establish criteria.	Yes ☐ No ☐	
Eliminate candidates not satisfying the mandatory PI criteria.[1]	Yes ☐ No ☐	
Identify component features	Yes ☐ No ☐	
Identify component properties	Yes ☐ No ☐	
Identify Basic violations	Yes ☐ No ☐	
Identify feasible process chains for each candidate.	Yes ☐ No ☐	
Select the most likely process chain for each candidate.	Yes ☐ No ☐	
Eliminate candidates not satisfying the mandatory PD criteria.[2]	Yes ☐ No ☐	
Draw a graph of cost vs. utility.	Yes ☐ No ☐	

[1] In Experiments 1 and 2, screening had not been divided into Process Independent and Process Dependent stages, so this row was not included in the questionnaire.

[2] In Experiments 1 and 2, screening had not been divided into Process Independent and Process Dependent stages, so this activity read "Eliminate candidates not satisfying the mandatory criteria"

Appendix 4: Design Experiments

A4.1: Design Experiment 1: Disposable Pen

Background

The participants were presented with seven requirements (shown in Table 45), two available manufacturing processes (shown in Table 46), and five candidates. Each candidate was a single component, representing new designs for the barrel of a simple disposable pen, to replace the current design (a simple, hollow, cylinder:

1.Enlarged Barrel: A hollow cylinder, whose barrel has a much wider diameter than the current design, to allow a more comfortable grip.

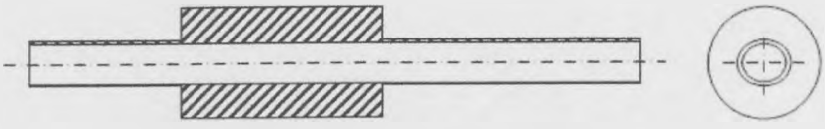
2.Enlarged Grip: Similar to the Enlarged barrel, but only the gripped part of the barrel is enlarged.

3.Moulded Grip: Similar to the enlarged grip, but with indentations moulded in for the user's fingertips.

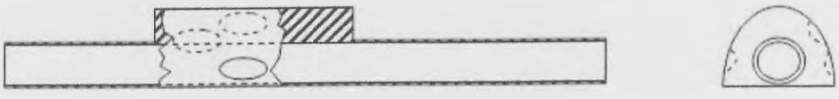
4.Textured Grip: Exactly like the existing design, but with a ribbed surface allowing for better grip.

5.Triangular Barrel: A simple, hollow triangular prism.

Candidate 1: Enlarged Barrel



Candidate 2: Enlarged Grip



Candidate 3: Moulded Grip

Candidate 4: Textured Grip

Candidate 5: Triangular Barrel

Figure 51: Candidate designs for Experiment 1

Documents

Preliminaries

Table 45: Requirements with priority and classifications for Experiment 1

Requirements	M	PD
Fit into a shirt pocket, pencil case, and penholder.		
Fit comfortably into user's hand.		
Keep cap, cartridge and endpiece attached until removed by the user.	✓	
Function identically for both left- and right-hand users.		
Contain ink within body in the event of the cartridge leaking.	✓	
Production rate of 20,000 units per annum.	✓	✓
Cost less than 30 pence per unit	✓	✓

Table 46: Processes available in Experiment 1

Available Processes
Injection Moulding
Continuous Extrusion

Validation

Figure 52 and Figure 53 highlight the contrast between the first and second iterations in Validation. The example given is the moulded grip design, and this was typical of the problems encountered in the first iteration. No features were identified, and properties were included in the software that could not be defined (e.g. Surface finish and tolerance), and the identification of violations is very simplistic. In the second iteration, features and properties were identified in depth, violations were identified correctly and additional feedback was provided.

Feature	Property Type	Description	Available Processes	
			Injection Moulding	Continuous Extrusion
Basic Component	Material	Pp		
	Shape	See figure 2.3.5		X
	Surface Finish	None		
	Dimension	See figure 2.3.5		
	Tolerance	None		

Figure 52: Compatibility matrix for Moulded Grip design in 1st Iteration of Experiment 1

Feature	Property Type	Description	Processes	
			Injection Moulding	Continuous Extrusion
Basic Component	Material	pp		
	Dimension	diameter: see figure 2.3.5 no2		
	Dimension	length: see figure 2.3.5 no1		
Enlarged Barrel	Shape	section of elipse	1	
	Dimension	height: see figure 2.3.5 no5	X	
	Dimension	length: see figure 2.3.5 no4		X
	Dimension	position; see figure 2.3.5 no3		
	Dimension	width: see figure 2.3.5 no6	X	
Indentations	Shape	see figure 2.3.5		X
	Dimension	Depth	2	
Thru-hole	Shape	cylindrical		
	Dimension	diameter: see figure 2.3.5 no7		
	Dimension	length: see figure 2.3.5 no1		

1 = requires fillet on interface with main component.
2 = maximum value of 4mm.

Figure 53: Compatibility matrix for Moulded Grip design in 2nd Iteration of Experiment 1

Table 47 shows the process chains recommended by the participants for each design. In the first iteration, they erroneously passed the enlarged barrel for injection moulding (despite its containing an enclosed hollow that would be impossible to remove the core from) and passed both the enlarged grip and moulded grip for

injection moulding (despite both containing a sudden change in cross section which the PRIMA suggests is unacceptable). On the second iteration, these problems were correctly identified.

Table 47: Feasible candidates and their process chains for Experiment 1

Candidate	Process Chains	
	1st Iteration	2nd Iteration
Enlarged Barrel	Injection Moulding	Infeasible
Enlarged Grip	Injection Moulding	Infeasible
Moulded Grip	Injection Moulding	Infeasible
Textured Grip	Injection Moulding	Injection Moulding
Triangular Barrel	Injection Moulding *or* Continuous Extrusion	Continuous Extrusion

Framing

As no criteria were established in the first iteration, Table 48 summarises only those from the second iteration. Every requirement is accounted for by at least one criterion.

Table 48: Requirements and associated criteria from Experiment 1

Requirement	Criterion	M	PD
Contain ink within body in the event of the cartridge leaking	Thru-Hole End Piece Interface Length to be at least 3mm	✓	
	Thru-Hole Cartridge Interface Length to be at least 3mm	✓	
	Thru-Hole End Piece Interface Diameter must be nominally 5mm	✓	
	Thru-Hole Cartridge Interface Diameter must be nominally 5mm	✓	
Keep cap, cartridge and endpiece attached until removed by the user	Barrel Cap Interface Diameter must be greater than 6mm	✓	
	Barrel Cap Interface Diameter must be less than 8mm	✓	
	Thru-Hole Cartridge Interface Diameter Must be nominally 5mm	✓	
	Thru-Hole End Piece Interface Diameter Must be nominally 5mm	✓	
Less than 30 pence per unit	Estimated cost (using Swift and Booker's Design Costing Methodology) less than 10 pence per unit	✓	✓
Production rate of 20,000 units per annum	Presence of process chain in selection matrix Material and production rates are capable of this requirement	✓	✓
Fit comfortably into user's hand	No sharp areas on outer surface		
	Minimise mass		
Fit into a shirt pocket, pencil case, and penholder	Minimise Diameter of barrel		
	Should have a gap between barrel and clip (shirt pocket)		
Function identically for both left- and right-hand users	Should have Radial symmetry		

Screening

As Screening had not been divided into PI and PD stages at the time of this experiment, all mandatory criteria are covered by the single elimination matrix in Figure 54.

Condition \ Candidates:	Triangular Barrel	Textured Grip
Thru-Hole End Piece Interface Length to be at least 3mm		
Thru-Hole Cartridge Interface Length to be at least 3mm		
Thru-Hole End Piece Interface Diameter must be nominally 5mm	1	
Thru-Hole Cartridge Interface Diameter must be nominally 5mm	1	
Barrel Cap Interface Diameter must be greater than 6mm		
Barrel Cap Interface Diameter must be less than 8mm	2	
Estimated cost (using Swift and Booker's Design Costing Methodology) less than 10 pence per unit		
Presence of process chain in selection matrix Material and production rates are capable of this requirement		

1 = Requires that external diameter is greater than 10mm.
2 = Requires that internal diameter is less than 4mm.

Figure 54: Elimination matrix for Screening in Experiment 1

Ranking

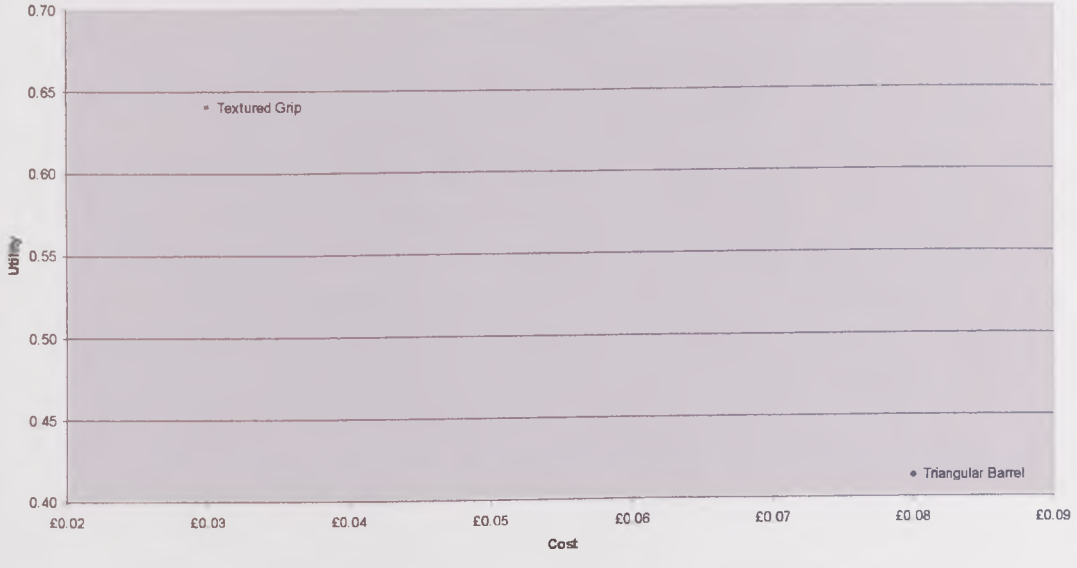


Figure 55: Graph of Cost vs. Utility for Ranking in Experiment 1

Feedback Questionnaire

The feedback questionnaires and comment support the view that there were problems with identifying features, and with establishing criteria in the first iteration, and that these problems were resolved in the second iteration.

Table 49: Results from feedback questionnaires for Experiment 1

	1st Iteration				2nd Iteration			
ACTIVITY	**A**	**B**	**C**	**D**	**A**	**B**	**C**	**D**
Classify requirements as process dependent or process independent.	✓	✓	✓	✓	N/A			
Prioritise requirements	N/A							
Identify manufacturing processes to be considered.								
Establish criteria.	×	×	×	×		✓	✓	✓
Identify component features	✓	×	✓	✓		✓	✓	✓
Identify component properties	✓	×	✓	✓		✓	✓	✓
Identify Basic violations	✓	×	✓	✓		✓	✓	✓
Identify feasible process chains for each candidate.	✓	✓	✓	✓		✓	✓	✓
Select the most likely process chain for each candidate.	✓	✓	✓	✓		✓	✓	✓
Eliminate candidates not satisfying the mandatory criteria.	×	×	×	×		✓	✓	✓
Draw a graph of cost vs. utility.	×	×	×	×		✓	✓	✓

Comments - 1st Iteration

Activity	Comment
Identify Features	C: No clear definition of "features" D: Not completed in its entirety. Some ambiguity over "features" and "properties"
Establish Criteria	A: Unable to distinguish between what was a criteria [sic] and an attribute also how criteria linked to req't. Was it of product, process or both. C: Incomplete examples and description of this process D: Difficulty in defining criteria and hence attributes.

Comments – 2nd Iteration

Activity	Comment
Identifying Features	C: Much better description of features. D: Purpose of identifying features how relate to (1) requirements; (2) properties (process requirements)
Identifying Violations	D: How improvements id'ed by phase, to candidates, are documented or included in matrix.

Observation

Table 50: Data gathered through observation for Experiment 1

Activity	Segments: 1st Iteration	Segments: 2nd Iteration
Classify requirements as process dependent or process independent.	1	0
Prioritise Requirements	0	0
Identify manufacturing processes to be considered.	0	0
Establish criteria. (including Classification)	2	31
Eliminate candidates not satisfying mandatory PI criteria.	0	0
Identify component features	0	5
Identify component properties	5	16
Identify Basic violations	2	24
Identify feasible process chains for each candidate.	2	2
Select the most likely process chain for each candidate.	0	0
Eliminate candidates not satisfying the mandatory PD criteria.	0	2
Draw a graph of cost vs. utility.	0	2

Triangulation

Table 51 summarises the results of the data gathered from documentation, interview and observation for the first and second iterations of Experiment 1.

Table 51: Triangulation for Experiment 1

	1st Iteration				2nd Iteration			
ACTIVITY	**Docs**	**Quest**	**Obs**	**Conc**	**Docs**	**Quest**	**Obs.**	**Conc.**
Classify requirements as process dependent or process independent.	✓	✓	✓	✓	N/A			
Prioritise Requirements	N/A							
Identify manufacturing processes to be considered.								
Establish criteria.	○	○	✓	◉	✓	✓	✓	✓
Identify component features	×	?	○	○	✓	✓	✓	✓
Identify component properties	×	?	✓	×	✓	✓	✓	✓
Identify violations	×	?	✓	×	✓	✓	✓	✓
Identify feasible process chains for each candidate.	×	✓	✓	×	✓	✓	✓	✓
Select the most likely process chain for each candidate.	×	✓	○	○	✓	✓	○	✓
Eliminate candidates not satisfying the mandatory criteria.	○	○	○	○	✓	✓	✓	✓
Draw a graph of cost vs. utility.	○	○	○	○	✓	✓	✓	✓

✓= done; ?=conflicting evidence about it being done; × = done, but incorrect; ○ = not done; ◉= done, but not completed

For the first iteration, all three sources agree that the classification of requirements was completed correctly, and that the final two stages – screening and ranking – were not completed at all. Observation tells us that all other stages (except identifying features and selecting the most likely process chains) were attempted.

Documentation shows that no features beyond the basic component for each candidate were identified, while feedback from the participants shows disagreement on the matter. Participants A and C indicate that this stage was completed, while B indicates that it was not; and D comments that it was "not completed in its entirety". Therefore, it is assumed that the participants did not make a serious attempt to identify features, and the stage was therefore not really attempted.

For the other stages of Validation, documents were present but incorrect, with properties incorrectly defined, and erroneous judgements entered into the compatibility matrix. There is disagreement from the participants about these phases – three argued that the stages were completed; one argued that they were not. The

conclusion has to be that the stages were completed, but not correctly. Although the participants unanimously agreed that they had selected the most likely process chain for each candidate, two process chains had been entered onto the system for the triangular barrel candidate, suggesting that the participants had not actually attempted this stage.

Finally, although observation indicates that the participants attempted to establish criteria, no criteria were entered onto the software, and the participants unanimously argued that the stage was not completed. Therefore, the conclusion is that the stage was attempted, but not completed.

For the second iteration, all three sources agree that every activity was attempted and completed correctly. The only exceptions to this are the Preliminaries, which were not repeated in the second iteration, and Selecting the most likely process chain for each candidate. Documentation and feedback from the participants suggests that the stage was attempted, whereas observation indicates that it was not – in fact, the stage was redundant, as there was only one process chain for each candidate, therefore this was completed by default.

A4.2: Design Experiment 2: Rollerball Deodorant Applicator

Background

The participants were presented with 22 requirements (shown in Table 52, although they eventually revised these to the 36 requirements shown in Table 53), two available manufacturing processes (shown in Table 54), and six candidates. Each candidate was an assembly, comprising of either four or five parts, and was a variant of the existing four-part design they were intended to replace:

Candidate One: Added a single new component to the existing design, to trap fluid near the rollerball, and create a "sump" that prevents the rollerball drying out.

Candidate Two: Stores fluid in the rollerball itself, rather than in the bottle, with holes in the ball allowing the fluid to seep out for application purposes.

Candidate Three: Replaced the removable cap of the existing design with a two-part cap that was attached by hinges to the bottle, so that it did not need to be separated. This also required a new bottle design to fit the hinges.

Candidate Four: Like the first candidate, this introduced a new component, which would provide bristles that could "clean" the ball as it turned, reducing problems caused by crusting. The participants subsequently suggested that this might be produced more cheaply by breaking the new platform down into several simpler components, and this variant was analysed as 4a.

Candidate Five: Like the third candidate, this replaced the cap of the design, but this time had a single cap that slid aside to access the rollerball. This meant a redesign of the bottle to accommodate the sliding cap, and adjust the angle of the bottle's neck.

Candidate Six: This replaced the bottle of the existing design, which stood vertically, with a horizontal version which would lie on its side, again, creating a sump effect to keep the rollerball from drying out.

Table 52: Original requirements for Experiment 2

Requirements	**M?**
The product must transfer formula from inside the packaging, to the user's armpit via the rollerball.	✓
The product must not cause the consumer any discomfort during use.	✓
The product must not require more effort to operate than current rollerballs.	✓
The product must prevent air coming into contact with formula when the product is not being used.	✓
The product must continue to function correctly if splashed with a small amount of water (up to 75ml).	✓
Formula must not be allowed to leak from the product during use or storage.	✓
The product must continue to function correctly dropped from a height of up to a metre.	✓
Formula must not leak from the product if dropped from a height of up to a metre.	✓
The product must prevent outside substances such as air or water contaminating the formula.	✓
The product must be in a stable equilibrium when placed upright on a flat surface.	✓
The product must fit on a supermarket shelf.	✓
The product must hold at least 50ml of formulation.	✓
The packaging of the product shall not prevent the rotation of the roller ball.	✓
The product must be intuitive to use.	✓
It should be possible to share the product hygienically among several users.	
The product should be small enough to fit into a small bag (a maximum space envelope of 110 x 60 x 60mm).	
The product should indicate to the user how much formula remains.	
The roller ball should not attract dust, dirt particles and hair during normal use.	
It should be possible to operate the product with the least possible consumer movements.	
It should be possible to use the product in both the "fingertip" *and* the "full hold" positions	
The product should be as light as possible, with a maximum weight of 150g when full.	
The product should hold the maximum possible volume of formula.	

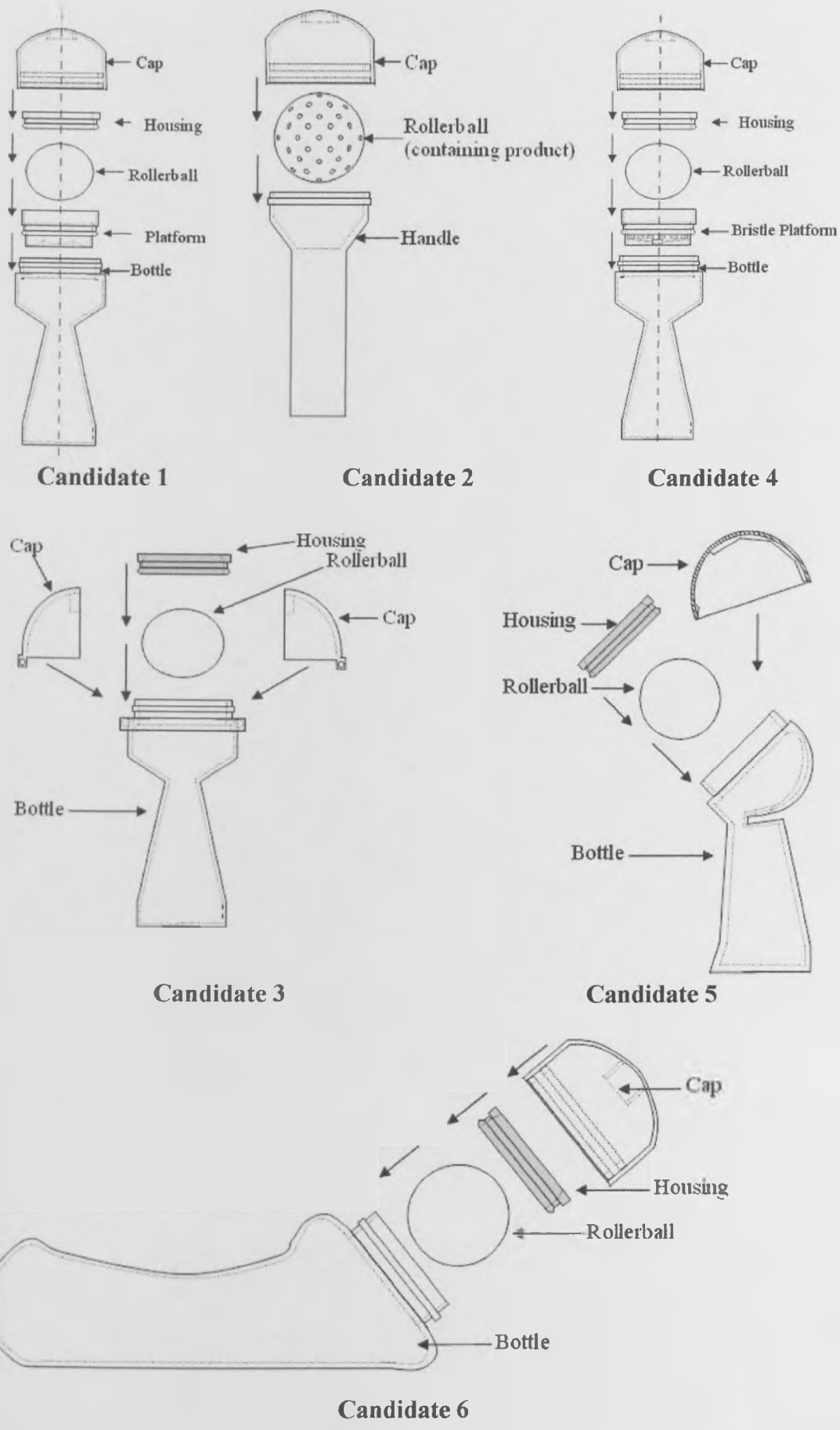


Figure 56: Candidate designs for Experiment 2

Documents

Preliminaries

Upon beginning to establish criteria, the participants decided that they were unhappy with the requirements presented to them, and were allowed to develop their own requirements instead (see Figure 26, page 128, 11:45:00-13:55:00). Therefore, the documentation reflects the requirements that they generated, rather than those given originally.

Table 53: Requirements with priority and classifications for Experiment 2

Requirement	M	PD
The product must transfer formula from inside the packaging, to the user's armpit via the rollerball.	✓	
The product must prevent air coming into contact with formula when the product is not being used.	✓	✓
The product must continue to function correctly if splashed with a small amount of water (up to 75ml).	✓	
Formula must not be allowed to leak from the product during use	✓	
The product must continue to function correctly after being dropped from a height of up to a metre.	✓	
Formula must not leak from the product if dropped from a height of up to a metre.	✓	
The product must prevent outside substances such as air or water contaminating the formula.	✓	
The product must be in a stable equilibrium when placed upright on a flat surface.	✓	✓
The product must hold at least 50ml of formulation.	✓	
The packaging of the product shall not prevent the rotation of the roller ball.	✓	✓
The product must be intuitive to use.	✓	
The product should indicate to the user how much formula remains.		
It should be possible to operate the product with the least possible consumer movements.		
The product should be as light as possible, with a maximum weight of 150g when full.		
Formula must not be allowed to leak from the product during storage	✓	
Bottle shape must accept label of 30x20mm	✓	
Container must not scratch or cut user	✓	
Rate of application must be no greater than existing applicators		
Shape must be modern		
Product must not pluck hairs from user's armpit	✓	
Product must not cause irritation to the user's armpit	✓	
The force required to turn the rollerball should not exceed that of the current design.	✓	
The force required to remove the cap should not exceed that of the current design.	✓	
Total number of movements to open and reseal the packaging should be no greater than current design.		
Longest side of product's space envelope to be no more than 300mm	✓	
Second Longest side of product's space envelope to be no more than 300mm	✓	
Shortest side of product's space envelope to be no more than 200mm	✓	
Longest Side of product's space envelope to be no more than 110mm		

Continues on next page

Table 53 *continued*

Requirement	M	PD
Second longest side of product's space envelope to be no more than 60mm		
Shortest side of product's space envelope to be no more than 60mm		
Product must be possible to use in "fingertip" position.		
Product must be possible to use in "full hold" position		
The design should require no additional fixed costs.	✓	
The design should require no additional capital investment.	✓	
Unit cost (accounting for materials, manufacture and assembly) to be no greater than £0.60 per unit.	✓	
Contact area of existing rollerball with skin should be no greater than existing rollerball.	✓	

Table 54: Processes available in Experiment 2

Available Processes
Injection Moulding
Extrusion Blow Moulding
Injection Blow Moulding

Validation

As with the second iteration of Experiment 1, the participants this time identified full features and properties for each component, and compared them with the PRIMAs provided. Figure 57 (overleaf) shows an example compatibility matrix, from the new component in Candidate One. Components that did not change from the existing design were not validated, as they were already known to be feasible.

Table 55 shows the process chains recommended by the participants for each new component in each design that survived to Validation.

Table 55: Feasible candidates and process chains for Experiment 2

Candidate	Component	Process Chain
1	Cap	Injection Moulding
	Platform	Injection Moulding
4	Bristle Platform	Injection Moulding
	Cap	Injection Moulding
4a	Ball Rest	Injection Moulding
	Bristle Washer	Injection Moulding
	Platform	Injection Moulding
6	Bottle	Injection Blow Moulding

Feature	Property Type	Description	Processes		
			Injection Moulding	Extrusion Blow Moulding	Injection Blow Moulding
Basic Component	Material	HDPE			
	Shape	See fig 8		X	X
	Dimension	Ext Diameter = 31			
	Dimension	Height = A			
	Dimension	Base ext dia = B			
	Tolerance	General tolerance +/- 0.5mm			
Ball Rest	Shape	refer to fig 8		X	X
	Dimension	height of rest = G			
Push Fit Edge	Shape	V-shape around circum			
	Dimension	Diameter of edge = F			
	Tolerance	Diameter of edge +/- 0.2mm		X	X
	Dimension	height to top of push fit setcion = E			
	Dimension	height to bottom of edge = C			
	Dimension	height to top of edge = D			
Push Fit Section	Shape	Cylindrical with push fit on int surface - fig 8			
	Dimension	Int dia = 27			
	Tolerance	on int dia = + push fit tolerance		X	X
	Dimension	ext dia = 31			

Figure 57: Compatibility matrix for Candidate 1, Platform Component

Framing

25 of the requirements were deemed essential and a set of twenty-nine criteria were established to represent these requirements in the decision, shown Table 56.

Table 56: Requirements and associated criteria from Experiment 2

Requirement	Criterion	M	PD
Bottle shape must accept label of 30x20mm	Space for 30x20mm label on bottle	✓	
Contact area of existing rollerball with skin should be no greater than existing rollerball.	Ball diameter <25mm	✓	
Container must not scratch or cut user	Manufacturing defects should not lead to irritation.	✓	✓
	Design should not cause pain during application processes	✓	
Formula must not be allowed to leak from the product during storage	No leakage paths exist	✓	
	No potential for the formula to leak during use.	✓	
It should be possible to operate the product with the least possible consumer movements.	Minimise number of consumer movements needed to use product.		
Longest Side of product's space envelope to be no more than 110mm	Estimated length of longest side of product. <=110mm		
Longest side of product's space envelope to be no more than 300mm	Estimated length of longest side of product. <=300mm	✓	
Rate of application must be no greater than existing applicators	Diameter of ball <25mm		
Second longest side of product's space envelope to be no more than 60mm	Estimated length of Second longest side of product<=60mm		
Shortest side of product's space envelope to be no more than 200mm	Estimated length of shortest side of product<=200mm	✓	
Shortest side of product's space envelope to be no more than 60mm	Estimated length of shortest side of product <=60mm		
The design should require no additional capital investment.	No additional capital investment needed	✓	
The design should require no additional fixed costs.	No additional fixed costs required.	✓	✓
The force required to remove the cap should not exceed that of the current design.	Force not expected to exceed that of current design.	✓	
The packaging of the product shall not prevent the rotation of the roller ball.	Manufacturing defects should not prevent the rotation of the rollerball.	✓	✓
	No part of the packaging should prevent the rotation of the rollerball.	✓	
The product must be in a stable equilibrium when placed upright on a flat surface.	Manufacturing defects do not hinder product's ability to stay upright.	✓	✓
	Product stays upright on level surface	✓	
The product must be intuitive to use.	No complicated user processes	✓	

Continues on next page

Table 56 *continued*

The product must continue to function correctly after being dropped from a height of up to a metre.	Delivers formula to armpit according to all other requirements after being dropped from 1 metre	✓	
The product must continue to function correctly if splashed with a small amount of water (up to 75ml).	Still delivers formula to armpit after being splashed with water	✓	
The product must hold at least 50ml of formulation.	Bottle capable of holding 50ml	✓	
The product must prevent air coming into contact with formula when the product is not being used.	No unsealed airways when product is not in use.	✓	
The product must prevent outside substances such as air or water contaminating the formula.	The product must prevent outside substances such as air or water contaminating the formula.	✓	
The product must transfer formula from inside the packaging, to the user's armpit via the rollerball.	Uses rollerball principle	✓	
Total number of movements to open and reseal the packaging should be no greater than current design.	Number of movements <= 2		
Unit cost (accounting for materials, manufacture and assembly) to be no greater than £0.60 per unit.	Unit costs estimated with Swift and Booker's Design Costing Methodology <= £0.60	✓	✓

Eleven requirements were deemed nonessential, as shown in Table 57. These were deemed nonessential, because it was considered that any of the designs could potentially satisfy them, depending upon subsequent decisions.

Table 57: Nonessential requirements for Experiment 2

Requirement	Justification
Formula must not be allowed to leak from the product during use	None of the designs introduced new leakage paths not found in the original rollerball design. The prospect of leakage after a drop could not be tested at this stage, and the participants did not feel that any one design was more susceptible to leakage after a drop than any other.
Formula must not leak from the product if dropped from a height of up to a metre.	
Product must be possible to use in "fingertip" position.	Any of the designs could be held in either position.
Product must be possible to use in "full hold" position	
Product must not cause irritation to the user's armpit	Issues of irritation and hair-trapping were considered to be inherent to the rollerball concept, which all of the designs worked from.
Product must not pluck hairs from user's armpit	
Second Longest side of product's space envelope to be no more than 300mm	If a design's longest side is less <= 300mm, then by default its second longest side must satisfy this criterion.
Shape must be modern	All the new designs were felt to provide a shape that was at least as modern as the current rollerball.
The force required to turn the rollerball should not exceed that of the current design.	All the designs worked upon the rollerball principle, and without detailed calculation or testing, there was no reason to assume that any of the designs would increase the force needed to use the applicator.
The product should be as light as possible, with a maximum weight of 150g when full.	This depended entirely on detail parameters, which were not available – and could not reasonably be estimated – at the time of the decision.
The product should indicate to the user how much formula remains.	Any of the designs could be made from a translucent or transparent plastic.

Screening

When Experiment 2 began, Screening was still intended to be a single stage, occurring after Validation and Framing. However, after the participants abandoned some of the candidates *before* Validation, by comparing them against the requirements when they first saw them, it was decided that Screening should be split into Process Independent and Process Dependent phases. Therefore, when Screening took place after Validation and Framing, the participants were asked to screen against process independent and process dependent criteria independently. Figure 58 and Figure 59 show the elimination matrices for these screening stages. Notice that, as soon as a candidate was found to violate a mandatory criterion, the participants stopped evaluating it, on the basis that there was no point in spending more effort on a design that would not be used.

Criterion \ Candidate	1	2	3	4	4a	5	6
Bottle shape must accept label of 30x20mm							
Contact area of existing rollerball with skin should be no greater than existing rollerball.		X					
Container must not scratch or cut user			X			X	
Formula must not be allowed to leak from the product during storage							
Longest side of product to be no more than 300mm							
No part of the packaging should prevent the rotation of the rollerball.							
Potential for the formula to leak							
Product must have a low centre of gravity							
Shortest side of product to be no more than 200mm							
The design should require no additional capital investment.							
The force required to remove the cap should not exceed that of the current design.							
The product must be intuitive to use.							
The product must continue to function correctly after being dropped from a height of up to a metre.							
The product must continue to function correctly if splashed with a small amount of water (up to 75ml).							
The product must hold at least 50ml of formulation.							
The product must prevent air coming into contact with formula when the product is not being used.							
The product must prevent outside substances such as air or water contaminating the formula.							
The product must transfer formula from inside the packaging, to the user's armpit via the rollerball.							

Figure 58: Elimination matrix for PI Screening in Experiment 2

Criterion \ Candidate	1	4	4a	6
Manufacturing defects should not lead to irritation.				
No additional fixed costs required.				
Manufacturing defects should not prevent the rotation of the rollerball.				
Manufacturing defects do not hinder product's ability to stay upright.				
Unit cost (accounting for materials, manufacture and assembly) to be no greater than £0.60 per unit.		X	X	

Figure 59: Elimination matrix for PD Screening in Experiment 2

Ranking

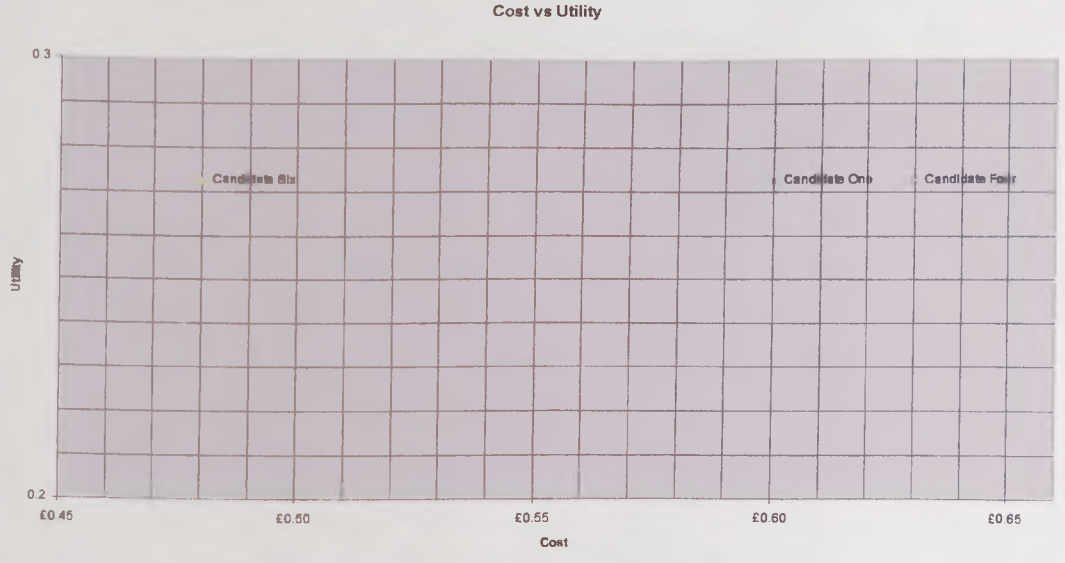


Figure 60: Graph of Cost vs. Utility for Ranking in Experiment 2

Feedback Questionnaire

Table 58 summarises the feedback from the questionnaire administered to the participants. Notice that Candidates A and B were absent from one stage each, and therefore could not provide feedback on that stage. For two activities (Classifying Requirements and Selecting the Most Likely Process Chains), none of the participants provided feedback, leaving that part of the questionnaire blank.

Table 58: Results of feedback questionnaire for Experiment 2

Activity	A	B	C	D
Classify requirements as process dependent or process independent.				
Prioritise requirements	N/A			
Identify manufacturing processes to be considered.				
Establish criteria.		✓	✓	✓
Identify component features	✓	✓	✓	✓
Identify component properties	✓	✓	✓	✓
Identify violations	✓		✓	✓
Identify feasible process chains for each candidate.	✓		✓	✓
Select the most likely process chain for each candidate.				
Eliminate candidates not satisfying the mandatory criteria.	✓	✓	✓	✓
Draw a graph of cost vs. utility.	✓	✓	✓	✓

Stage	Comments
Assigning Basic Properties	A: We went through all six candidates and fitted in features and properties we also identified a candidate 4a Some candidates were immediately discounted without features and properties. We identified candidates and interfaces for cap, mechanism and bottle with a single common interface to all candidates but 3x3x3 possible candidates based on module candidates.
Checking Basic Violations	A: Filled in violations (possible & definite)
Plotting cost vs. Utility	D: So easy it was done for me.

Observation

Table 59: Data gathered through observation in Experiment 2

Activity	Segments
Classify requirements as process dependent or process independent.	0
Prioritise requirements	0
Identify manufacturing processes to be considered.	0
Establish criteria. (including Classification)	54
Eliminate candidates not satisfying mandatory PI criteria.	5
Identify component features	9
Identify component properties	23
Identify Basic violations	13
Identify feasible process chains for each candidate.	1
Select the most likely process chain for each candidate.	0
Eliminate candidates not satisfying the mandatory PD criteria.	2
Draw a graph of cost vs. utility.	1

Triangulation

Table 60 summarises the results of the data gathered for Experiment 2, for ease of comparison. For most stages, all three sources agree that stage was completed correctly. The only exceptions to this are the classification of requirements and selecting the likely process chains. In both instances, none of the participants filled in the appropriate section of the questionnaire – not even to say that these stages *hadn't* been completed – and no evidence of them is found in the observation. However, documentation is correct in both cases, suggesting the activities must have been carried out. In the case of classifying requirements, this occurred as the new requirements were generated, and therefore occupies too small a space in each case to show up on the protocol analysis. It may also explain the confusion of the participants when filling out the questionnaire. Similarly, there was only one feasible process chain for each candidate, and therefore selecting the most likely process chain was done by default. Therefore, neither stage indicates a problem with applying the methodology.

It is worth noting that the documents for Validation are only correct if one accepts that the participants were correct to eliminate three candidates prior to Validation. As these three candidates were eliminated during the subsequent PI screening, this suggests that their early elimination was acceptable, and if the methodology had been applied exactly as described in Chapter 4, then the same designs would have been eliminated prior to Validation. Therefore, the documents may be treated as correct, given this caveat.

Table 60: Triangulation for Experiment 2

ACTIVITY	Docs	Quest.	Obs.	Conc.
Classify requirements as process dependent or process independent.	✓	?	○	✓
Prioritise requirements	N/A			
Identify manufacturing processes to be considered.				
Establish criteria	✓	✓	✓	✓
Eliminate candidates not satisfying the mandatory PI criteria.	✓	✓	✓[1]	✓
Identify component features	✓	✓	✓	✓
Identify component properties	✓	✓	✓	✓
Identify violations	✓	✓	✓	✓
Identify feasible process chains for each candidate.	✓	✓	✓	✓
Select the most likely process chain for each candidate.	✓	?	×	✓
Eliminate candidates not satisfying the mandatory PD criteria	✓	✓	✓[4]	✓
Draw a graph of cost vs. utility.	✓	✓	✓	✓

✓= done; ?=conflicting evidence about it being done; × = done, but incorrect; ○ = not done ◘= done, but not completed

A4.3: Design Experiment 3: Shaving Gel Applicator

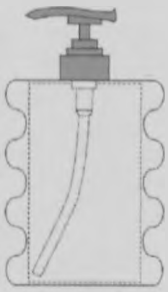
Background

The participants were presented with a scenario (the design of a pump-actuated shaving gel dispenser for low-foam shaving gel), a set of five candidate designs, and a set of five available processes (Blow Moulding, Continuous Extrusion, Injection Moulding, Thermoplastic welding and Vacuum Forming). This time, the participants developed the requirements themselves, and these are summarised in Table 61. The candidates were presented with five initial designs, based on an existing pump-actuated dispenser mechanism:

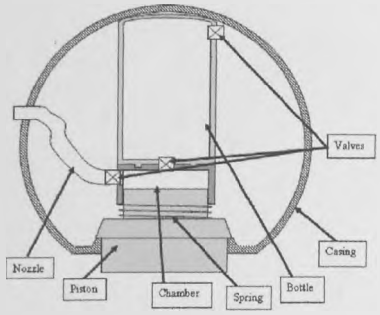
Candidate 1: This was a straightforward bottle design, which used an existing pump actuated dispenser for handwash. The bottle featured ribbed sides, which did not allow for a label to be applied, so the participants revised the design to have a smooth surface, but with a narrow "waist" to allow an easy grip. This was candidate 1v2.

---

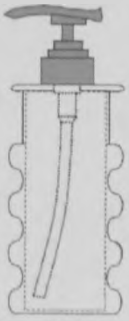
[1] As the separation of Screening into PI and PD stages was only introduced during this case (in response to the participants' comments during Validation), it was not reflected in the questionnaires supplied to them However, the feedback questionnaires indicated that screening was completed, suggesting that the participants felt that they had screened using all the relevant criteria.



Candidate 1

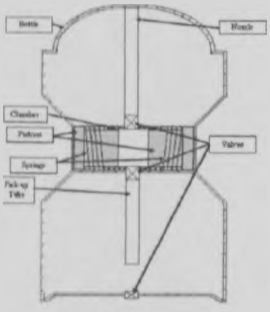


Candidate 1v2

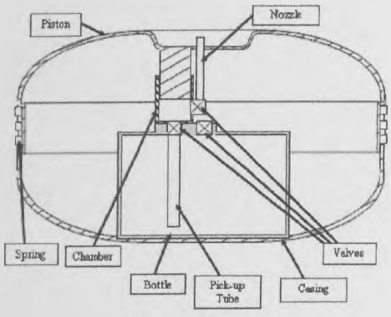


Candidate 2

Candidate 3

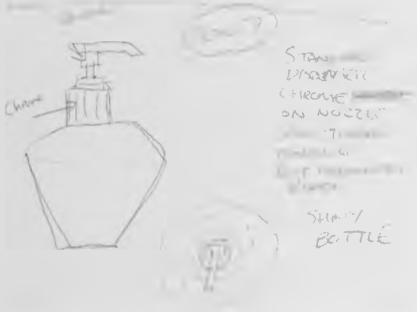


Candidate 4



Candidate 5

Candidate 6



Candidate 7

Candidate 8

Candidate 9

Figure 61: Candidate designs for Experiment 3

Candidate 2: This was similar to Candidate One, but only part of its surface was ribbed, meaning that it already had space for a label.

Candidate 3: This was the most complex of the designs, being a globe with a flattened base. Pressing down on the globe would dispense fluid: however, this required an entirely new dispensing mechanism, and could not use any existing components. The participants observed that this design contained a lot of redundant space, and would need to be prohibitively large to include the required shaving gel, the new dispenser mechanism *and* retain its spherical shape. They therefore suggested an alternative version that retained the globular shape, but used the existing mechanism, activated by a button on top of the dispenser, allowing a very similar external appearance, but in a much smaller space. This was Candidate 3v2.

Candidate 4: This was a tall bottle, with an internal pump mechanism that was activated by squeezing the bottle at its midpoint. Like Candidate 3, this required a new dispenser mechanism, but was much more compact.

Candidate 5: In external appearance, this was the most unusual of the initial designs, being a flattened ellipse, with a casing divided into upper and lower parts. The upper casing had a dish at its centre, and pressing the upper casing down would dispense gel into the dish, which could then be scooped out by hand. This also required a new dispensing mechanism, which was extremely complicated.

The participants also suggested a number of designs of their own:

Candidates Six and **Seven** were further variants of Candidate One, being new bottles for the existing dispenser with distinctive cubic and rhomboid shapes, respectively.

Candidate Eight: Was a more complex design, that required an alteration to the existing mechanism, by including a lever that could be used to activate the dispensing mechanism with the back of the hand, minimising the chance of leaving gel on and around the dispenser.

Candidate Nine: Candidate Nine required an entirely new dispensing mechanism, and featured a bottle, surrounded by a transparent outer casing. By pushing the outer casing down, the mechanism was activated, and fluid drawn from the base of the bottle, through a tube wrapped around the bottle, and out through a nozzle at the top, so that the flow of the gel would be visible.

Documents

Preliminaries

Table 61 shows the requirements generated by the design team, as well as their priority and classification. The participants incorrectly deemed several requirements process dependent because they depended on how the product would be transported from manufacturer to retailer. Such requirements are not affected by the way the product is manufactured, but the designers wanted to consult with the manufacturing team when deciding whether the requirement was satisfied.

Table 61: Requirements with priority and classifications for Experiment 3

Requirement	M	PD
The mechanism must provide sufficient force to deliver 5ml of gel hygenically through the nozzle with every actuation	✓	
Bottle must hold a target of 175ml of gel (31 shaves + 10%)	✓	
The product must be able to be stable and freestanding on a level surface	✓	✓
Final product must not be vulnerable to damage while in batch transit	✓	✓
The mechanism must be able to recover 95% of the volume of product stored in the bottle	✓	
Product must fit on a supermarket shelf	✓	
Final product must not be vulnerable to damage while in transit from supermarket to home	✓	
Dispenser must be suitable for a production rate of 50,000 units per week using current facilities.	✓	✓
Dispenser must cost no more than 30p per unit (considering manufacture, assembly and materials).	✓	✓
Minimise volume of non-recoverable product.		
It should be possible to operate final product using one hand, left or right.		
Label must not detach when wet.		
Product must withstand a humid bathroom environment.	✓	
Minimise volume required for storing and transporting a single batch of the final product for benefit of the product manufacturer		✓
The final product must not leak during regular use		
The product and characteristics of the product must stand out on the supermarket shelf to encourage purchase		
User to be able to view quantity of product remaining in dispenser.		
The mechanism must provide sufficient pressure to draw 5ml (+10%) of gel from the bottle with every actuation	✓	
There must be room for a single 40mm x 40mm label for legislative purposes.	✓	
There must be room for a single label for branding purposes (40mm x 60mm) in a viewable position while freestanding.	✓	
The final product must be no taller than 150mm.	✓	
The final product must be no shorter than 80mm.	✓	
The final product must be able to fit conveniently in a bathroom cabinet/shelf/side of sink	✓	

Table 62 shows that the participants only considered three of the five processes during Validation. The manufacturing team decided that vacuum forming and thermoplastic welding were not suitable for the production volumes required, and were therefore not worth considering.

Table 62: Processes available in Experiment 3

Available Processes
Injection Moulding
Blow Moulding
Continuous Extrusion

Validation

Figure 62 shows a sample compatibility matrix from Experiment 3. As with Experiment 2, the participants have included features, and have reflected information from the PRIMAs in the matrix.

Feature	Property Type	Description	Processes		
			Injection Moulding	Blow Moulding	Continuous Extrusion
Basic Component	Material	Thermoplastic			
	Shape	Hollow Cylinder, open at one end with two square holes (see Figure 3.2 - Chamber)	1	X	X
Inner Pocket	Shape	Cylindrical Blind Hole	2		X
	Surface Finish	0.8 microns			

1=Needs Draft Angle of 0.25 degrees to 4 degrees
2 = Inside Corner radii of 1.5mm required

Figure 62: Sample compatibility matrix for Candidate 3v2, Chamber component.

Table 63: Feasible candidates and process chains for Experiment 3

Candidate	Component	Process Chain
1v2	Bottle	Blow Moulding
2	Bottle	Blow Moulding
3v2	Bottle	Blow Moulding
	Chamber	Injection Moulding
	Piston	Injection Moulding
	Upper Casing	Injection Moulding
6	Bottle	Blow Moulding
7	Bottle	Blow Moulding

Framing

Table 64: Requirements and associated criteria from Experiment 2

Requirement	Criterion	M	PD
The mechanism must provide sufficient force to deliver 5ml of gel hygenically through the nozzle with every actuation	Force required for activation should be within a comfortable press by a single finger for all age groups [agreement from third party]	✓	
	Volume of Chamber>5ml (+10%)	✓	
	Is the delivery mechanism hygenic?	✓	
Bottle must hold a target of 175ml of gel (31 shaves + 10%)	Bottle Volume>175ml	✓	
The product must be able to be stable and freestanding on a level surface	Critical Tip Angle>Z	✓	
	Non-convex, non-slip base.	✓	✓
Final product must not be vulnerable to damage while in batch transit	No features susceptible to compression or appendage damage in transit.	✓	✓
	Bottle not susceptible to normal impact damage.	✓	✓
	Mechanism not susceptible to normal impact damage.	✓	✓
The mechanism must be able to recover 95% of the volume of product stored in the bottle	There should be nothing inherent in the design that prevents delivery system accessing 95% of the volume of product stored in the bottle.	✓	
Product must fit on a supermarket shelf	Fits Space Envelope of Supermarket Shelf (supplied by 3rd Party)	✓	
Final product must not be vulnerable to damage while in transit from supermarket to home	No features susceptible to compression or appendage damage in transit from supermarket to home	✓	
	Bottle not susceptible to normal impact damage in transit from supermarket to home	✓	
	Mechanism not susceptible to normal impact damage in transit from supermarket to home	✓	
	Mechanism must not be susceptible to accidental activation in transit from supermarket to home	✓	
Dispenser must be suitable for a production rate of 50,000 units per week using current facilities.	Agreement from Manufacturing Engineers	✓	✓
Dispenser must cost no more than 30p per unit (considering manufacture, assembly and materials).	Cost Estimated via Swift and Booker's Design Costing Methodology < 30p	✓	✓
Minimise volume of non-recoverable product.	Minimise estimated Distance to Base		
	Minimise internal Cross-Sectional Area of Bottle		
	Internal Shape Should not Prevent Product Gathering in one place - by the delivery system.		
It should be possible to operate final product using one hand, left or right.	Operable using one hand.		
	Suitable for both left and right-hand operation.		
Label must not detach when wet.	Suitable bonding surface for all labelling surfaces		
Product must withstand a humid bathroom environment.	Prevent water contacting gel while in storage.		
	Water resistant material selection.		

Continues on next page

Table 64 *continued*

Minimise volume required for storing and transporting a single batch of the final product for benefit of the product manufacturer	Agreement from Manufacturing Engineers		
The final product must not leak during regular use	Fit between mechanism and bottle to prevent leakage		
The product and characteristics of the product must stand out on the supermarket shelf to encourage purchase	Pleasing Affective design - Shape, Material, Colour, Design of Features [as judged by Marketing]		
User to be able to view quantity of product remaining in dispenser.	Can view quanitity of product in dispenser.		
The mechanism must provide sufficient pressure to draw 5ml (+10%) of gel from the bottle with every actuation	(Spring Stiffness * Travel of Spring) - Piston Resistance>Y [Where Y is force required to draw piston out]	✓	
	Chamber and Piston Materials and tolerances must allow pressure difference. [Acceptance of Piston and Chamber Design from 3rd Party]	✓	
	Return actuation of the mechanism must draw fluid from the bottle	✓	
There must be room for a single 40mm x 40mm label for legislative purposes.	Single legislative label	✓	
	Size Envelope fits 40mm x 40mm	✓	
There must be room for a single label for branding purposes (40mm x 60mm) in a viewable position while freestanding.	Single branding label	✓	
	Size Envelope fits 40mm x 60mm	✓	
	Branding Label is visible when final product is freestanding.	✓	
The final product must be no taller than 150mm.	Height of final product in bathroom<150mm	✓	
The final product must be no shorter than 80mm.	Height of final product in bathroom>80mm	✓	
The final product must be able to fit conveniently in a bathroom cabinet/shelf/side of sink	Fit within Volume Envelope 150mm (high) x 80mm x 80mm	✓	

PI Screening

Criterion \ Candidate	1	1 v2	2	3	3 v2	4	5	6	7	8	9
Is the delivery mechanism hygenic?							X				
Volume of Chamber>5ml (+10%)											
Force required for activation should be within a comfortable press by a single finger for all age groups											
(Spring Stiffness * Travel of Spring) - Piston Resistance>Y											
Chamber and Piston Materials and tolerances must allow pressure difference.											
Return actuation of the mechanism must draw fluid from the bottle											
Single legislative label	X										
Size Envelope fits 40mm x 40mm			1		2						
Single branding label											
Size Envelope fits 40mm x 60mm			3		2						
Branding Label is visible when final product is freestanding.											
Height of final product in bathroom<150mm				X	2						
Height of final product in bathroom>80mm					2						
Fit within Volume Envelope 150mm (high) x 80mm x 80mm					2						
Bottle Volume>175ml					2						
Critical Tip Angle>Z											
There should be nothing inherent in the design that prevents delivery system accessing 95% of the volume of product stored in the bottle.						X					
Fits Space Envelope of Supermarket Shelf (supplied by 3rd Party)											
No features susceptible to compression or appendage damage in transit from supermarket to home											
Bottle not susceptible to normal impact damage in transit from supermarket to home											
Mechanism not susceptible to normal impact damage in transit from supermarket to home										X	
Mechanism must not be susceptible to accidental activation in transit from supermarket to home											

1 = Provided height of label area is greater than 40mm
2 = Subject to size of sphere
3 = Provided height of label area is greater than 60mm

Figure 63: Elimination matrix for PI Screening in Experiment 3

PD Screening

Candidate Criterion	1v2	2	3v2	6	7
Non-convex, non-slip base.					
No features susceptible to compression or appendage damage in transit.					
Bottle not susceptible to normal impact damage.					
Mechanism not susceptible to normal impact damage.					
Dispenser must be suitable for a production rate of 50,000 units per week using current facilities.					1
Cost Estimated via Swift and Booker's Design Costing Methodology < 30p					X

1 = subject to sufficient injection moulding capacity being available for all parts

Figure 64: *Elimination matrix for PD Screening in Experiment 3*

Ranking

Figure 65: Graph of Cost vs. Utility for Ranking in Experiment 3

Feedback Questionnaire

Table 65: Results of feedback questionnaire for Experiment 3

ACTIVITY	D1	D2	M1	M2
Classify requirements as process dependent or process independent.	✓	✓	✓	✓
Prioritise Requirements	✓	✓		
Identify manufacturing processes to be considered.			✓	✓
Establish criteria.	✓	✓		
Classify criteria as PI or PD.	✓	✓		
Eliminate candidates not satisfying mandatory PI criteria.	✓	✓		
Identify component features			✓	✓
Identify component properties			✓	✓
Identify Basic violations			✓	✓
Identify violations due to precedence			✓	✓
Identify feasible process chains for each candidate.			✓	✓
Select the most likely process chain for each candidate.			✓	✓
Eliminate infeasible candidates.			✓	✓
Eliminate candidates not satisfying the mandatory PD criteria.	✓	✓	✓	✓
Draw a graph of cost vs. utility.	✓	✓	✓	✓

Observation

Table 66: Data gathered through observation in Experiment 3

Activity	Segments
Classify requirements as process dependent or process independent.	1
Prioritise Requirements as mandatory or optional.	3
Identify manufacturing processes to be considered.	4
Establish criteria. (including Classification)	42
Eliminate candidates not satisfying mandatory PI criteria.	14
Identify component features	9
Identify component properties	13
Identify Basic violations	6
Identify feasible process chains for each candidate.	2
Select the most likely process chain for each candidate.	0
Eliminate candidates not satisfying the mandatory PD criteria.	3
Draw a graph of cost vs. utility.	5

Triangulation

Table 67 summarises the data gathered from Experiment 3. In this case, triangulation is straightforward, as all three sources agree on every stage, with the exception of selecting the most likely process chain for each candidate. This stage does not show up in observation, but – given that there was only one feasible process chain for each candidate – it was completed by default, and does not indicate an error in applying the methodology.

Table 67: Triangulation for Experiment 3

ACTIVITY	Docs	Quest.	Obs.	Conc
Classify requirements as process dependent or process independent.	✓	✓	✓	✓
Prioritise requirements	✓	✓	✓	✓
Identify manufacturing processes to be considered.	✓	✓	✓	✓
Establish criteria.	✓	✓	✓	✓
Eliminate candidates not satisfying the mandatory PI criteria.	✓	✓	✓	✓
Identify component features	✓	✓	✓	✓
Identify component properties	✓	✓	✓	✓
Identify violations	✓	✓	✓	✓
Identify feasible process chains for each candidate.	✓	✓	✓	✓
Select the most likely process chain for each candidate.	✓	✓	×	✓
Eliminate candidates not satisfying the mandatory PI criteria.	✓	✓	✓	✓
Draw a graph of cost vs. utility.	✓	✓	✓	✓

✓= done; ?=conflicting evidence about it being done; × = done, but incorrect; ○ = not done ⊙= done, but not completed

Appendix 5: Transcripts

This appendix contains transcripts of excerpts from the audio recordings from the design experiments, which are cited in support of the conclusions in Chapter 6. They are presented here in the order that they referenced from Chapter 6, which is not necessarily the same as the chronological order in which they occurred on the recordings. Participants are each referred to by the same letter, A through D for Experiments 1 and 2, and as D1, D2, M1 and M2 in Experiment 3 to distinguish the design team from the manufacturing team. The researcher is denoted obs (for observer) in the first iteration of experiment 1, and as Fac (for facilitator) thereafter.

A5.1 Experiment 1 Transcripts

Transcript One: 1st Iteration, 01:55:03 – 01:55:48

Line	Speaker	Statement
1	C	We're going to go through injection moulding for the enlarged barrel. Now the enlarged barrel is OK for injection moulding.
2	D	Well, do you want to put "y", "y" everywhere, to implement your suggestion?
3	B	No, I think I better stick with the software.
4	D	Is that how it's specified?
5	B	Yeah.
6	A	Remember which, which order to do the properties in.
7	C	Okay. Material, Shape, Surface – We we don't need to to bother. Injection moulding will do that easily, won't it? We know that.
8	D	Well, injection moulding will do all the materials.
9	A	We can't just say that. We need to fill it in.
10	C	Okay. Material, Shape, Surface Finish, Dimension and Tolerance. It'll do all that.
11	A	Let's do it for the top one. Triangular Barrel.
12	C	We've already done it for the top one
13	A	Have we?
14	D	Mmm.
15	B	Ah! You see, that's the problem. (*laughs*)
16	A	Oh, right.
17	C	Right. For the Enlarged Barrel…
18	D	He's had it vindicated, he said that.
19	A	I don't even need to leave the room and, er…
		[*Laughter*]
20	C	For the Enlarged Barrel, Injection Moulding will do the lot- the Enlarged Barrel.
21	A	Yes.

Transcript Two: 1st Iteration: 01:61:15-01:62:45

Line	Speaker	Statement
1	C	What's a PRIMA?
2	B	[Laughs]
3	Obs	Process Information Maps, contained in "Process Selection from Design to Manufacture.
4	A	This.
5	Obs	This book here.
6	C	I would state that, you know, in part of the… even though you've referenced it as brackets three
7	D	It did say right at the beginning though, when you've said um…
8	C	Sorry?
9	D	Right at the beginning.
10	C	But how does that relate to PRIMA, though? I don't know.
11	A	It forms it forms another interesting question which is is your handbook targeted for academics to read it or is it targeted for people to understand it?
12	Obs	Interesting point.
13	A	'Cause there's probably… there's an awful lot of information in there… and you know… maybe more diagrams… more steps.
		[Silence, 6 seconds]
14	C	So why why are we doing this?
15	B	Yeah, where does it go into the software?
16	C	Are we are we basically going back through what we've already done and just deciding that it's validated?
17	Obs	Well, basically, this is the point where you should now be looking at your compatibility matrix and deciding where to put Xs in based on the information contained in these PRIMAs.
18	C	Ah!
		[Laughter]
19	A	We didn't know that. We didn't know that.
20	C	Right, right. Well carry on, carry on, we've already done that. One thing that you do need to consider that as designers you will, some people – namely me – will just fly through it slapdash and try and circumvent any…
21	B	Hang on, I think that's everybody, isn't it?
22	A	I think you're right it's case of we've tried to run before we can walk. But we didn't know, because we didn't read ahead because we didn't know that we had to read ahead.

Transcript Three: 1st Iteration, 02:43:39-02:45:43

Line	Speaker	Statement
1	B	I think we need some more explanation between the difference between these two.
2	A	Yeah.
3	Ob	Right.
4	A	That's…that's something I'm thinking at the moment is that I mean I'm feeling as though I'm in a situation I can't answer.
5	B	Because you don't know the definitions.
6	A	Because of I don't know how… I could write things in boxes but I don't know if they're right or not.
7	C	That's very true. Because we have no guidance… we don't really know…we're just just shooting...
8	A	Yeah. There's no…
9	D	In the dark.
10	A	To be honest, there's examples in here…
11	C	Yeah. Shooting in the dark.
12	A	the thing is it's not just the text you need you need to know what a criteria is
13	D	Yeah.

Continues on next page

Transcript Three *continued*

Line	Speaker	Statement
14	C	We're trying to make an informed decision based on those three lines within the the within the thing and that isn't really aimed at being an example is it?
15	Ob	No, no. Exactly.
16	C	Just demonstrating...
17	Ob	It's just illustrating what the form looks like.
18	A	You need instance data, and you need supporting information as well.
19	Ob	Well, in that case why don't I suggest that we just skip this stage and move onto the next one...
20	C	Which is...
21	B	Really?
22	Ob	...and attempt that.
23	B	Ok. sure.
24	C	I think that's a good idea.
25	A	Still on this subject erm up until now before we got to this bit what I've been feeling although all we've been doing is just entering data.
26	B	Mmm.
27	A	I feel I've done a little bit about process selection but in a way that's something that can be done in many ways off-line, like a decision making process...
28	B	Hmm.
29	A	...whereas now I feel we're in a decision-making process and I just don't know what that process is.
		[Silence 5 seconds]
30	B	I think what you mean...
31	A	I don't know what I'm supposed to be deciding. I mean I know we're supposed to be deciding on erm candidate designs...
32	B	Hmm.
33	A	Or are we supposed to be...
34	D	On what you mean, on what what how how we how we're supposed to judge this decision is that what you're saying? It's not really clear.
35	A	Yeah, I mean this is sort of, this is erm
36	C	Flogging a dead horse comes to mind.
37	A	What, me?
38	C	No, with regards to – yeah.
		[laughter]
40	D	His ears pricked up at "dead horse". He's a dead horse.
41	C	Yes, you my laddy!
42	A	Well, some people said I'm dead, but er...
43	C	No but regards to this we we're just shooting in the dark....we're clutching at straws... we're.
44	B	No but this is this is what the intention is, isn't it, really, is to find out where it needs strengthening...
45	Obs	Well, I'll say yes, that's the whole point.
46	B	And I think this is possibly the the the point

A5.2 Experiment 2 Transcripts

Transcript One: 09:37:59-09:38:20

Line	Speaker	Statement
1	A	Inputting into the decision making process is equally important as the needs and the requirements is the design of that process. Because if, for example, as I said before, because we've not internalised the requirements and we've not... we... we've commented that these requirements are not .. have not had their meanings developed to a sufficient state where we can use them.

Transcript Two: 09:48:55-09:49:22

Line	Speaker	Statement
1	Fac	What you're actually doing is abstracting from those definite measures at the end, not specifying from vague requirements, which is what I've given you here. I'm a fool! Sorry.
2	A	No you're not. You need to go through the process to learn the thing.
3	Fac	Well, that's the exact point of doing it really, isn't it?
4	A	That's a point that we've not really considered which is what would we have done if we hadn't had a set of requirements? We'd have assessed the candidates on merit, rather than against a set of requirements that we have openly ridiculed.

Transcript Three: 10:16:35-10:17:26

Line	Speaker	Statement
1	Fac	I think the issue that we've identified is that I've made a mistake about what framing is, and the requirements that we've got are not fit for purpose... effectively, they're not fit for our purpose because if we accept framing as being an abstracting back from concrete measures of effectiveness to more abstract measure of effectiveness more appropriate for an incomplete candidate, we don't have the concrete measure of effectiveness here. So there's one of two things-
2	C	We don't have the concrete measures of effectiveness?
3	Fac	No, we don't. They just didn't define them.
4	C	No we don't. No. You're absolutely right.
5	Fac	So there are two things we can do either we can sit down and try to define them. Or I can sit down and try to define them, and then we can try to abstract from them.
6	A	Why don't we say that we sit down and try to define them, but if it's a facilitated process, why don't you say "you've got ten minutes to do them?" so we don't sit there for three hours doing it?

Transcript Four: 3:30:09-3:31:01

Line	Speaker	Statement
1	Fac	Framing is trying to establish things you can measure about the candidates so that you can compare them against each other, so you couldn't frame for just one candidate.
2	A	So may- maybe the approach is to do framing before you do your candidate features.
3	Fac	In fact originally, when I first laid out the methodology, it went preliminaries, framing, validation, evaluation, and there's no- in fact, what I've got in some diagrams for my paper it's actually framing and validation sit right next to each other.
4	B	Right. Yeah.
5	Fac	You could overlap them, because they can be done independently.
6	A	So what are we doing here?
7	Fac	Uh, you're doing the Validation stage.
8	A	We're doing Validation. I mean, maybe framing makes- it probably depends entirely on what type of thing you were doing or- or- you know on this sort of code what sort of stage you're at because we're at a stage where we probably need to frame the requirements before we need to go to the candidates.

Transcript Five: 3:51:55-3:52:55

Line	Speaker	Statement
1	A	In summary: I think the things we mentioned are: one, the suggestion that about having a warm up decision in the start of the process. Two, for erm... in this case for us we feel as though looking at Framing before the Validation might have been more applicable. Three, the candidates that we've got here, we're making decisions on their viability without necessarily interpreting the requirements or fully relating to the requirements. Four was a sort of more general point, about that you don't just need the methodology, you need the method to go with it, and that method is not generic. They're sort of the four things that I lifted out.

Transcript Six: 08:39:27-08:39:58

Line	Speaker	Statement
1	Fac	So basically what we'll do is we'll look at each requirement in turn, and try to work out some suitable criteria for representing that requirement in the analysis.
2	C	Okay.
3	A	Isn't this not something we could do at the start?
4	Fac	Well, this was something we discussed actually that perhaps it would have been better to do framing before we started looking at the candidates. That way, we would have been through the-
5	A	Yeah, 'cause we were rejecting designs based on instinct rather than... then finding we had to go back to the requirements to find out why we rejected it or to justify our instinct.

Transcript Seven: 06:40:02-06:42:55

Line	Speaker	Statement
1	A	In the same process we- the same method we went through of doing this for manufacturability, we looked at other things as well. It might not be in the same co-ordinated fashion, but you can get a report out, you know, sorted by-
2	B	That's not a bad idea.
3	Fac	So what you're saying is that you're making sure that that information doesn't just disappear.
4	B	Yeah, that was my concern.
5	A	No, not just disappear, but it's also that we're using information other than manufacturability to make this decision, based on the- certainly based on the requirements... and erm... that needs to be used in this demonstrator because this demonstrator, it's not just using manufacturability, no matter what you say, or no matter what people say-
6	Fac	No.
7	A	-because it is using all the requirements
8	B	They're not directly linked.
9	A	Well, no, but it's, cause, you're right, in that if it's like a closed system, you're running like a real pilot thing, you just look at these things, but because actors are involved...
10	Fac	The thing is this chunk here...
11	A	Yeah.
12	Fac	...deals with manufacturability. It doesn't consider, "Do they work according to the requirements?" it doesn't consider anything else. This on here doesn't consider "Can they be made?", it just considers how well they perform against these criteria that we've discussed based on the requirements.
13	A	Yeah.
14	Fac	So my argument is that what you do here is screen out the ones that can't be made then you run them through this process here.
15	A	Can I describe the problem we're in?

Continued on next page

Transcript Seven *continued*

Line	Speaker	Statement
16	Fac	Uh-huh.
17	A	We're doing design. We've been trying to fit the work that we've been doing today, in design, into this methodology, which I think is wrong. Not the methodology – we're trying to pigeon hole what we've done into this.
18	Fac	Yeah.
19	A	And maybe, in hindsight, we need to think about what we've done and how the two are related, not to fit one to the other.
20	B	I don't know what you mean.
21	A	We've done- we've been doing- Today, we've been looking at work on design. We've got requirements in front of us, we've got candidates, we've been looking at candidates.
22	B	Yes.
23	A	We've been looking at whether or not they meet requirements.
24	B	Yes.
25	A	We've been talking about possible modifications to designs. We've been talking about "can it be made?", erm, you know, "how- how's it going to be held?"
26	Fac	Yeah. The point is you've been going through identifying properties and features-
27	A	We have, we have. Correct. Correct. But I personally believe we've not been following a set process, we've been doing design. We've been doing an iterative thing. We've been doing it relatively ad hoc-
28	B	But isn't- One of the- Okay. One of the ways I saw this methodology perhaps evolving was the fact that it, as you say, it's not a methodology it doesn't require you to do things in order.
29	A	Yeah. Yeah, and I might be wrong, but I feel as though-
30	B	It's a facilitator not a prescribor
31	A	I've not felt facilitated by this methodology today.
32	B	I think we have. How come we've just-
33	A	We've been recording information in a demonstrator which is a part of the methodology, but we've also been recording information which isn't part of that methodology
34	B	That's true.

Transcript Eight: 09:52:14-09:53:05

Line	Speaker	Statement
1	A	To be fair, going through this process, we've not really gone through the requirements at all, because there was no need to
2	C	Until we reach framing.
3	A	Yeah, I mean I know when we were going through the designs, we did, but we were making decisions based on those requirements because we were seeing a design which was blatantly crap. Something which had a centrifugal force of, you know, a 35,000 rpm motor to get the force to get the deodorant out of the ball, but... is that... I mean, there's no need for us to look at those requirements. Only because our instincts said that "this design is wrong" that we did that. If we'd followed the process we wouldn't have looked at requirements until now... It's a different approach. It would have been a more time-consuming process, because we'd have had to go through every single possible component.
4	Fac	I see what you mean, because perhaps really the evaluation stage should be- you should perhaps screen for function before you validate, in the sense that if it doesn't do what you want it to do, then why are you- why are you worried about whether or not it can be made.
5	D	Interesting.

Continues on next page

Transcript Eight *Continued*

Line	Speaker	Statement
6	Fac	On the other hand, my original argument was that if it can't be made, why worry about whether or not it can do what you want it to do? But given the amount of effort involved in Validation, perhaps it is better to do it the other way around. It may be something that's...
7	A	Why do you need to do them as distinct separate sections, why can't they overlap?
8	Fac	Oh, they could. I mean, I-I-I think actually that perhaps it may be context dependent, if you've got complicated shape, and only a few requirements, it's going to be a lot easier to screen for function first. If you've got a lot of requirements and a very simple shape, it might be simpler to do validation first.
9	A	Again, it brings us to that you're designing the design process
10	C	And by making it flexible, you allow people to sort of be, use the things that are intuitively the best things first, don't you? Even though your process detail...
11	A	If you're doing a facilitated process, I mean, if it was us making the decision, we would not necessarily have decided- we'd have probably gone through it in the way we were told to go through it. If it's a facilitated process, you can say "Right, this is what we're gonna do", and we'll do it, but you need the experience to be able to say "Right, this is what we're gonna do to modify it", because of this reason. As you said, the shape, or the or something like that. That makes a lot more sense, doing the screening earlier on.
12	Fac	Yeah.
13	A	Do you need properties before you do the screening?
14	Fac	No, you don't.

Transcript Nine: 10:03:19-10:03:54

Line	Speaker	Statement
1	A	From the process we talked about before, about doing the screening early on. If we do like the requirements then the- we could do the candidates in the screening, we'd understand what we were supposed to be doing... we'd filter out the candidates which were blatantly not right, based on some real information about the requirements.
2	Fac	Yeah.
3	A	I mean, we'd be screening at the same time, or just after it, to say "right, this is what does meet the functional requirements, this is what doesn't". Then we'd go into the validate where we're actually looking at the process and we can evaluate. And that to me, is so logical.

A5.3 Experiment 3 Transcripts

Transcript One: 09:42:08-09:42:57

Line	Speaker	Statement
1	M1	You know in terms of things like like like the base we probably don't even have to have features for that base. Do we?
2	M2	I don't know.
3	M1	We probably don't. I don't think we do.
4	M2	You see, this is the thing: we don't know what-
5	M1	But, you know, we've got some knowledge based on last time's trial run of manufacturability of thermoplastics, okay? So, we know thermoplastics are not going to have a problem with a base like that, don't we? We know it's not going to make any difference, so to an extent, why are we putting it in as a feature? There's no reason, is there? So I think what we should do is discount those bases purely from the perspective that because we produce shedloads of these and you know, you see it every day, don't you?
6	M2	Yeah.
7	M1	We won't worry about it at the moment – let's not go through and delete it – but we'll bear that in mind.

Transcript Two: 09:46:40-09:49:27

Line	Speaker	Statement
1	M1	If a designer knows what he's doing, you don't prescribe to a designer, so if the designer knows that it won't be a problem, in terms of surface finish, what's the point in going through it in a rigorous fashion? Do you know what I mean? You know, if you know... if you use thermoplastics and we're talking about a plant that uses thermoplastics all the time, you're not going to go through to the nth detail thinking ooohh, does that, is that going to... if they know. This is obviously a unique design, so I suppose we could look at the tolerances there, but in terms of things like necks and things like that when you come to tolerances on necks, as long as they – as long as the neck is the right size, it's not going to break or snap or anything, in terms of like the tolerances, well, they know, they're thermoplastic machines, they're fitting these things onto them all the time. Why start looking at the tolerances?
2	M2	But then then we get to the point where we're saying there are no features.
3	M1	No, you don't, you just break it down to the essential features, the features that are absolutely essential.
4	M2	Down to shape.
5	M1	Down to things that are... you know... things like... you know... there is a legitimate... you know if a designer has designed this, we need to explore it, just to make sure he hasn't put in anything that that'll throw us. Things like, you know, dimensions, you know, that make sure the size-
6	M2	But then you're contradicting what you just said earlier, which is if you're stuffing this stuff into the machine all the time, you know what the-
7	M1	Yeah, but there's a difference between- I don't know what that tolerance is.
8	M2	Right.
9	M1	Right? So so I'm going to have to make sure that that I find out what that is. But if I know what the dimension is, I don't have to know a tolerance because I know that my machine will handle it. Do you know what I mean? In terms of what the designer gives me, I need to make sure that the designer's given me the right dimensions for my machine to handle it. But in terms of, if if, you know, I could, I could start to say "Well, that tolerance has got to plus or minus whatever", but I know the machines can handle it, so I don't have to... you know, the thermoplastic machines we use at the moment do whatever hundreds... I mean, this is just for fifty thousand, so we can assume the capacity of the plant must be two-hundred-odd thousand, a week.
10	M2	Okay, let's let's um, okay. Um
11	M1	We don't have to worry about this now, because all we're doing at the moment is just highlighting features, when we start to break these down into, you know, into the actual attributes of those features, like, material, shape, surface finish, dimensions and tolerances, we can then please ourselves
12	M2	Ah, sorry. Sorry. That's what you're trying to say, then. You're trying to say that you're not selecting whether it's a feature based on whether it has some criteria about it – shape, surface finish, tolerance, whatever - that make it different, you're just saying "Let's go with it, if it looks like it's different".
13	M1	Yeah. Yeah, absolutely.
14	Fac	I suppose you could argue that this is kind of a rough cut feature identification, when you start looking at properties, you can-
15	M1	Yeah, definitely, things that are going to stand out and potentially caused issues for the manufacturing cycle. That's all that we're-
16	M2	I know. I understand. Let's go with that.

Transcript Three: 10:46:45-10:47-31

Line	Speaker	Statement
1	M2	Yes, we can injection mould that [reads from PRIMA]. It says surface finish: "excellent surface detail obtainable"..."surface roughness a function of die condition"
2	M1	So it can do all these. Is there anything about like, the edges, you know the um, angles that we need to put in?
3	M2	Um... [Reads from PRIMA] "draft angles"... which one is the draft angle?
4	Fac	Draft angle is where you give it a slight incline,
5	M1	I'm on about the edges, because these edges are square.
6	M2	[Reads from PRIMA] "Minimum"...ooohh... "radii should be as generous as possible... minimum inside radii 1.5mm but it doesn't say anything about outside".

Transcript Four: 10:14:46-10:15:27

Line	Speaker	Statement
1	M1	Is there anything on here that's going to cause us question marks in terms of blow moulding?
2	Fac	Well, why not have a look at what it says about blow moulding and size constraints on it?
3	M2	[Reading from PRIMA] Uh... transfer moulding... rotational moulding.. blow moulding. Economic considerations...Design aspects...complexity limited to hollow parts with a low degree of asymmetry...um...
4	M1	Does it give like angles or anything? Cause this angle is very shallow. Although it's hardly...
5	M2	Corner radii must be as generous as possible (>3mm)
6	Fac	That's a lot more than 3mm on there... as corner radius.

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