DEVELOPING THE NEXT GENERATION OF DESIGN FOR ENVIRONMENT (DFE) TOOLS

Thesis submitted in accordance with the requirements of the University of Liverpool for the degree of Doctor in Philosophy by Andrew Birch

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ABSTRACT

Research on the incorporation of environmental considerations into product design is now into its third decade. A recognised way of reducing environmental impacts is through the adoption of DfE tools into the design process. These design tools are intended to assist the designer when attempting environmental design. The potential benefit of DfE tools is fundamental to the success of future design and manufacture. However, utilization by design specialists remains limited.

Investigation of the structure and internal mechanisms present in DfE tools has painted a clearer picture for why some tools work well and why others do not. By understanding what makes some tools better than others it has been possible to distil the fundamental features and characteristics from the tools that perform the best, and develop the next generation DfE tool framework. Verification has been possible through quantitative analysis and user testing using a prototype tool, which exploits the framework.

The increase in effectiveness could potentially reduce the time taken to conduct an environmental assessment of a product and therefore lead to tools with improved appeal, potentially improving adoption by designers in industry.

The significance of this study is that it will lead to a better understanding of how designers interact with DFE tools and methods. By understanding this relatively unknown aspect of DFE tools it will be possible to design future tools to be more effective and useful for the designer.

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Andy Birch

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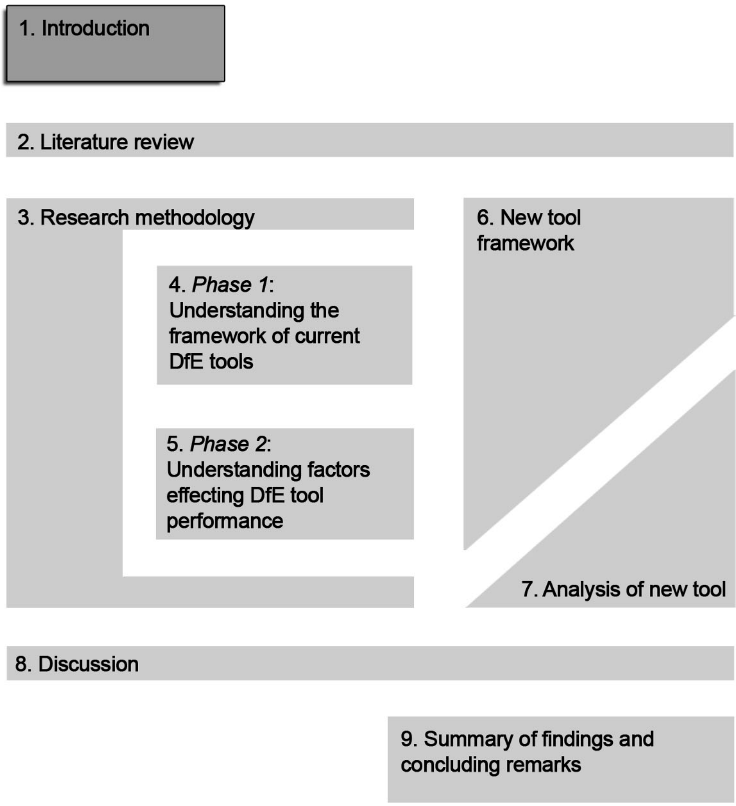


CHAPTER 1 – Introduction

The inclusion of environmental principles into the design process is now widely accepted as a fundamental part of the global push to reduce the negative effects of man made activities. Its prominence is spurred on by growing EU legislation, especially the Ecodesign Directive (2009/125/EC), and increasing public approval for environmentally considerate products (Dimache, Dimache et al. 2007). Over the last few decades a vast number of tools attempting to facilitate Design for Environment (DfE) principles into design have been developed (Baumann, Boons et al. 2002, Byggeth, Hochschorner 2006, Simon, Evans et al. 1998). Despite some successes with Life Cycle Assessment (LCA) methods in the early 1990's, no tool or method has so far become accepted as norm within industry (Luttropp, Lagerstedt 2006, MacDonald, Short 2007).

Suggested barriers to DfE adoption range from low priority being assigned to environmental issues against functional performance and economics, through to an apparent lack of usability and real value of the tools available (Lagerstedt 2003, Fitzgerald, Herrmann et al. 2010, Sakao 2007). Common complaints from designers about DfE tools include a lack of sufficient support during design and a lack of the necessary eco-information required for full implementation (Byggeth, Hochschorner 2006, Bhamra, Lofthouse 2003). Despite numerous investigations, the fundamental reasons for this lack of DfE tool take-up are still unclear (Baumann, Boons et al. 2002, Lagerstedt 2003, van Hemel, Cramer 2002, Knight, Jenkins 2009, Lindahl 2005).

Many researchers suggest that the earlier environmental issues are considered during the development of a new product, the higher the chance of reducing their associated impacts (Fiksel 1995). Effective tools that enable designers to reduce these issues early are of clear benefit as they limit the cumulative impacts ‘locked-in’ to the product (Lewis, Gertsakis et al. 2001).

For designers to move into line with essential practices required for sustainability, relevant tools and effective methodologies in a user-oriented format are needed. This research project intends to build a greater understanding of the needs and requirements of modern designers attempting to design products with less environmental impact. Using real world case studies on small electrical household appliances this project aims to show how the different elements from various DfE tools can be pulled together to provide user-friendly solutions to the current barriers to the take-up of design incorporating environmental issues.

1.1 A Brief history of Environmental Consideration in Design

Ever since the book *'Silent Spring'* shattered the assumption that the environment had an infinite capacity to absorb pollutants, public and commercial interests in the field of environmental consideration has gathered pace (Carson 1962). The book documented detrimental effects of pesticides on the environment, and later facilitated the banning of the pesticide DDT in the US in 1972.

In 1969 Coca Cola Company funded the first Life Cycle Assessment (LCA) study investigating the associated environmental impacts of their beverage cans. This fuelled LCA development within the manufacturing industry, and in 1979 Ian Boustead published the *Handbook of Industrial Energy Analysis* which became the basis for modern LCA (Boustead 1996). The subsidence of the 1970's energy crises produced an *'oil glut'* which in turn demoted the importance of energy analysis, and consequently slowed LCA development through out the 80's (Jensen, Hoffman et al. 1998, Hershey Jr 1981).

The late 1980's saw a rapid surge of interest in environmental issues, with further development of 'cradle to grave' assessments of materials and products, leading to a widely held opinion that LCA methodologies were the *"most promising new tools for a wide range of environmental management tasks"* (Jensen, Hoffman et al. 1998). This opinion proliferated at the UN Conference on Environment and Development (UNCED) in Rio De Janeiro, '92. During UNCED, the Declaration of the Business Council for Sustainable Development (BCSD) was drawn up between 50 chief executives from major corporations in industrialised nations worldwide (Alting 1995). They declared that '*business will play a vital role in the future health of the planet*', and that as business leaders, they '*are committed to sustainable development*'.

The aim was to achieve *sustainable development*, a concept that had been introduced in the Our Common Future report released by the Brundtland Commission - more commonly known as the Brundtland Report - in 1987. Brundtland served *"an urgent notice based on the latest and best scientific evidence that the time has come to take the decisions needed to secure the resources to sustain this and coming generations"*. The report proposes a *sustainable development,* which is defined as: *"A development that satisfies the needs of today without compromising the ability of future generations to meet their needs"* (Brundtland 1987).

The sustainable development concept aims at designing industrial progress across the industrial world, and is therefore by definition a macro level view. In order for every day business to develop and integrate sustainability requirements into processes there is a need for a micro level view (Sun, Han et al. 2003). A promising view for this came in the form of DfE.

Originating shortly after UNCED in '92, DfE was first coined to describe the concerted effort by many electronics firms attempting to build environmental awareness into their product development (Sun, Han et al. 2003). Initially defined as '*the systematic consideration of design performance with respect to environmental, health, and safety objectives over the full product and process life cycle'* (Fiksel 1995), DfE was similar to other concurrent engineering techniques popular at the time such as Design for Assembly (DfA) and Design for Assembly (DfA) (Boothroyd, Dewhurst et al. 1994), as it seeks to address product life cycle concerns early in the design phase (Fitzgerald, Herrmann et al. 2007).

LCA is considered to be the first DfE methodology, or tool. However, by the mid 90's many tools began appearing attempting to exploit the benefits of LCA. Over the years more than 100 DfE tools have been developed (Simon, Poole et al. 2000).

DfE, meaning the incorporation of environmental consideration into the design of a product, translates as an effort towards reducing the environmental impacts which come as a result of a products entire lifetime. The approach is based on the understanding that every action taken, from the beginning of a products conception through to its end of life has some impact on the natural environment. This holistic view includes everything, from the oil used to lubricate the machinery used to excavate the raw materials, to the energy used to separate an assembly into recyclable groups at its end-of-life. All of these actions have some adverse effect on the environment.

1.2 Problem statement and aims

There is an accepted consensus that the issues causing environmental impacts need to be accounted for during product development within the engineering industry to allow designers to minimise or design them out. Although the necessity of design tools for this job is not without its opposition, many studies have praised the use of DfE tools and methodologies as a viable method for environmental consideration (Lindahl 2005).

Evidence from the literature review shows there is a lack of understanding of what the user requires from a tool, and therefore the tools do not meet the needs of the designer. This results in many of the current shortfalls associated with DfE tools. The main issue is that the current tools do not provide sufficient guidance and support to enable users to bridge the gap between identification of environmental problems and their resolution.

For example, the best performing tool found in this study, which specifically investigated how to generate and deliver design guidance (*Information/Inspiration*) out performed the others by beginning to link solutions to identified problems (see page 67) but it was clearly apparent that there was potential for improvement. The shortfalls in *'Information/Inspiration'* was its strategy-specific focus which relied too heavily on the users own knowledge of DfE for decision making. Other tools were more product-specific (*SortED*) but lacked sufficient content to effectively provide adequate design solutions because vital components of the decision making process were missing.

'*Developing the next generation of Design for Environment tools*' proposes that a tool can be of more use to a designer if the design support and guidance is delivered by an improved output mechanism in a framework better suited to a designers requirements.

To prove this claim this research has two primary aims. The **first** aim is to investigate the different types of design support and guidance available, and the, **second**, it to understand how support and guidance can be best formulated and output from a DfE tool for the greatest impact.

The overall intention is to generate a deeper understanding of the interaction between the designer and DfE tools, and how this relationship can be improved to develop more accessible and more effective tools. By doing this, we'll be enabling the whole of the design world to take greater account of the importance of designing products that have minimum impact on the world's resources both in production and during their lifetime. Creating a truly effective DfE tool, which is both thorough and easy to use, will have a real impact on both resource use and climate change.

1.3 Research objectives

In order to achieve the research aims it is necessary to complete two main research objectives. The first of these consecutive objectives is:

O1 – To explore and develop recommendations for how Design for Environment tools can better fit the requirements of the designer.

To fulfil this objective it is necessary to address two research questions.

Q1 – Are current DfE tools letting the designer down?

Q2 – What changes need to be made to DfE tools to improve performance?

The first research question (**Q1**) aims to understand a wide range of DfE tools and evaluate their performance using a metric devised to enable comparison. It asks whether or not a DfE tool could be of more use to the designer if it was improved in some way. To answer this question it is necessary to understand what a designer expects from a DfE tool. Current attitudes towards DfE tools highlight a number of barriers to adoption relevant to the structure and presentation of these tools.

Q1 is intended to identify what designers require from DfE tools in order to adopt them into common use. One of the most common issues is the lack of support and information offered by these tools when dealing with environmental design issues. Given that DfE information is often widely dispersed, it makes the ability of a tool to provide information and guidance to the designer all the more important (Tischner, Charter 2001).

Q2 asks whether there are any particular changes that can be made to the structure and framework of DfE tools which would ensure that the requirements of the user are more successfully met. To answer this question it is necessary to understand which features and aspects of a tools framework are responsible for its performance. This will require detailed analysis of many tools enabling a performance ranking to be conducted and an in depth assessment of the components which constitute each tools structure to allow all relevant frameworks to be mapped and analysed. Once this has been done the framework for the next generation DfE tools can be considered using the best performing components.

The next step of the research is to use the findings and improved understanding of DfE tools obtained during **O1** to complete the second research objective (**O2**):

O2 - To develop and evaluate an innovative Design for Environment tool with a next generation framework.

The main deliverable from this project is a novel Design for Environment prototype tool. The tool will bring together all the new knowledge learned whilst meeting **O1** into a working prototype to test enhancements to the tools structure and framework. To complete this objective it is necessary to answer the two following research questions:

> **Q3 – What specification does the next generation framework include?**
>
> **Q4 – Can a framework with increased design support improve a Design for Environment tool's performance?**

Q3 asks what specific details will be responsible for the new ideal tool specification. This will include a number of novel improvements to the framework resulting from the analytical investigation of current DfE tools. It will also include many improvements derived from literature. The combination of new and innovative improvements, coupled with the high performance, tried and tested features of best performing current tools will come together to generate a specification for an ideal DfE tool.

Before **Q4** can be addressed, it will be necessary to develop a working prototype tool, as defined in the specification, to demonstrate the new framework in the viable way. **Q4** will be addressed with the aid of a two-fold analysis of the new tool prototype. The first step of the analysis will be a comparison against the current best tools. These results will be considered along with the second step, consisting of collecting feedback data from user testing to assess the success of the new concept.

A primary intention of this investigation is to study the evolution of DfE tools and methodologies through the evaluation of current tools and methods. Through the collation of the highest ranked ideas and practices learned from current DFE tools, it will be possible to evolve the design of tools and methods to generate an improved next generation concept.

1.4 Thesis structure and research papers

This thesis reports the findings of a study consisting of three phases and the development and testing of a new DfE tool framework. The approach discussed in this chapter outlines how the aims and objectives of this research will be achieved. A brief outline of the approach is as follows:

Initial phase – Initial activity highlighted a number of potential enhancements to DfE tools which would result in improved performance and potentially greater acceptance by industry. This initial phase took a qualitative approach to evaluate four DfE tools and proposed that new features, including an 'Alternative recommendations' feature, could dramatically reduce the time required to implement improvements (Paper I) (Birch, Hon et al. 2010)).

Phase 1 – The findings from the *Initial phase* led to *Phase 1* being conceived to further investigate the highlighted potential enhancements with the aim of gaining an enhanced understanding. *Phase 1* deployed a mixed research method. A qualitative, interpretive research method was used to investigate and explore the output mechanisms and guidance components of 22 DfE tools, whilst a quantitative, deductive method was used to determine their performance. The results concluded that there were four common output mechanisms linked to tool performance, which existed as either strategy-specific or product-specific. The study also identified four common guidance components (Paper II) (Birch, Hon et al. 2012)).

Phase 2 - The identification of a number of DfE tools with desirable attributes in *Phase 1*, namely the four guidance components, led to the conception of an investigatory study, *Phase 2*. *Phase 2* also took a mixed research approach. A qualitative method was used to induce a better understanding of the guidance components. A quantitative approach was taken to further investigate the guidance components and how their presence would affect performance (Paper III) (Birch, Short et al. 2011)).

The enhancements resulting from the investigatory study presented huge potential for improvement to the usability and performance of a DfE tool. An improved DfE tool framework was conceived utilising the enhancements, which resulted in the development of a prototype DfE tool that exploited the new framework. The testing of the framework and the verification of the underlying theory required a predominantly quantitative approach involving user testing and assessment against benchmark examples (Paper IV) (Birch, Hon 2012)).

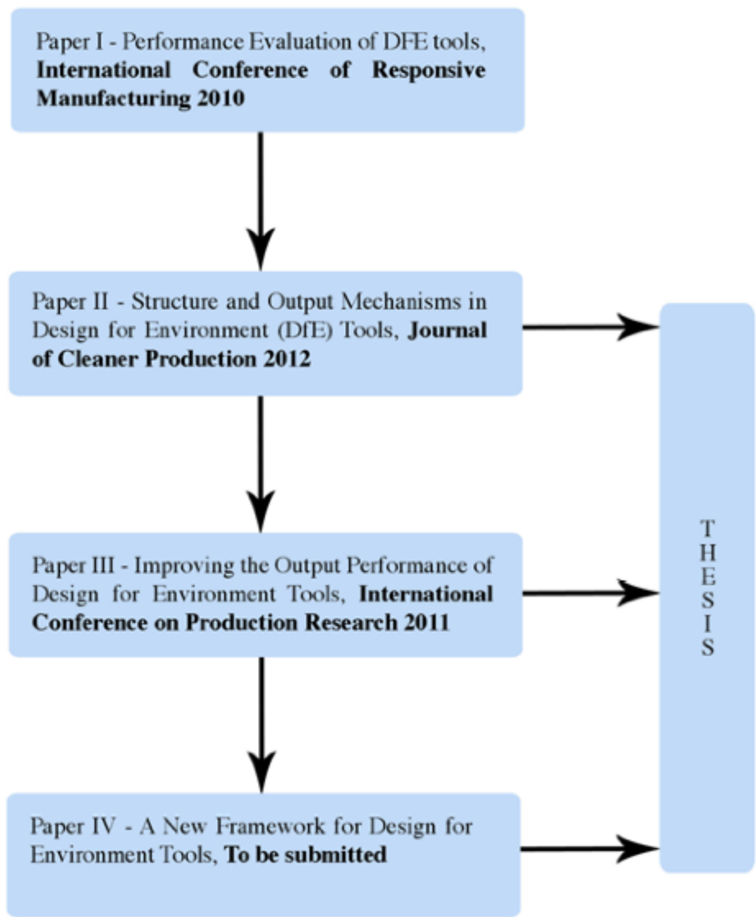
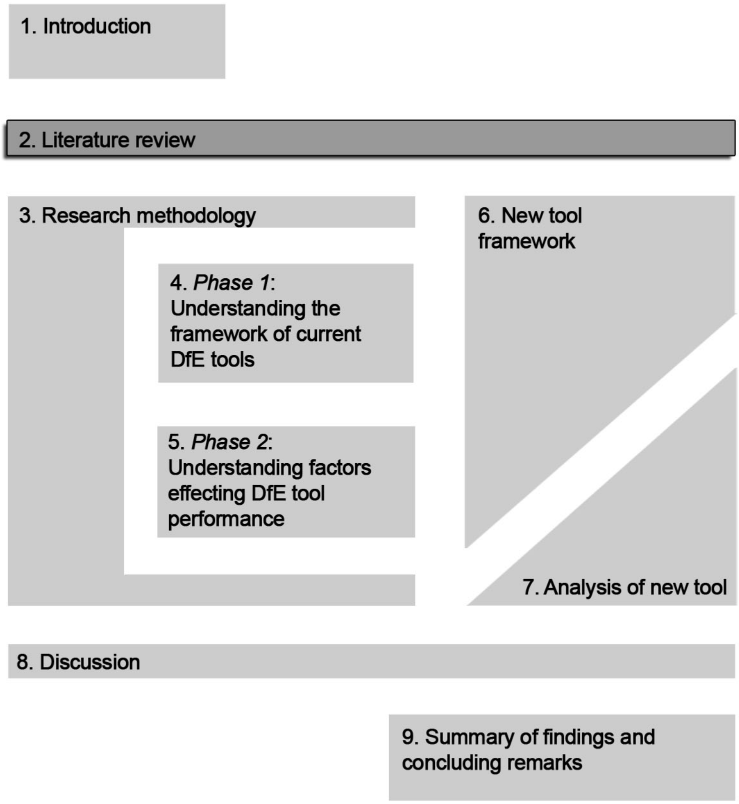


Figure 1 - Illustration of how the papers fit into the thesis report



CHAPTER 2 – Literature review

2.1 Design Process and the Environment

The product development process is defined as "*a sequence of steps or activities which an enterprise employs to conceive, design and commercialise a product*", and it is best expressed by Pahl and Beitz, as Figure 2 (Pahl, Beitz 2007, Ulrich, Eppinger 2008). The process consists of an initial stage, often referred to as planning, where the identified *task is clarified* and defined, before a Product Design Specification (PDS) begins formulation.

The PDS is a comprehensive and unambiguous document which envelops all design activity and constitutes all the aspects of a product which must be met for a product's success. The *conceptual design* phase consists of initial creative efforts to generate solutions to satisfy the task within the limitations of the PDS. Once successful concept variants have been established design embodiment begins.

The *embodiment design* phase, also referred to as the system-level design, consists of the steps necessary for the development of a product layout, including functional specification and a preliminary process flow diagram for final assembly.

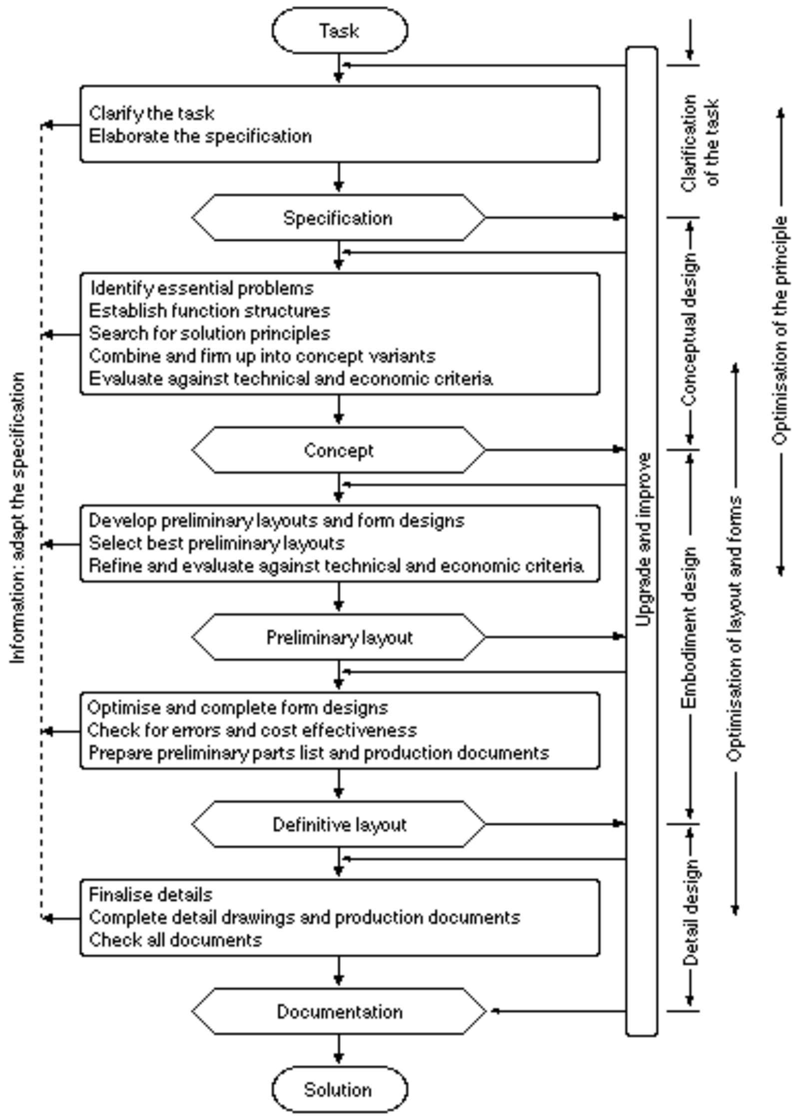


Figure 2. A general approach to design (Pahl, Beitz 2007)

The final phase, *detailed design*, results in the achievement of all of the requirements of the PDS. Dimensions of individual parts are laid down, materials are specified, production possibilities are assessed, costs estimated and all drawings and other production documents produced.

This systematic approach is rarely so clearly defined in practice and neither is it necessary for it to be. The boundaries between the phases are often blurred as activities overlap, for example defining layout issues in the conceptual design phase. Nevertheless, this division is essential for work planning and ensuring nothing is forgotten.

The design process is integral to the product life cycle. This cycle represents a process of developing a solution to a perceived need, resulting in an economic product with high added value (Pahl, Beitz 2007).

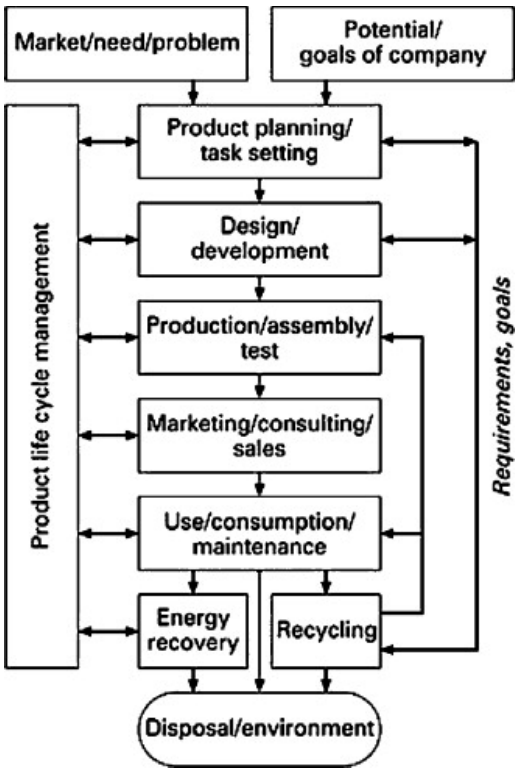


Figure 3 - Product life cycle (Pahl, Beitz 2007)

Manufacturing industry has been accused of adopting operations that takes, makes and wastes. However, it has the potential to create products that generate ecological and social value, as well as economic value (McDonaugh 2002). At every stage of the product's commercial life cycle there is enormous potential for reducing the environmental impacts of the final product. Equally true is that at every stage of the process negative environmental impacts are generated. These impacts result from the intended and unintended outputs generated during a product's lifetime. Outputs such as the product itself, intermediates, co-products and by-products amass to generate a range of impacts, such as:

- depletion of resources;
- ozone depletion;
- smog formation;
- eutrophication;
- climate change;
- alteration of habitats;
- acidification;
- reduction of biological diversity;
- air, water and soil pollution.

Consideration and limitation of these environmental impacts is required, without causing detrimental effect to product performance. In the specific case of the design process this might involve the adoption of a DfE approach (Knight 2009), requiring that, *"environmental issues and demands must be integrated in to the product development process"* (Lagerstedt 2003).

2.3 Design for Environment terminology

Over the previous 30 years, DfE has been associated with many terminologies, including Environmentally Benign Design, Green Design, Environmentally Conscious Design, Clean Design, however the most common alternative is Eco-design.

There is a lack of agreement when differentiating between DfE and Eco-design. Some parties argue that Eco-design is a broader term than DfE, incorporating not only the products life cycle environmental impacts, but also the design effort in a more balanced view (Simon, Poole et al. 2000). Others suggest that the difference in terminology is simply geographical with DfE finding favour in the US and Eco-design in Europe (Baumann, Boons et al. 2002). Bhamra suggests that the differing terminology may be due to the traditions which began with DfE emerging from the Design for 'X', which is prevalent in engineering, and life cycle design, in contrast, developing from environmental sciences and ecology terminology resulting in Eco-design (Bhamra 2004).

Additionally some researchers argue that Eco-design is a more holistic term, with the "*eco*" not only referring to *ecology*, but also to financial aspects and the *economy* (Karlsson, Luttropp 2006). However largely the two terms are taken to be synonymous (Baumann, Boons et al. 2002, Knight, Jenkins 2009, Bhamra 2004, Lindahl, Sundin et al. 2007, Fleischer, Schmidt 1997).

Design for Sustainability (DfS) is also sometime wrongly taken to be synonymous with DfE. DfS is distinct as it encompasses not only DfE factors, but also societal factors making up the 'Triple Bottom Line' of sustainability (Short 2008). Either way, the purpose of this work is not to argue terminology, therefore this thesis uses the term Design for Environment, to mean *"The development of products by applying environmental criteria aimed at the reduction of the environmental impacts along the stages of the product life cycle"* (Bakker 1995).

2.2 Designers role

Holding the central role in the design process, the impetus is on the designers to execute DfE. Due to the multi-faceted nature of product development, the designer has a whole host of tasks and activities that require their attention and time. In a commercial environment time is very limited, the addition of environmental issues to a product's specification makes the designer's job all the more harder and time scarce.

There are organisations that believe protecting the environment should play a greater role in the development of new products. With the increasing cost of raw materials and emissions of greenhouses gases they argue that for the future of the planet it is essential that all future products should be produced to use the minimum of energy and materials in their construction, and use as little energy as possible during their lifetime.

For example, Friends of the Earth are focussing heavily on how to reduce the use of the world's mineral resource by encouraging recycling and ending built-in obsolescence of consumer goods. It is calling for:

• **Lean production:** re-design products to reduce material weight. This is extremely effective as it influences a wide range of goods sectors and saves costs for producers (Lutter 2011).

• **Longer product life:** more durably designed products could cut discard rates by a third by 2020. Linked to this - a third of products are thrown away still working, of which a third could be used to their full lifetime by 2020 (Kirby 2010).

Short (2008) suggests that successful product design demands satisfaction of, above all, the functional requirement of the product as expected by the consumer. This means that the environment cannot take centre stage. Given a task with such complexity it is no wonder that generally, both academia and industry agree *"design methods and tools are important for improving product development performance*" (Lindahl 2005).

A strong opinion for why environmental consideration isn't more wide spread in industry, is the concession that environmental issues are only as important as each of the other requirements of the PDS, i.e. they are one segment of a proportionality ‘cake’ which includes all aspects of a product. Luttropp succinctly depicts the issue in Figure 4, where each of the segments is the same size. This is, of course, an unrealistic proportionality. In practice, some segments are valued over others, i.e. cost and performance often demand a larger representation.

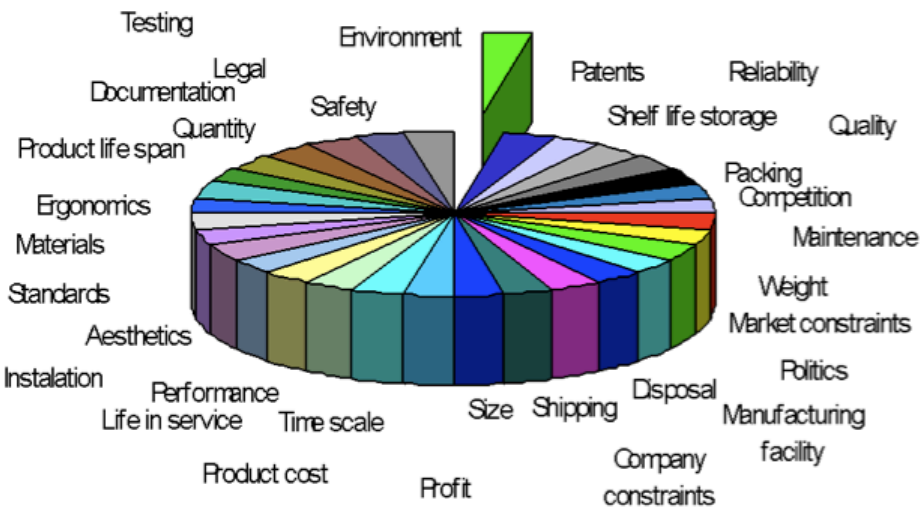


Figure 4 - Representation of all the requirements that need to be addressed during product development. Note that ‘*Environment’* is just one of the many (Luttropp 1999).

Governments and EU regulation will drive the need for greater focus on environment in design, therefore it is essential to have high quality DfE tools in place so that private sector is capable of meeting the challenge.

2.4 Approaches to improved environmental performance

According to Fett (1999) there are four viewpoints for improving environmental performance, three within a company - a process level, a product level and a company level – and a societal level. The three company achievable levels have different achievable goals. This can be explained in conjunction with Figure 5. Process level approaches such as environmental accounting and methods of cleaning up production techniques have a focus on assessing impacts and applying last minute, ‘end of pipe’ solutions which are often criticised due to their relatively small, incremental improvements in impact reduction (Re-pair and Re-fine).

Product level approaches are deployed by designers, and are characterised by their attempts to build in environmental accountability into products during development from the early stages resulting in tools and methods that allow evaluation and improvement achieving greater environmental inclusion. Therefore the design of products can be altered to improve environmental performance (Re-design).

The next level up is company level approaches. Operating at an organisational level these approaches offer a means for deploying and managing an organization's environmental programs in a comprehensive, systematic, planned and documented manner, such as Environmental Management Systems (EMS) (TC 207/SC 2004). Tischner (2000) discusses the benefits of these methods and explains their employment to bring about not only new ways of designing and generating solutions, but new ways of thinking about problems (Re-think) and even the requirement of a new product to solve a problem (Lindahl 2007).

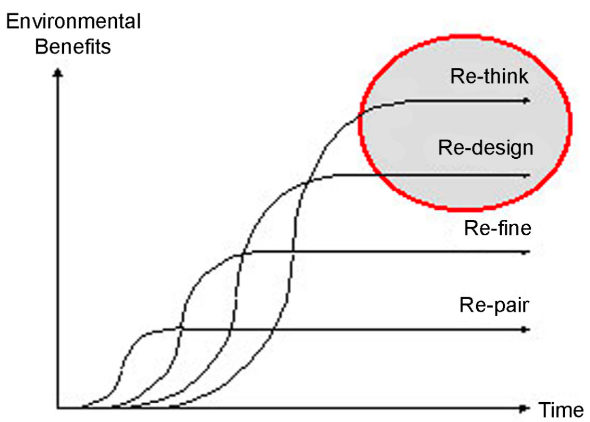


Figure 5 – Charter’s four-step model of ecodesign innovation

These numerous approaches can be deployed at the appropriate level of an organisation with the overall aim of reducing environmental impacts. Our understanding of what DfE is and how it is conducted has led some researchers to suggest it is “not a specific method or tool” which has to be deployed but more “a way of thinking and analysing” (Lindahl 2006). This belief then identifies the requirement of applicable tools and their integration in to the design process as a way of assimilating DfE principles in to an organisation.

2.4 Design for Environment tools

Design for Environment tools and methodologies give a structured approach to the incorporation of environmental impact reduction measures. The benefits of this holistic lifecycle view of a product and its associated processes found common acceptance among academics and industry, with the development of ISO 14040:1997 series, which details the Life Cycle Assessment method (LCA). LCA was the first formal method that gave a structured methodology for evaluating environmental impacts associated with products and services (ISO/TC 207 2006b).

The popularity of LCA resulted in growing interest and subsequent development of a wide range of LCA based DfE tools aimed at addressing perceived issues with the method, such as the long completion time and high level of detail required for accurate analysis. Parallel development of non LCA based DfE tools led to a variety of tools with a focus on other aspects. Prioritisation of important criteria such as Voice of the Customer (VOC) in Quality Function Deployment (QFD) and Design by Analogy – designing products by applying proven techniques used on previous solutions – drove more function oriented tools.

Though a common complaint from LCA users is the amount of time it takes to complete, the main barrier to its use relates to the required information needed for its completion. For example, a client asks a designer to design a household kettle, and wants the product to be new and innovative with minimal environmental footprint. As the designer works through the design process he or she makes decisions which define aspects of the product, generating the information needed to assess the product whilst at the same time building up ‘embedded’ environmental impacts. So as the product takes shape and more decisions are made the amount of information available to assess the product increases. As this happens the potential for improvement becomes reduced as the environmental impacts are locked in as a result of design decisions.

Figure 5 illustrates that as the designer advances the product design from initial definition through to detailed design the index of influence reduces as development decisions are made and the product takes shape. It is only when decision constraints have been made that the information to allow analysis becomes available. Hence information is needed at the start of the development where it can be used to inform analysis and therefore influence the design most.

This issue highlights the importance of tools for use in the early stages of design where the majority of the decisions are made. The perceived issues with the LCA coupled with the potential benefits brought by DfE led to continued development of tools and methods.

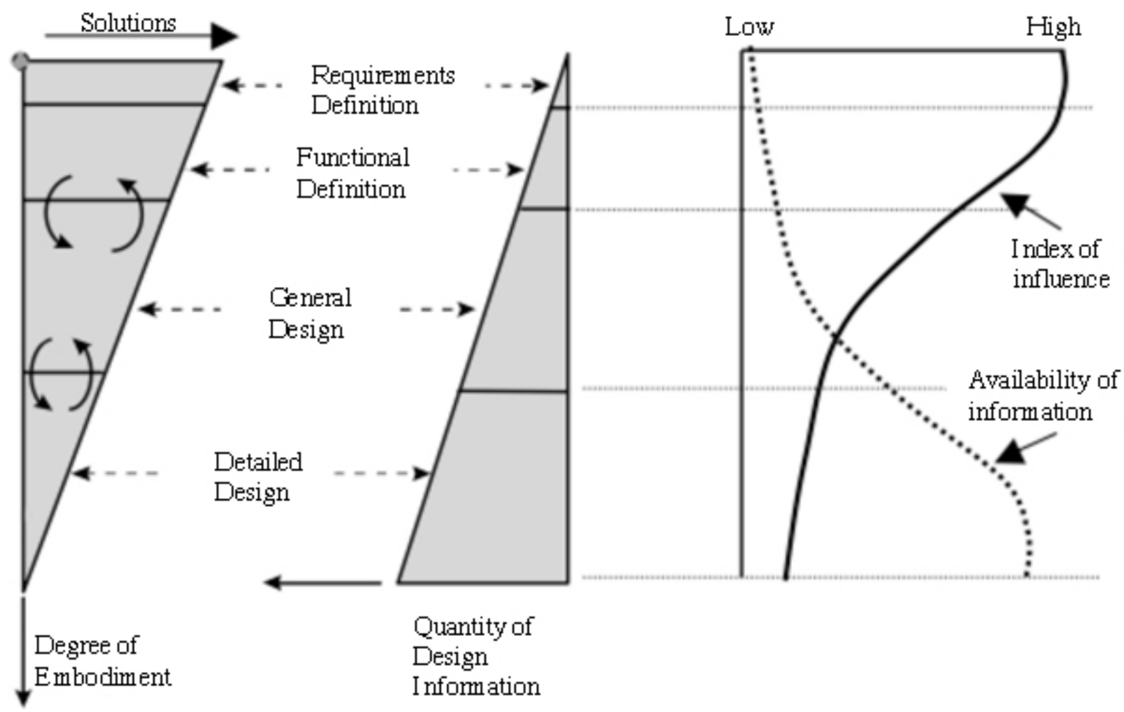


Figure 6 - The degree of embodiment of design versus quantity of environmental information (Adapted from (Man, Diez-Campo et al. 2002)).

2.5 Deriving DfE tool categories

Many companies and institutes drove the tool development, resulting in a vast number of tools and methodologies being made available to designers. Simon et al (1998) details 54 tools in the 'Ecodesign Navigator' (Simon, Evans et al. 1998), whilst Luttropp (2006) documents 32, and Byggeth (2006) considers a further 15 tools with only a few duplication of tools.

Historically, tools have been categorised in many ways, often at the discretion of the researcher. The categorisation adopted here has been derived from four articles, and adapted to best fit the requirements of the study (Byggeth, Hochschorner 2006, Luttropp, Lagerstedt 2006, Knight, Jenkins 2009, Simon, Poole et al. 2000).

Six categories were identified: Full LCA; Simplified LCA; Prioritisation; Eco-design resource; Guidelines and Material selection. These categories are not mutually exclusive with many tools encompassing different aspects, however they describe the main purpose of the tools.

2.5.1 Full LCA tools

Full LCA tools represent the most successful attempts to structure environmental consideration and accountability into tool form (Millet et al. 2007) and have been practiced by industry worldwide for over three decades (Bhander, Hauschild et al. 2003). The methodology began formalisation in 1997 as part of the ISO 14040 series, and now exists in its fifth revision, ISO 14040:2006 (ISO/TC 207 2006a). From the beginning, practitioners of LCA have intensified the belief that the method had great value for environmental management (Jensen, Hoffman et al. 1998). However, its emergence into the mainstream has always been hampered by characteristics intrinsic to its success.

LCA is a four-phase methodology that uses techniques for identifying and evaluating the adverse environmental effects associated with a product system over its entire life cycle. It involves *"compiling an inventory of relevant inputs and outputs of a system, evaluating the potential environmental impacts associated with those inputs and outputs, and interpreting the results of the inventory and impact phases in relation to the objectives of the study"* (ISO/TC 207 2006a).

Its successes are due to its accuracy and holistic view characterised by a very wide scope of inclusion and quantitative data to give credible reports via a structured framework. However, this holistic view and wide scope requires an enormous amount of data for completion. This makes the tools very time and resource intensive, often taking a team of practitioners a number of weeks to complete an LCA for a relatively simplistic product. Issues with the LCA are compounded further by the relative complexity and resultant necessity of expert knowledge to interpret and translate the output results.

Tools that exploit the full LCA methodology are characterised by the same issues as the method itself. Although computer based efforts, such as SimaPro and GaBi can assist the user in many ways, including data collection and analysis, and organisation of results, a large amount of data is still required, hence a large time frame, and the complexity of the results still requires expert translation.

2.5.2 Simplified LCA tools

Simplified LCA tools are a direct descendant of the full LCA and comprise of a cut-down, sometimes called abridged or streamlined, version of the full methodology. These tools were developed out of the necessity to improve usability by reducing the scope, cost and effort required for studies that use an LCA framework (Weitz, Todd et al. 1996). There was a great urgency to develop Simplified LCA tools, such as Material Energy Chemical Other (MECO) matrix, Environmentally Responsible Product Assessment (ERPA) matrix and Material Energy Toxicity (MET) matrix, from the mid to late 90's resulting from their claims to overcome issues related to a full LCA (Wenzel 1998, Graedel 1998, Brezet, van Hemel 1997). Inputs are often both quantitative and qualitative and the outputs are presented and structured for non-experts. It is common to present the impact per life cycle stage as a percentage of the overall impact, allowing comparison. The early efforts discussed above were paper based matrices, however, later tools, such as Eco-Design online Pilot and Eco-Audit, exploit computers to further improve usability for the user, by simplifying and reducing the data collection required and by automating the outputs (Wimmer, Ostad-Ahmad-Ghorabi et al. 2008, Ashby 2009).

2.5.3 Prioritisation tools

Prioritisation tools are characterised by outputs focused on potential product improvements derived from a non life-cycle internal structured method. These tools prioritise issues which are relevant to their underlying methodology. The Tool for Environmentally Sound Product Innovation (TESPI) is based on the Quality Function Deployment (QFD) method so the prioritised issues are relevant to the voice of the customer (Misceo, Bounamici et al. 2004). The Design for Manufacture and Assembly (DFMA) '09 tool has its foundation in the DFMA principles therefore cost reduction through part simplification and reduced manufacturing costs are focused upon (Boothroyd 1994). The Eco-Functional Matrix (EFM) prioritises the functional characteristics of a product to maintain that function should not be superseded by environmental issues throughout improvement development (Lagerstedt 2003). Envirz uses the Theory of Inventive Problem Solving (TIPS, or in its original Russian, TRIZ) as its structure which allows the user to prioritise criteria for improvement while reducing environmental issues (Fitzgerald, Herrmann et al. 2006). For this group of tools inputs are mainly qualitative. The user informs every stage of the decision process with inputs or selections as the tool prioritises the outputs (Lofthouse, Bhamra 2005).

2.5.4 Eco-resource tools

Eco-resource tools are fairly simple in structure. They are often large resources of information and product examples detailing environmental product improvements. They have few inputs and qualitative data is often required to assist decisions. Case studies can be navigated in search for particular information or merely for inspirational purposes. The Information/Inspiration website acts as a library of environmental improvements and opportunities which the user navigates in search of relevant concepts and case studies beneficial to their project (Lofthouse 2006).

2.5.5 Guideline tools

Some of the simplest DfE tools are sets of guidelines. Often passive, i.e. requiring no inputs, these tools summarise key environmental aspects which should be considered during decision making processes. They often act as a checklist to ensure that the user is aware of the main issues during design. The Ten Golden Rules are a compact list of best practice rules which pick up on the key issues necessary when attempting and teaching eco-design (Luttropp, Lagerstedt 2006). The Lifecycle Design Strategy wheel is a pictorial list surrounded by strategic options at every stage of development prompting the user to consider the necessary issues (Brezet, van Hemel 1997). Both of the above tools are simplistic and paper-based. The Sustainability Design-Oriented toolkit is a more complex set of guidelines hosted on a website, and it also allows product assessment. There are a series of guidelines covering general issues which the user reads and applies during product development. The user is then encouraged to assess their product against a benchmark (Vezzoli, Tishner 2009).

2.5.6 Material selection tools

Material selection tools allow the user to investigate potential material substitution for reduced associated environmental impacts. They comprise of large databases of materials information, such as physical properties and characteristics. IdeMAT '05, uses quantitative user inputs coupled with materials data to inform material uses and potential substitution (Design for Sustainability Program, TU Delft 1999). Whereas the Cambridge Engineering Selector, developed by Granta Design, allows the user to explore and refine potentially useful materials using a series of filters to optimise the selection of a material for a purpose (Ashby 2005).

2.6 Barriers to adoption

Although a vast number of tools offering a huge variety have been developed, there still appear to be barriers to their adoption into common use.

Many studies have been conducted investigating different aspects of DfE tools (Knight, Jenkins 2009, Ashby 2009, Goedkoop, Effting et al. 2000, Dimache, Brennan et al. 2007, Graedel 1998, Hunt, Boguski et al. 1998, Ashby, Ball et al. 2008, Stevels 2007, Bhamra, Lofthouse 2003, Lofthouse 2006).

O'Hare et al (2009) compiled a comprehensive list of reasons for poor industrial uptake of tools. The list draws from common reasons found in literature from a number of authors:

A lack of demand - A lack of environmental criteria in the product requirement specification, translating to a lack of need for environmental consideration and hence no need for DfE tools (Luttropp 2006, Olundh 2006, Lee-Mortimer 2009).

Not enough time – Due to the relative importance of environmental impacts among the many other constraints designers must meet when developing a product, i.e. environment is only one piece of the pie (See Figure 4), they have very little time to dedicate to them (Luttropp 2006).

Lack of consideration of designers' requirements – The developers of DfE tools lack a thorough understanding of the designer's considerations when choosing to use a tool or not (Lindahl 2006).

Too much choice – The wealth of tool now available to the designer ends up having a negative effect on usage due to the complexity and time needed to select an appropriate tool. Too many options and a lack of time means designers often use inappropriate tools or nothing at all (Ernzer 2002).

Poor integration – Due to the treatment of DfE activities as a separate stream, this can marginalise efforts resulting in them struggling to gain acceptance by the mainstream product development activities (Lindahl 2005).

Tools not adapted to a specific application – A number of variations exist in the product development activities depending on different companies, i.e. organisational, cultural, process and product differences. These need consideration as tools may need adaption for different situations, however, this is rarely conducted (Ritzen 2001).

This list suggests barriers for what is stopping DfE tools being taken up in companies, and it contains a number of points which are not down to the tool itself. They refer more to the organisational issues and integration. We have already established the value of tools and their use by designers on projects. Therefore we will consider the barriers to tool adoption from the perspective of maximising tool performance as a driver for its use.

Apparent in literature are the building blocks to potentially overcome some of these issues leading to more accessible, beneficial tools. A large puzzle is emerging, with many pieces that are beginning to fit into place. It is generally agreed that these tools should be used as early as possible in the design process, as 85% of the decisions about the product are made at the early design stage (Knight, Jenkins 2009). It is widely accepted that a DfE tool should consider the whole life cycle of a product, from raw material extraction through to end-of-life in order to ensure that detrimental environmental effects are reduced and not just relocated to other areas of the products life (Ashby 2009). The format of the results given by LCA tools and methods has been investigated (Ashby 2009, Goedkoop, Effting et al. 2000, Dimache, Brennan et al. 2007), with studies proposing the eco-indicator milli-points, numbers that express the total environmental load of a product or process, and the more common units of MJ of energy used and kg of Carbon Dioxide emitted.

For Life Cycle Assessment tools and methods, very little work has been done in the transformation of the results from the assessment into useable information for the designer. Although the relative evaluation of alternate designs is possible by comparison, it became apparent that when a tool is used to evaluate a product the results given would only inform the designer which life cycle phase was the largest in relation to other phases. This is a useful identification for further work, however, it results in the designer asking the question, *"How do I solve this issue?"*

The focus of Design for Environment tools and methods to date has been on informing the user where the environmental impacts occur with the product, including the scale of the damage, so that the user can attempt to reduce them. A commonly accepted trend with these tools is to output the results showing the environmental impacts of each life cycle phase, i.e. Raw materials extraction, Manufacturing, Distribution, Use and End-of-life (ISO/TC 207 2006b, Graedel 1998, Hunt, Boguski et al. 1998, Ashby, Ball et al. 2008).

These results inform the designer which life cycle phases are responsible for generating the environmental impacts. For example, if the product assessed was a small electrical appliance then the 'Use' phase can account for around 80% of the environmental impacts caused over the product's life (Stevels 2007). This suggests that in order to reduce the environmental impacts of the product, the most effective way would be to reduce the energy consumption during use (Ashby 2009). Though this information is essential for the understanding of 'where to start' attempting to minimize impacts, the information attained is often too vague and general, or too complex and abstract to immediately highlight possible solutions.

Designers say that although the current tools for eco-design highlight the issues they need to consider, they fail to offer the support needed to resolve them (Bhamra, Lofthouse 2003).

Lofthouse (2006) generated a framework for eco-design tools for designers that included the incorporation of 'Guidance, Information and Education' aspects.

This study suggested that designers wanted simple guidance in order to get them started on eco-design, though this should then be backed up with appropriate information, legislation and product examples. Product examples are offered as case studies where the particular environmental problem has been overcome. Different forms of guidance and design support are offered by other DfE tools ranging from simple generic guidelines to specific strategies, for example with the LCA Calculator by IDC the results of the analysis are translated into generic guidelines such as *"Manufacture and extraction is the largest use of energy in your products' life cycle. Value engineering would help to remove any unnecessary components reducing product impact"*.

2.7 Searching for solutions

The search for solutions is intrinsic to the resolution of the problem-solving task. For designers to overcome the environmental issues faced during product development they must be able to find an appropriate solution from a number of tools at their disposal that can assist them with general problem solving. Creative techniques such as brainstorming and lateral thinking can generate ideas and solution in a fairly free form manner allowing the designer to search a wide design space using the resources to hand and their own knowledge. Improvements on these simple techniques led to Creative Problem Solving (CPS). CPS separates the idea generation stage of the process from the idea evaluation stage, maximising potential solutions. Creative techniques such as brainstorming and morphological matrices generate ideas which evaluation techniques such as evaluation matrices and idea comparison can distil to find solutions.

Design by Analogy and TRIZ

According to Hipple (2005) an enhancement to the CPS model is Theory of Inventive Problem Solving (TIPS, or in its original Russian TRIZ). Whereas CPS requires the designer to analyse many alternatives to find the best fitting, TRIZ has the capability to produce an optimum solution without this step. TRIZ deploys Design by Analogy, a process of mapping knowledge from one situation to another through a supporting system of relations or representations between situations and is well recognized for its innovative power (Linsey 2007). Fitzgerald (2011) discusses the benefits of TRIZ and Design by Analogy and concludes that its verification during use within companies such as Proctor and Gamble, Ford Motor Company and Boeing make it a strong tool for assisting solution generation (Fitzgerald 2011).

The development of increasingly perfect systems and products could not be possible without the wealth of past development knowledge and discoveries. Until the 1950's it was commonly accepted that inventing, or innovating was a random act where a large improvement to a product or system is achieved through applying a radical change to a design.

Genrich Altshuller, a Russian patent examiner, identified that over 90% of 1.5 million patents had a fundamental engineering problem which had been previously solved. By studying the solutions Altshuller and his team were able to identify principles and process that can be used to direct the designer towards solutions. The result was the Theory of Inventive Problem Solving (TIPS or in its original Russian, TRIZ), a creative problem solving methodology especially tailored for scientific and engineering problems (Serban, Man et al. 2004).

The benefits of incorporating aspects of the TRIZ into DfE tools has been widely documented and it has experience many successes (Fitzgerald 2011, Jones, Harrison 2000, Chen, Liu 2001, Chen, Chen 2007, Chang, Chen 2004). The main difference between TRIZ and other creative and inventive methods is the reduction of ineffective solutions by using a systematic procedure to overcome the psychological inertia barrier (Serban, Man et al. 2004).

This is achieved by TRIZ through generalising the specific problem into an analogous problem. Comparison of the current problem with similar standard solutions well known in other scientific areas and industries is made, before transferring the analogous standard solution back to a specific solution. Instead of randomly searching the design space for a solution to a problem, TRIZ tools are able to direct designers to possible solutions, providing an extensive knowledge base (Fitzgerald 2011). Key TRIZ standard tools are the 40 Inventive Principles (IP's) and the contradiction matrix. The 40 Inventive Principles are design principles that have been found to repeat across many fields, as solutions to many general contradictions, which are at the heart of many problems. The contradiction matrix gives a recommendation of relevant IP's based on an evaluation of contradictions.

Design by Analogy is also achievable through other methods. The research and consultation company *Creax*, specialise in innovation development (Creax 2012a). It has developed two very useful free online databases: *Function database* and *MoreInspiration*. The *Function database* is a resource tasked with helping users find alternate methods of achieving a similar function (Creax 2005). It allows the user to search all methods for 'heating a liquid', for example. The database gives a short explanation of the different methods and uses animations to secure the understanding. The method of Design by Analogy is very simple to use, and potentially very useful to designers when overcoming environmental issues.

The *MoreInspiration* database is an innovation tool, which supports product innovation (Creax 2012b). It is an online database which allows users to search key terms in a database of over 4000 innovations (Accessed: July 2012). Each innovation has a brief description highlighting its benefits, and an image of a product exploiting it. The database combines innovations from all sectors allowing the user to explore solutions which they may not usually consider. The advanced search allows the user to cross reference innovations using common ‘clusters’ to organise the search results. This cross-sector search ability and the capability to explore such a large database gives this resource a huge potential for assisting designers.

2.8 Guidance for environmental design

An initial study and literature review identified various types of guidance delivered by DfE tools which are not being fully optimised in order to maximise tool performance. **An initial study identified a tool that had the capacity to offer guidance to the designer by recommending appropriate action based on where the greatest impact occurs (Birch, Hon et al. 2010). It used** the results of an abridged LCA to identify which life cycle phases are most detrimental over its life-time and then gave advice as to what the user can do to reduce them. It was observed that while the advice did help to highlight the issues a designer needs to consider, it failed to offer the support needed to resolve them.

Research into the handling of trade-off situations with DfE tools by Byggeth and Hochschorner observed that some tools offered guidance (Byggeth, Hochschorner 2006). This study used the term guidance as a broad term to define any type of support expressed across these situations. Many of the tools showed examples of guidance. It was often no more than a short sentence or phrase stating an environmental goal, such as to minimise material input or increase service potential. Though this type of support is defined as guidance in as much as it attempts to direct the designer towards some issues needing consideration, it does not offer sufficient support to resolve the issues.

Lofthouse confirms the need for guidance, stating that designers want simple guidance to get them started with DfE (Lofthouse 2006). This study identified that neither guidance nor information should be provided in isolation, and therefore rather than simply stating the need to consider disassembly, a tool should provide links to useful information for solving a particular problem. Identifying the ability of a tool to link together guiding questions and comments to information sources that provide potential solutions shows the potential of these types of guidance to assist the designer.

The contrast in the style and content of guidance types present in DfE tools suggests that some effort has been made to incorporate them into tools. However, little seems to be known about their structure and performance. Identified in literature are examples of guidance types present in tools with varying degrees of performance (Birch, Hon et al. 2012).

Tools such as, The Ten Golden Rules and Life-cycle Design Strategy Wheel showed guidance that is of little direct use to the designer, consisting mainly of generic statements broad enough to cover a range of issues, such as "*Use the lowest energy-consuming components available"*, without any additional information to back it up (Byggeth, Hochschorner 2006, Knight, Jenkins 2009). Comparing that to guidance delivered by *Information/Inspiration*, which links guiding comments to potentially useful information, suggests that a better understanding of the guidance component could improve DfE tools.

This identification of numerous types and formats of design support and guidance offered by some DfE tools highlighted the lack of sufficient agreement by tool developers and consequently, the users. A large number of the DfE tools investigated in this literature review did not offer any noticeable design support or guidance to the designer, even though a common complaint with the full quantitative LCA is that the results obtained are often difficult to interpret (Lagerstedt 2003). Although some studies communicate the necessity of guidance for designers given the complexity of DfE (Lofthouse 2006, Lindahl 2006), especially given its relative importance among all the other aspects requiring attention during the product development process (Luttropp, Lagerstedt 2006), there is very little research into how it should be delivered.

Very few studies that have interpreted this issue specifically for DfE tools. **However, it is directly related to a fundamental problem which designers face: 'How do you actually 'Design for Environment'?**'. The results from any DfE tool alone are not sufficient to lead directly to design alternatives, in the case of the simplified LCA they can only direct the designer to the specific life cycle stage where the majority of the impact is occurring. The designer must then return to their usual resources and design process, which resulted in the previous flawed designs, in order to generate alternate solutions.

But results from these tools have the potential to offer significantly better design support and guidance to the designer, resulting in improved designs whilst taking less time.

Byggeth et al (2006) highlight the importance of an eco-design tool having a method of evaluation which provides support in trade-off situations where it is not always clear which design alternative should be chosen. Their study showed, however, that none of the 15 eco-design tools they analysed offered sufficient support, with only 9 having a valuation system to rate criteria, suggesting insufficient beneficial features to attract designers to use them. Lindahl (2006) backs this up by highlighting that whether a designer actively and frequently utilises a tool depends on four reasons,:

- the tool has been found to be beneficial;
- the customer requires its use;
- the tool covers issues handled on a daily basis
- the tool is not unnecessarily complicated to use.

Lindahl (2006) goes on to state that *'there is a need for more research about designers' requirements for methods and tools', suggesting* that existing requirements need to be less vague and imprecise and instead better defined, more detailed and quantified.

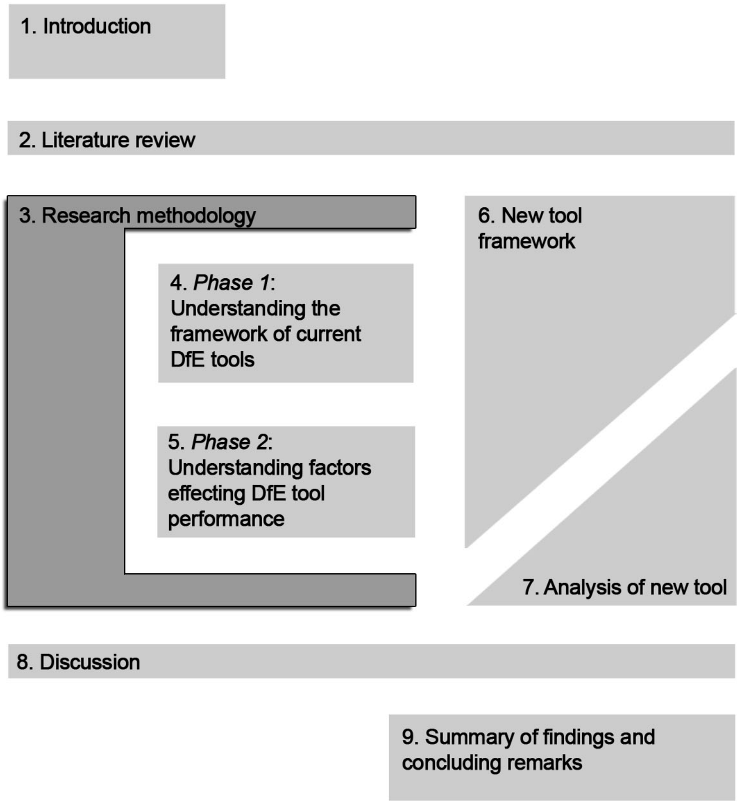
A recurring theme throughout this research is the lack of support offered by tools when the designer is attempting to overcome eco-design issues (Byggeth, Hochschorner 2006, Bhamra, Lofthouse 2003). A plausible reason could be that DfE tools are designed to be universally applicable, with the designer given the same assistance no matter what kind of product is being designed. A common complaint is that much of the guidance given to the designer is not relevant to the product they are developing - a designer attempting to design a small electrical appliance will find much of the information and guidance regarding large non-electrical products will be of no direct use.

Our research prioritises investigating the types of guidance and recommendations for further work offered by DfE tools. Many tools have been identified that have the capacity to offer the designer some form of guidance or design support in order to make their job of environmental accountability easier, however, to date no tool has been able to capture and exploit this significant benefit. Designers argue that there is a severe lack of information available for eco-design, and therefore attempts to conduct it are met with resistance, due to time constraints (Lofthouse 2006, Bhamra, Lofthouse 2003). It is evident that further work in this area is required to capture and enhance this feature to benefit designers.

2.9 Reasons for continued tool development

The research carried out in this thesis investigates the types of guidance and recommendations offered by DfE tools and identifies the potential capacity of many tools to offer the designer some form of guidance or design support in order to make their job of environmental accountability easier. General opinion is that the tools are not yet at a stage where designers are happy with them, and consequently it is argued that their potential hasn't yet been met.

This finding answers the first research objective (**Q1**) – **Are current DfE tools letting the designer down?** – by identifying that more could be done to improve current tool performance. The development of a new tool is essential. Current efforts have failed to capture all the requirements of the designer, indicating that the current best frameworks underlying the most successful tools are still deficient. Over the next few chapters this thesis will compile a comprehensive argument for the need for improved DfE tools and complete the development and review of an effective novel approach.



CHAPTER 3 – Research approach

The previous chapter has put forward the argument that designers are not using current DfE tools because the tools do not meet their expectation of function. The hugely beneficial area of design guidance and supportive assistance has to-date been unsuccessfully utilised, resulting in tools that are of little direct benefit to the user. The reason for this neglect is due to a lack of understanding of the functional aspects of delivering and structuring these beneficial features. This research strives to understand the components and mechanisms necessary for successfully developing a framework that meets the designer's requirements. Explicitly this research will create an understanding of the output mechanisms which govern the way DfE tools deliver guidance.

3.1 Research strategy

The intention of this scientific study was to generate and explore theories and then test and evaluate their validity. Consequently a mixed method research design was adopted. A qualitative research methodology was adopted to induce knowledge from research in order to generate theories. The research then took a quantitative approach to deduce the validity of those theories through testing.

The area of Design for Environment tools is little known, reflected in the low use of the tools in industry (Lee-Mortimer 2009). Therefore, it was expected that researching the issues interpretively, i.e. asking designers then interpreting their responses, would be the wrong approach. Instead, a positivistic approach was taken where data and values were collected from the tools themselves, in order to induce theories about favourable characteristics. The process took a mix of qualitative and quantitative approaches in order to capture sufficient information in an attempt to explain and describe how DfE tools are structured and perform.

This study is structured in two phases. *Phase 1* study aims to investigate the frameworks of current DfE tools, and establish a greater understanding of their structure. *Phase 2* study aims to investigate and develop a better understanding of the components that make up the frameworks. The outcome will be a new framework which exploits the new knowledge derived from the tools and literature.

A quantitative approach was adopted for theory testing in order to capture feedback for numeric analysis. User feedback was gathered through a questionnaire completed by two sample groups to assess the success of aspects of the new framework. Benchmark testing was also used to assess the new framework against the previous best using a quantitative approach. These activities were then combined to verify the study findings and address the second research objective.

3.2 *Phase 1* study methodology

The first stage of the research involved a large quantitative study designed to inspect and investigate 22 DfE tools and methodologies that are currently available to designers. The purpose of this study was to derive and induce features and approaches that are favourable to the performance of a DfE tool. During the study information regarding each tool was collated into a spreadsheet for analysis.

3.2.1 Selecting the tools

Initially 33 DfE tools were considered for inclusion in the study. These tools were identified for potential inclusion by reference from journal papers and books. Four main criteria were then used to narrow down the number of suitable tools:

- They must be product oriented;
- They must be intended for primary use by a designer;
- They must have sufficient literature available for them to be understood;
- They must be accessible.

Table 1 shows the 22 Design for Environment tools that complied with the criteria. 11 tools listed in Table 2 were rejected from the study. Three tools were rejected because there was insufficient literature available for them to be fully understood, four tools were rejected because they were not intended for primary use by the designer, and four tools were rejected because a version of the tool was not accessible and could therefore not be used.

Table 1 – List of the 22 tools selected for *Phase 1* study, with source.

Tool name	Category	Source
Granta Eco-Audit*	Simplified LCA	(Ashby 2009)
Pre ECO-it (Evaluation version)	Simplified LCA	Product Ecology Consultancy
EuP eco-profiler	Simplified LCA	LiMaS Eco-innovation
IDC LCA Calculator*	Simplified LCA	Industrial Design Consultants
LCALight tool	Simplified LCA	ABB Corporate Research
Eco-Design online Pilot*	Simplified LCA	(Wimmer, Ostad-Ahmad-Ghorabi et al. 2008)
Material Energy Toxicity*	Simplified LCA	(Brezet, van Hemel 1997)
Environmentally Responsible Product Assessment*	Simplified LCA	(Graedel 1998)
Material Energy Chemical Other*	Simplified LCA	(Wenzel 1998)
SimaPro 7.1 (Demo)	Full LCA	Product Ecology Consultancy
GaBi 4.2 (Demo)	Full LCA	PE International
BDI Design For Manufacture and Assembly '09*	Prioritisation	Boothroyd Dewhurst Inc.
Envriz*	Prioritisation	(Fitzgerald, Herrmann et al. 2006)
Tool for Environmentally Sound Product Innovation*	Prioritisation	(Misceo, Bounamici et al. 2004)
Eco-Functional Matrix*	Prioritisation	(Lagerstedt 2003)
Design for Environment Method*	Prioritisation	(MacDonald, Short 2007)
IdeMAT '05*	Material selection	Faculty of Design, TU Delft
SortED*	Prioritisation	(Lofthouse, Bhamra 2005)
Information / Inspiration*	Educational resource	(Lofthouse 2006)
Lifecycle Design Strategy wheel	Guidelines	(Brezet, van Hemel 1997)
Sustainability Design-Orienting toolkit*	Guidelines	(Vezzoli, Tishner 2009)
The Ten Golden Rules*	Guidelines	(Luttropp, Lagerstedt 2006)

Table 2 – Information about rejected tools, including reason for rejection

Rejected tool	Category	Reason for rejection
Tool A	Full LCA	Not primarily used by designer
Tool B	Metric	Not primarily used by designer
Tool C	Prioritisation	Insufficient literature available
Tool D	Abridged LCA	Insufficient literature available
Tool E	Guidelines	Insufficient literature available
Tool F	Guidelines	Could not access
Tool G	Full LCA	Not primarily used by designer
Tool H	Metric	Not primarily used by designer
Tool I	Guidelines	Could not access
Tool J	Guidelines	Could not access
Tool K	Prioritisation	Could not access

The full versions of some tools were unattainable due to high cost, therefore evaluation or demonstration versions were used instead. These criteria are intentionally broad in order to allow DfE tools with a wide range of scopes to be evaluated. It was conjectured that this would allow for the evaluation of different types of tool, giving a better representation of the large body of tools available.

The literature on DfE tools documents a trend in the simplification and adaption of tools and methods for use during early stages of the product development process – this can be seen through the Sources listed in Table 1. Sixteen of the tools are specifically intended for use by designers (denoted by an asterisk). A "Simplified LCA" suggests a simplified version of a LCA also allowing use in the earlier stages of design, often by a designer. It is acknowledged that the Full LCA tools will not be primarily used by a designer as stipulated in the selection criteria. It does however, represents the most successful DfE tool (Millet et al. 2007), hence its worldwide practice since 1997 and its formalisation into an ISO (Bhander et al. 2003, ISO/TC 207 2006). It will be included as a reference for these reasons.

As previously discussed in Chapter 2, the categorisation of the tools was conducted with reference to many sources (Byggeth, Hochschorner 2006; Luttropp, Lagerstedt 2006; Knight, Jenkins 2009; Simon, Poole et al. 2000). Six categories were identified, Simplified LCA; Full LCA; Prioritisation; Guidelines; Material selection and Eco-design resources.

3.2.2 Testing the tools

Preparation

To ensure ecological validity of the research the author decided it would be necessary to replicate as best as possible the usual working environment that the tools would be used in. To replicate a commercial environment the product information required to complete these DfE tools had to be generated and collected. This was done using a structured method to reverse engineer two small, electrical household appliances (Appendix 2). A kettle and a food blender were disassembled and a bill of materials generated. Basic tests and Resin Identification Codes (RIC) were used to identify each component's material and primary process. The components were then weighed and the information recorded in a spreadsheet along with the component's estimated end of life path (Appendix 2).

Re-design

The product data was used to complete each tool from a **re-design** perspective. Attempts to use the tools in a New Product Development (NPD) process would have required the generation of 22 new products, beyond the time and resources available for the research, and provided results that would have been difficult to compare. Although restricting the research to re-design is noted as a limitation, the study is concerned only with the assistance given by the tools during the design process – which is as applicable to product re-design as it is to NPD. Given the intended early use of many of the tools, it is anticipated that similar issues will exist with NPD.

Time limit

The application of each tool for both products aimed to be completed over one working day, the morning used to gain familiarity with the tool, i.e. reading literature, including manual, and taking tutorials. The full evaluation of the tool, using the product data from the two case studies, was then conducted in the afternoon. This tight time restriction approximates to the constraints placed on designers in industry given their pressure of work. However, due to the relative simplicity of some tools and complexity of others this time frame was not always fully adopted. Four of the 22 tools required more than one day in this study, i.e. SimaPro, GaBi, DFMA and DFEM.

Order of tool testing

The tools were tested and evaluated in the order shown in Table 1. The tools were grouped into similar categories – Simplified LCA, Full LCA, Prioritisation, Material selection, Educational resource and Guideline. The reason for this is that the researcher intends to gain familiarity with the category of tool and a general overview of their workings before attempting to carry out the evaluation process. A conscious attempt was also made to approach each tool objectively and minimise bias during the evaluations by reinforcing the research objectives after each tool had been looked at.

The researcher gained familiarity during the morning session, by reading the available literature and conducting test-runs of the tool using fabricated data. Once familiar the researcher then used the afternoon session to fully evaluate the tool using the product information from the two case study products.

During this evaluation, information about each tool was gathered and entered into a spreadsheet. Abbreviated names were assigned in order to simplify their discussion. Information describing the fundamental aspects of the tools was then collected. The categories discussed in Chapter 2 were assigned to each tool, noting the tools format and full purchase price. The input type was then stipulated as either quantitative or qualitative and the presence of eco-design resources noted, before the output format was determined.

3.2.3 Performance rating

Given the wide-ranging scope of the chosen tools it was necessary to set a metric allowing for the comparison of the performance of all these different categories of tool. The performance metric is defined as, *the capability of a tool's content and output to assist the user towards a better understanding of environmental issues and improve their ability to generate viable solutions*. The author, to rate how well they satisfy this metric, qualitatively assessed each tool. The VDI 2225 rating system in Table 3 was used as guidance to allow a fair assessment relative to the other tools and ensure consistent scrutiny.

Table 3 - The **performance rating** system derived from the VDI 2225 scale and rating system (Pahl, Beitz 1996).

VDI 2225 scale	VDI 2225 rating
0	Unsatisfactory
1	Just tolerable
2	Adequate
3	Good
4	Very good (Ideal)

The VDI 2225, as described by Pahl and Beitz (1996) (see Table 3), includes a rating system which dispenses with weightings and instead relies on evaluation criteria of approximately equal importance to allow fair assessment. In order to assess the performance against the above metric, it was necessary to break the tools into two parts, assistance and structure. The ability of a tool to perform well is dependant on the level of assistance it offers, as well as the ability of its structure to support the designer and deliver an output. Table 3 shows the rating system that spans from unsatisfactory to very good, and the corresponding numerical scale. Tools that are **unsatisfactory** offer very little to no assistance to the user, and lack a visible structure. **Just tolerable** tools offer some assistance, however, they too lack a robust structure. **Adequate** tools have, either, the necessary structure, or the appropriate assistance, and those with both have shortcomings. Tools that offer both the appropriate assistance, and, the necessary structure are considered **good**, however, those that offer both to a superior level are **very good**.

The collected data and results from the performance rating for each tool were then used to identify and assess the tool frameworks and generate conclusions. These are discussed in Chapter 4.

3.3 *Phase 2* study methodology

Phase 2 aimed to further investigate and clarify findings from *Phase 1*. It was built on the observation that of the 22 tools investigated during *Phase 1*, the 10 best performing tools have some form of design advice feature. This *Phase* aims to understand how this feature works, and why it improves tool performance.

3.3.1 Selecting and testing the tools

10 tools from the previous study were selected and further investigated, with focus on the guidance components and how each tool delivered their output. The selection of applicable tools was done as a result of the *Phase 1* study and are therefore presented and discussed in Chapter 4. An additional consideration was the idea that the more advice a tool can give then the better it will perform. To investigate this, the frequency of the four guidance components, strategies, advice, case studies and eco-resources, were recorded allowing further analysis to be done.

3.3.2 Overall rating

The overall performance of each tool was quantitatively assessed using the ‘performance rating’ scale - documented in section 3.2.3 - and the overall rating system shown in Table 4. Each guidance component has been broken down into ranges that correspond to a rating value. The ranges for the ‘strategy’ and ‘advice’ columns were defined according to estimates for the number of each. Initially, extreme ranges, i.e. very low and very high frequencies were assigned 0 and 4 respectively, the remaining ranges were then considered relatively, at regular intervals. The ‘case study’ and ‘eco-resource’ ranges were defined based on whether the tool had the feature, additionally, the number of case studies were quantified. The number of each component was established and rated according to the scale. The ratings for all four guidance components were then summed up to give the tools overall rating. The relative importance of each component was equally weighed. This was because there was no evidence at this stage to suggest that one was more important than the other.

Table 4 - The **overall rating** system, modified from the VDI 2225 scale (Pahl, Beitz, 1996).

	Overall rating scale				
	0	1	2	3	4
Strategy	0	1-3	4-6	7-9	10>
Advice	0	1-49	50-99	100-149	150>
Case study	0	-	-	1-99	100>
Eco-resource	No	-	-	-	Yes

After the information had been collected and entered into a spreadsheet, evaluation and assessment of the data commenced. Comparison of the two ratings for each tool were scrutinised in order to identify trends and draw conclusions, these are discussed in Chapter 5.

3.4 Feedback generation strategy

The main conduit for feedback retrieval during user testing was an online self-administered questionnaire consisting of ten questions (Appendix 1). The development of the questionnaire followed a process that includes the five key steps identified as essential: consideration of research objectives; determination of survey administration; questionnaire construction, including wording, sequence and response choice; extensive pretesting; data collection and analysis (Fowler 2009, Synodinos 2003).

3.4.1 Design of questionnaire

Consideration of research objectives

The aim of this questionnaire was to address research objective 2, namely:

O2 – To develop and evaluate an innovative Design for Environment tool with improved performance.

The questionnaire results are the method of evaluating the success of the new tool. Therefore, it was necessary to define two sub-objectives that would determine the success of the outcome. The sub-objective were defined as follows:

1. To assess the users experiences with the tool regarding the performance of individual aspects.
2. To assess the performance of the guidance components and content relevance.

The outcome from this questionnaire will determine the successful completion of **O2**.

Determination of survey administration

According to Bryman and Bell (2007) the self-administered questionnaire and the structured interview are in many ways very similar methods of research, the main difference being that with the structured interview method there is a trained interviewer present to ask the questions. However, with the self-administered questionnaire the respondent is responsible for reading, understanding and answering the questions. There are many disadvantages to the use of a self-administered questionnaire, including issues such as the respondent can not be prompted or probed further regarding answer choice, there is a greater risk of missing data and low response rates causing bias, and issues with asking to many non-salient or open-ended questions or inducing respondent fatigue (Bryman, Bell 2007). Despite these disadvantages there are some prominent advantages which make the self-administered questionnaire more attractive than structured interviews. The self-administered questionnaires are cheaper and quicker to administer. This is especially appropriate for this research given the nationwide location of potential respondents and the limitation of resources available.

The self-administered questionnaire was hosted online for quicker administration and completion at the respondent's convenience, eliminating possible 'interviewer effects'. Online hosting at SurveyMonkey.com ensured the greatest availability with the aim to maximise response rates, allowing respondents to access the questionnaire via a URL link embedded in correspondence emails. The added bonus of this method meant that the completed questionnaires were managed via the online host enabling instant access to respondent completed questionnaires, reducing time spent gathering feedback.

Questionnaire construction

Fowler (2009) gives five guiding principles for the design, format and layout of self-administered questionnaires. These guidelines take into account the fact that the respondents, who have not received training for the task and often lack motivation to do the job well, are solely responsible for understanding and completing the questionnaire. These have been summarised as following:

1. *A self-administering questionnaire should be self-explanatory;*
2. *A self-administered questionnaire should mainly be closed-answers, i.e. checking a box, clicking on a response, or circling a number;*
3. *The question forms in a self-administered questionnaire should be few in number;*
4. *A questionnaire should be laid out in a way that seems clear and uncluttered;*
5. *Provide redundant information to respondents by having written and visual cues that convey the same message about how to proceed* (Fowler 2009).

These principles were adopted throughout the design and development of the questionnaire. Care was taken to ensure the self-explanatory nature of the questionnaire with minimal written instructions. All questions led to closed answers, with only a few open ended 'text-boxes' where it was thought unpredicted answers would occur. The questionnaire consisted mainly of questions with attitude scale answers, i.e. either Yes/No or five-point Likert scale. The sequence and layout was considered to reduce clutter. Clear 'next' and 'previous' buttons were used for simple navigation.

<u>Wording</u>

The wording of the questions and answers were kept simplistic in order to avoid ambiguity, and to reduce completion time. Questions are formulated to ask respondents for information that can be readily accessed. Attention was taken to ensure that each question *"was as clear and precise as possible so that all respondents interpret and all understand the same thing"*(Synodinos 2003). The questions were simply phrased to ensure the respondents fully understood and gave relevant answers. Care was taken so that all questions were *"as concise as possible to convey the intended meaning and respondents should be able to answer them with relatively minimal effort"*. Care was also taken to ensure questions were asked within frames of reference that are meaningful to the respondents where necessary, i.e. common units and metrics. This was especially important due to the overseas origin of many postgraduate students.

Sequence

A flow chart was used to assess and optimise the questioning sequence during the initial generation of the questions and through content and intention refinement. As recommended by Synodinos (2003) "similar questions should be grouped together and the within topic order should be from the general to the specific". The questions were subsequently organised into four parts, namely:

1. Previous tools – the use of environmental design tools before this study;
2. Proposed tool – the use and performance of the new tool;
3. Strengths and weaknesses – the strengths and weaknesses of the new tool;
4. Improvements – potential areas for tool improvement.

Response choice

When designing the questions, the type of choice given for the answers of each question is integral. In order to avoid ambiguity and ensure the respondent finds an appropriate degree of agreement with an answer it was necessary to use a five-point subjective continuum scale, from very positive to very negative. The respondent is then *"asked to consider the labels, consider their own feelings or opinions, and place themselves in a proper category"*(Fowler 2009). There are two main issues with this type of response as explained by Fowler. Firstly, the respondents will differ in their opinion of what the labels mean, and secondly, an ordinal scale measurement like this is relative, resulting in different results depending on the scale presented (Fowler 2009). As a five-point scale was common to every subjective continuum scale used the concern of varying results due to scale was not an issue. As previously mentioned, simple language and points of reference were used to reduce any ambiguity and limit the possibility of misunderstanding the labels used. An example of a potential question and associated answer labels used is given as follows:

How easy did you find this tool to use?
1 = Very hard
2 = Hard
3 = Neutral
4 = Easy
5 = Very easy

Pretesting

Pretesting was conducted by three members of staff at the University of Liverpool and pilot testing was conducted by a small group of four post-graduate students. The pretesting helped to check that the questionnaire was easy and relatively quick to complete, and it ensured that the concepts under consideration were clearly explained.

3.4.2 Selection of respondents

Respondents were selected using convenience sampling methods. The necessity for this comes from the requirement of a certain level of knowledge and experience for inclusion in each sample group as shown in Table 5. The groups and selection criteria are discussed in the following sections.

Table 5 - Comparison of the test groups.

Group	Quantity	Product Design Knowledge	Product Design Expertise	Feedback type	Feedback data type
Student designer	37	Yes	No	Self-administered questionnaire	Quantitative
Professional designer	11	Yes	Yes	Self-administered questionnaire	Quantitative
Professional designer	2	Yes	Yes	Semi-structured interview	Qualitative

Student designer group

A sample of 37 postgraduate student designers were selected for this group. As a non-probabilistic, non-random sampling method selected for ease and the pre-requisite that members had an average to excellent knowledge of product design and the development process, not all elements of the population had a chance of selection, and so there is no way of knowing how representative the results are of the entire population (Bryman, Bell 2007). However, given that there was a 100% response rate, due to the participation in the study being nominally part of their study programme, it can be said that these results do give an accurate representation of the views of postgraduate product design students.

Table 5 details the resultant group which consisted of 37 post-graduate students who were studying Product Design and Management at Masters level at the University of Liverpool. Many of the students had a Bachelors degree in a product design related subject, including engineering and manufacturing, however some members of the group did not. Although each of the group members had the required knowledge of product design, none of them were experts in the field.

The student designer group gave feedback after using the tool during an assessed module where they were tasked with generating solutions to a problem. The students were encouraged to use the new tool to help with their solution generation and exploration. Shortly after the submission of the work they were asked to complete the self-administered questionnaire online detailing their thoughts as to specific aspects of the tool.

Professional designer group

Professional designers were recruited to participate in the testing and feedback exercise. A sample of 51 companies listed as members of British Design Innovation (BDI) members were chosen. The criteria required for inclusion by this non-probabilistic (non-random) sampling method was an expert knowledge of product design and design development, and practical experience of developing products. As this group was selected for ease of administration and prior experience in the field, not all elements of the population had a chance of selection, so again it is not possible to estimate how representative the results are of the entire population (Bryman, Bell 2007).

The sample group was recruited using three approaches. The first approach involved generating a list of suitable companies using the BDI directory database. British Design Innovation is the membership organisation for Industrial Designers involved in product, service and interaction design. For inclusion as a BDI member the company, often a consultancy must have *"at least five years commercial design related, post-graduate work experience – with case study evidence of repeat business, client testimonials and commitment to working to a shared code of professional conduct" (Britishdesigninnovation.com, 2012).* BDI has 71 members, 51 of them develop products. The second approach involved drafting a news bulletin with the assistance of Tonya Harman of the BDI in order to send out to all 51 of its members. The third approach involved asking colleagues and business contacts to recommend potential designers that could be involved in the study.

As well as collecting quantitative feedback on the tool using the questionnaire, two designers were also informally interviewed regarding their experiences. These two designers were chosen due to their availability and proximity allowing an interview period. The interviews took between 20-30 minutes and consisted of a semi-structured questions and answers format were the designer would give an elaboration of their chosen response to each question in the questionnaire. These responses were noted and are discussed later along with the quantitative results.

Approach 1 – List of designers

In order to recruit a number of designers successfully for the study it was necessary to gather the information outlined in Table 6. This information was usually available from the BDI database. However, on occasion it was necessary to refer to the company website.

Each designer was initially contacted by email. The email explained the study and invited them to take part. It covered all the necessary information, including the URL for the new tool, a link to the short questionnaire and a short description of the study, its intended outcomes and the part their input will play. Each email communication was later followed up by phone call. The phone calls acted as an informal introduction of the project to the designers, and served to express interest directly in the feedback from the designer and to prompt them into action.

Table 6 - Designer details required for inclusion in study.

Details collected
Name of company
Company address
Name(s) of the product design and developer(s)
Phone number
Email address

Approach 2 – BDI bulletin

The second approach acted as a reminder to the BDI members contacted during approach 1, and also included a number of members not contacted before. Tonya Harman, the marketing and membership manager at BDI was contacted regarding publicising the study with an intention of recruiting designers for the study. Tonya drafted a bulletin message to be sent out to all 51 BDI members who develop products. The bulletin included a brief description of the new tool stating its beneficial features, followed by a URL link to both the tool and the questionnaire. This was circulated with the regular Friday newsletter.

Approach 3 – Friends and colleagues

Due to a low initial response rate to approaches 1 and 2, it became necessary to draw from personal contacts in order to recruit designers. Colleagues and industrial contacts were asked whether they could recommend any designers to pursue. In each recommended case the designers details were determined and contact was made. The same protocol as approach 1 was used in each case.

Response rate

The response rate for the professional designer group shown in Table 7 was relatively high (21.5%) given the comparable frequencies obtained in other industrial surveys (Synodinos 2003). Additionally, the response rate for the student designer group was also very high (100%), and a small number of professional designers agreed to take part in a semi-structured interview. A mixed research method was therefore adopted in order to *"increase the validity of this research through triangulation"* (Bryman, Bell 2007). The predominantly quantitative self-administered questionnaires completed by the two groups were used to assess the success of aspects of the new framework and address the second research objective (**O2**). Whilst the qualitative semi-structured interviews were used to identify unforeseen aspects, potential tool improvements for future development, and to make inferences and back up trends identified in the quantitative data. The use of mixed methods research design enables the findings from the questionnaire to be complemented by valuable contextual information about the responses to each question (Bryman, Bell 2007).

Table 7 – Details of the 11 respondents to the questionnaire

Designer	Company	Company size	Experience	Products
1	A	Design consultancy/small firm	+10 years	Consumer products
2	A	Design consultancy/small firm	+5 years	Consumer products
3	A	Design consultancy/small firm	+1 years	Consumer products
4	B	Design consultancy/small firm	+5 years	Consumer products
5	C	Design consultancy/small firm	+5 years	Consumer products
6	D	Design consultancy/small firm	+5 years	Consumer products
7	E	Design consultancy/small firm	+5 years	Consumer products
8	G	Design consultancy/small firm	+5 years	Consumer products
9	H	Design consultancy/small firm	+5 years	Consumer products
10	I	Design consultancy/small firm	+5 years	Consumer products
11	J	Large	+5 years	White goods

3.4.3 Data collection and analysis

All of the data entered into the questionnaire by the respondents was collected and entered into a spreadsheet for analysis. All data was checked to ensure anonymity of respondents. During data collection and analysis great care was taken to avoid the four main sources of error: sampling error, sampling-related error, data collection error and data processing error. Special attention was given to data collection error and data processing error due to their concern with measurement validity and its inherent relevance to the results.

3.5 Quality of research

3.5.1 Reliability

"*Reliability is concerned with the question of whether or not the results of a study are repeatable*" (Bryman, Bell 2007). Reliability is particularly an issue when conducting quantitative research, as it is concerned with the question of whether a measure is stable or not, i.e. whether the measure or metric is reliable, and therefore can it be trusted as consistent. The two studies that generate the majority of the new knowledge in this project use metrics in order to induce theories about favourable characteristics. Although these metrics are based on an interpretation of the rating system and the definition of the favourable characteristics, all possible care was taken to ensure consistency throughout the data collection and analysis process.

During the tool evaluation stage of *Phase 1* study the issue of bias required consideration. The process of evaluating a number of tools one after another has the potential to affect the continuity of the findings as the researcher learns and forms opinions about certain tools that may affect their opinion of others. Steps will be taken to ensure that the researcher maintains an objective view of the tools by reinforcing the research objectives after each evaluation has taken place.

Care was also taken to ensure that ethical procedures - as directed by the University of Liverpool Committee on Research Ethics - where strictly adhered to during all data collection and participatory activities. A brief summary of the procedures included ensuring all participants were informed of the nature of the study before taking part and were informed that the participation was voluntary.

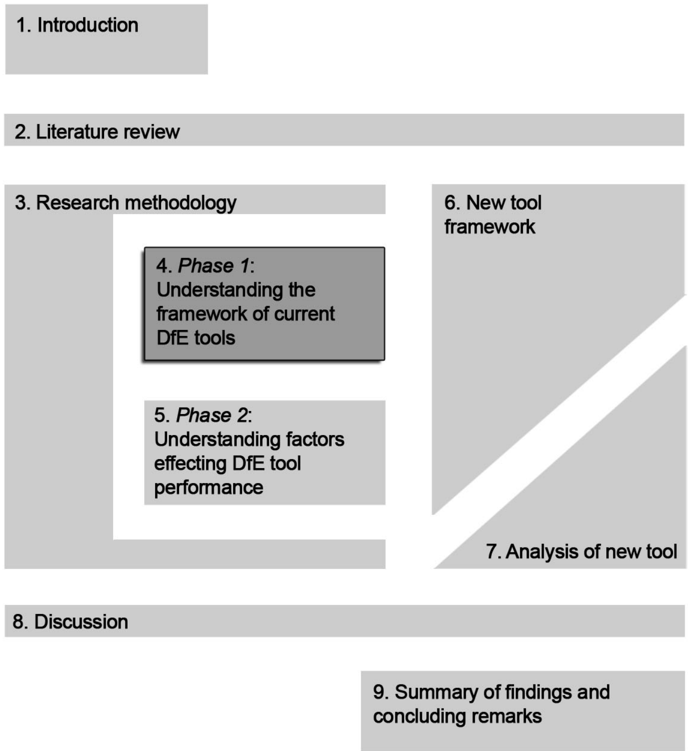
3.5.2 Replication

As previously hinted, reliability is very close to criterion of replication. This seems an obvious point, but for the reliability of results to be tested the procedure must be explained in great detail so that someone else can replicate the results. In order *"to assess the reliability of a measure of a concept, the procedures that constitute that measure must be replicable by someone else"*(Bryman, Bell 2007). The care taken to ensure consistency of the metrics used, and the detailed description of the rating systems adopted during the two studies ensures that replication of the studies by a third party would be achievable.

3.5.2 Validity of research

"Validity is concerned with the integrity of the conclusions that are generated from a piece of research" (Bryman, Bell 2007). There are four main types of validity: measurement, internal, external and ecological. Measurement validity is concerned with whether or not a metric devised to measure a concept really does reflect the concept it is supposed to be denoting. If they do not, then the study's findings will be questionable, i.e. unreliable. Internal validity is concerned with the issues of causality, and whether a causal relationship between two or more variables can be confirmed. External validity's concern is whether or not the results from a study can be generalised outside of the specific research context and setting. Ecological validity is concerned with whether the study findings are applicable to people's usual, everyday setting (Bryman, Bell 2007).

Although consideration of all of the validity criterion is essential, some are more prominent in this study than others. Great care was taken to ensure measurement validity of the quantitative aspects of the research, i.e. the metrics used in studies 1 and 2, and questionnaire findings. The issue of external validity was a main concern as the sample group of tools selected for the studies may not be a clear representation of the tool population as a whole. Effort was made to select as wide a variety as possible. However, finite time and resources limited the number of tools included in the studies, meaning generalisation of the study findings had to be verified. Verification of the study findings was therefore achieved through the development of a prototype tool using the new knowledge, exploiting user feedback and benchmark testing to increase validity. The ecological validity was an issue during the user feedback stage where the tool was being tested. The online nature of the tool prototype was intended to increase the ecological validity, as it allowed the users to implement it during their working day, the way they would act with any other design tool.



CHAPTER 4 – *Phase 1*: Understanding the framework of current DfE tools

Phase 1 of the research involved a large quantitative study designed to inspect and investigate 22 DfE tools and methodologies that are currently available to designers. The purpose of this study was to derive and induce features and approaches that are favourable to the performance of a DfE tool. A novel approach was used to interrogate the tools and led to the identification of four output mechanism common to all tools. The output mechanisms are presents and a novel assessment method is used to determine performance allowing comparison and evaluation. Using the methodology set out in Chapter 3, *Phase 1* begins by introducing and giving details about the tools that were selected. It then presents and discusses the findings.

4.1 *Phase 1* study findings

The following section presents the findings from the *Phase 1* study.

4.1.1 The tools

Table 8 - Characteristics of the 22 Design for Environment tools.

		Tool information						
					Input		Output	
Tool name	Abbrev.	Category	Format	Price	Type	Eco-design resource	Format	Source
Granta Eco-Audit*	Eco-Audit	Simplified LCA	Software	Medium	Quantitative	No	Report + Graphs	(Ashby 2009)
Pre ECO-it (Evaluation version)	ECO-it	Simplified LCA	Software	Low	Quantitative	No	Graphs	Product Ecology Consultancy
EuP eco-profiler	EuP profiler	Simplified LCA	Software	Free + cost of expert	Quantitative	No	Tables + Graphs	LiMaS Eco-innovation
IDC LCA Calculator*	LCA Calculator	Simplified LCA	Website	Free	Quantitative	No	Report + Graphs	Industrial Design Consultants
LCALight tool	LCA Light	Simplified LCA	Website	Free	Quantitative	No	Tables + Graphs	ABB Corporate Research
Eco-Design online Pilot*	Eco Design Pilot	Simplified LCA	Website	Free	Qualitative / Quantitative	Yes	Strategy	(Wimmer, Ostad-Ahmad-Ghorabi et al. 2008)
Material Energy Toxicity*	MET	Simplified LCA	Paper	Free + cost of expert	Qualitative	No	Checklist	(Brezet, van Hemel 1997)

Environmentally Responsible Product Assessment*	ERPA	Simplified LCA	Paper	Free + cost of expert	Qualitative	No	Prioritisation	(Graedel 1998)
Material Energy Chemical Other*	MECO	Simplified LCA	Paper	Free + cost of expert	Qualitative / Quantitative	No	Prioritisation	(Wenzel 1998)
SimaPro 7.1 (Demo)	SimaPro	Full LCA	Software	High	Quantitative	No	Tables + Graphs	Product Ecology Consultancy
GaBi 4.2 (Demo)	GaBi	Full LCA	Software	High	Quantitative	No	Tables + Graphs	PE International
BDI Design For Manufacture and Assembly '09*	DFMA	Prioritisation	Software	High	Quantitative	No	Reports + Graphs	Boothroyd Dewhurst Inc.
Envriz*	Envirz	Prioritisation	Website	Free	Qualitative	Yes	Prioritisation	(Fitzgerald, Herrmann et al. 2006)
Tool for Environmentally Sound Product Innovation*	TESPI	Prioritisation	Website	Free	Qualitative	Yes	Prioritisation	(Misceo, Bounamici et al. 2004)
Eco-Functional Matrix*	EFM	Prioritisation	Paper	Free	Quantitative	No	Prioritisation	(Lagerstedt 2003)
Design for Environment Method*	DFEM	Prioritisation	Paper	Free	Qualitative	No	Prioritisation	(MacDonald, Short 2007)
IdeMAT '05*	IdeMAT	Material selection	Software	Low	Qualitative / Quantitative	Yes	Resource	Faculty of Design, TU Delft
SortED*	SortED	Prioritisation	Software	Low	Qualitative / Quantitative	Yes	Resource	(Lofthouse, Bhamra 2005)
Information / Inspiration*	Info / Insp	Educational resource	Website	Free	Qualitative	Yes	Resource	(Lofthouse 2006)
Lifecycle Design Strategy wheel	LiDS Wheel	Guidelines	Paper	Free	Qualitative	No	Strategy	(Brezet, van Hemel 1997)
Sustainability Design-Orienting toolkit*	SDO	Guidelines	Website	Free	Qualitative	No	Graph + Guidelines	(Vezzoli, Tishner 2009)
The Ten Golden Rules*	10 Golden Rules	Guidelines	Paper	Free + cost of expert	Qualitative	No	Guidelines	(Luttropp, Lagerstedt 2006)

Table 9 - The structure of each tool's output mechanism.

	Type of guidance						Applicability		Performance rating
	Tool prioritised strategy	User prioritised strategy	Strategy-specific advice	General advice	Strategy-specific case study	Specific case study	Specific product/problem	Generic product/problem	
MET °		√							0
ERPA °		√							0
MECO °		√							0
Eco Audit °	√							√	1
ECO-it °	√							√	1
EuP Profiler °	√							√	1
LCALight °	√							√	1
SimaPro	√							√	1
GaBi °	√							√	1
EFM *		√							1
DFEM °		√							1
LiDS wheel *		√	√					√	1
10 Golden Rules				√				√	1
LCA Calculator °	√		√					√	2
DFMA °		√	√					√	2
IdeMAT °		√		√			√		2
SDO *		√	√					√	2
Eco Design pilot *	√		√					√	3
Envriz *		√	√		√		√		3
TESPI *	√		√					√	3
SortED °	√		√			√	√		4
Info/Insp °		√	√		√		√		4

4.1.2 Output mechanisms

This research identifies and presents a number of novel sections that make up the output mechanism of DfE tools. Each tool has an output mechanism, each mechanism has a number of components. These components consist of the elements of a tool involved in generating and delivering its output. Table 9 shows how the output components are divided into two sections, type of guidance and their applicability. These components consist of the main steps and aspects of the tools that form the mechanism for how an output is generated. Each mechanism has at least a component defining how the strategy is prioritised. The majority of them have a component from the applicability section, or one or more guidance components and an applicability component.

Common mechanisms

The most significant finding was the identification of the four common output mechanisms. Figure 7 shows Output mechanism 1. This first mechanism requires either the user or the tool to determine the strategy to prioritise, before delivering simple generic assistance or none at all. The second mechanism found common to all the tools, Output mechanism 2 - shown in Figure 8 - again requires either the user or the tool to prioritise a design strategy for attention, however, it then recommends issues to consider relevant to the specific design strategy in focus. Output mechanism 3, shown in Figure 9, goes a step further by allowing the user to prioritise design strategies before delivering relevant case study examples and advice for a product the user chooses. The final mechanism, shown in Figure 10 is drastically different to the other 3 mechanisms. Instead of allowing the user to choose a focal strategy or relying on a generic choice by the tool, Output mechanism 4 requires inputs from the user about the product they are developing so that relevant design strategies are used, leading to more focused advice on the users product.

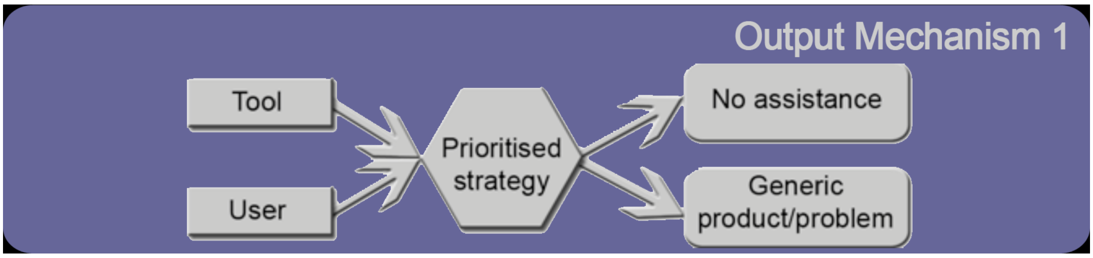


Figure 7 - Output mechanism 1.

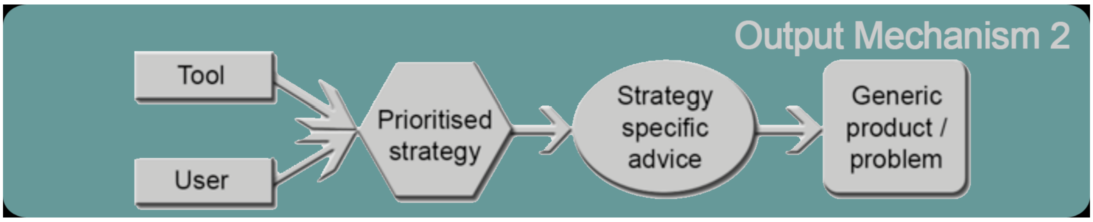


Figure 8 - Output mechanism 2.

Figure 9 - Output mechanism 3.

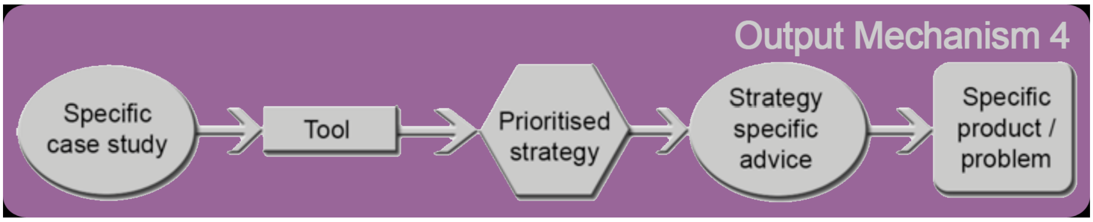


Figure 10 - Output mechanism 4.

4.2 Discussion of findings

Resulting from the 22 tool study are a set of findings that illustrate some of the shortfalls present in current DfE tools. These findings are analysed and discussed in this section where they are developed into a list of essential features that make up the framework of a new and improved DfE tool.

4.2.1 Strategy prioritisation

The output mechanism of DfE tools generally starts from a prioritisation of strategies. Out of the 22 tools studied, all but one started with some form of prioritisation, i.e. 10 Golden Rules. This step is critical as it simplifies and clarifies the issues and tasks the designer needs to consider (Simon, Poole et al. 2000). Either the user defines the strategies they wish to prioritise, or the tool dictates which strategies to prioritise.

Strategies demonstrated in the studied tools can be broken down into two main types. The first type is demonstrated by seven DfE tools, denoted in Table 9 by an asterisks (*). These highlight a specific factor for improvement relevant to a life cycle phase of the product, such as reduced consumption in the use phase. This method focuses the designer's attention on a specific issue within a life cycle phase that is causing an environmental impact. This can help to narrow down where resources should be directed. Eco-Design Pilot, TESPI and LiDS give good examples (Appendix 3).

The second type and most common (12 tools denoted by a degree sign (°) in Table 9) is a less direct method for strategising. Strategies in these tools have less direction, and operate more by informing the designers that they need to reduce impacts in relation to a broader area, often one or more life cycle phases. This is especially visible in the Life Cycle Assessment (LCA) based tools, as their focus is commonly to identify the life cycle phases where environmental impacts are occurring, e.g. Eco Audit, Eco-it, LCA Calculator. However, it is also observed in prioritisation tools where the user defines the strategies, such as Envriz, and DFEM.

In the majority of tools studied wherever the tool itself priorities the strategies it is due to the results of a Simplified or full LCA. By focusing the designer's attentions to a particular life cycle phase, the tool is, in effect, prioritising work in that area as a viable strategy. There are also tools that set priority of design strategy by a different means. TESPI uses the results of

Quality Function Deployment (QFD) to prioritise strategies, whilst in SortED the strategy is prioritised by the type of product. Tools where the user prioritises strategies require either a designer with sufficient experience and knowledge of eco-design, or the use of a separate life cycle based tool that can assist the designer. After the relevant strategies have been identified, they can be applied to the appropriate tool.

4.2.2 Reliance on expert input

It is apparent from investigation of paper-based tools that they rely on an individual with some expertise in environmental design to either customise aspects or interpret outputs from the tools so that the results can be applied by the designer or design team.

The experts roles is more apparent in some tools than others. For example, the 10 Golden Rules consists of 10 generic eco-design guidelines that have to be customised to a particular task before they can be used (Luttropp, Lagerstedt 2006). This customisation requires the input of an expert otherwise the rules remain too generic to be of any direct use. Paper-based Simplified LCA tools have the same reliance. Without an expert to advise on the input and interpretation of the output of tools such as MET, MECO and ERPA the results are of very little use. Expert input is required for accurate tool completion and interpretation, and therefore it adds an extra cost or constraint to product development. Computer-based tools have the capacity to delivery this expert knowledge without the necessity of an environmental expert.

4.2.3 Output mechanisms in use

Strategy-specific tools

a) Output mechanism 1

The most common output mechanism, illustrated in Figure 7, is demonstrated by 11 of the 22 tools, as Table 10 shows. In the case of the computer based Simplified and full LCA tools, such as Eco Audit, ECO-it, SimaPro, etc, the identification of the life cycle phase where the designer should focus resources is defined as the tools assistance to the designer directing them towards improvements to generic products or problems. With paper based Simplified LCA and prioritisation tools where the user prioritises the strategies, such as MET, MECO, ERPA, EFM, etc the tool offers negligible assistance.

Table 10 - Output mechanism 1 breakdown by tool.

	Tool prioritised strategy	User prioritised strategy	Generic product / problem	Performance rating
MET		√		0
ERPA		√		0
MECO		√		0
Eco Audit	√		√	1
ECO-it	√		√	1
EuP Profiler	√		√	1
LCALight	√		√	1
SimaPro	√		√	1
GaBi	√		√	1
EFM		√		2
DFEM		√		2

The performance rating for tools with this form of output mechanism is relatively low, containing tools ranked between 0 and 2 because although their reporting provides some support to prioritise areas that need improvement i.e. life cycle phases with large environmental impact they offer little to no assistance towards those possible improvements. The tools rated 1 or below are LCA based tools and have a focus on analysing and reporting the product.

b) Output mechanism 2

The second most common output mechanism is present in six tools, as shown in Table 11. After the strategies have been prioritised, the tool puts forward advice to assist the designer as illustrated in Figure 8. Depending on the different tools, the advice is delivered in different ways and with varying details. In the LCA Calculator, the tool prioritises strategies depending on the results of the LCA. The advice is given in short sentences in a PDF report, usually 2-5 pieces of advice per relevant life cycle phase. TESPI, however, prioritises strategies depending on the results of a Quality Function Deployment (QFD) needs analysis. Each prioritised strategy is linked to a page of eco-design resources, giving all of its advice specific to that strategy. Further examples of advice can be found in Appendix 3.

Table 11 - Output mechanism 2 breakdown by tool.

	Tool prioritised strategy	User prioritised strategy	Strategy-specific advice	Generic product / problem	Performance rating
LiDS wheel		√	√	√	1
LCA Calculator	√		√	√	2
DFMA		√	√	√	2
SDO		√	√	√	2
Eco Design pilot	√		√	√	3
TESPI	√		√	√	3

It is important to note that this advice is specific to a particular strategy. For example, the Eco-Design Pilot advises that 'in order to avoid excessive consumption at use stage, the level of consumption should be indicated to the user', under the "reduce consumption in use phase" strategy. Although this advice is specific to a particular strategy, it is intended for use on any product and not relevant to a particular functional requirement. The advice is structured and given in such a way as to be applicable to the majority of or all products. While this information can be useful, its generic applicability means that the designer has to screen an overwhelming amount of information, which is often not relevant to their current project (Lofthouse 2006).

c) Output mechanism 3

The third output mechanism which gives strategy-specific advice based on the prioritised strategies was only identified in two tools. However, these tools did receive a high performance rating as depicted in Table 12. The fundamental difference is that these tools use case studies in order to deliver advice that can be specific to a particular product, and therefore can be relevant to a particular functional requirement as shown in Figure 9. They require the user to prioritise strategies that lead to case study examples showing how a problem relevant to a strategy has been overcome. These effectively act as a database of proven solutions that can direct the designer towards answers to his own problems.

Table 12 - Output mechanism 3 breakdown by tool.

	User prioritised strategy	Strategy-specific case study	Strategy-specific advice	Specific product / problem	Performance rating
Envriz	√	√	√	√	3
Info/Insp	√	√	√	√	4

In the Envriz tool as shown in Table 12, the user chooses functional and environmental parameters to improve, i.e. prioritising a strategy. A set of inventive principles is investigated, using case studies that have been linked to from the prioritised strategies (Fitzgerald, Herrmann et al. 2006). These case studies are examples of products and patents where the inventive principles could have been applied in order to generate the solution. These give specific advice applicable to a specific product. With the Information/Inspiration tool, the user chooses a strategy from a list. Under each strategy are case studies that offer advice specific to those products covered in the case studies.

This mechanism requires the user to decide which strategies to prioritise, and then provides a wealth of proven solutions in the form of case studies, which could be applicable to their product or problem. A weakness of this mechanism is that it does not provide any indication of which strategies are best to tackle first. An inexperienced eco-designer might not know which to prioritise, wasting time and causing frustrating (Lofthouse 2006).

These tools are arguably the most useful to the designer, barring their previously mentioned shortcoming. The addition of case study examples to the eco-design resources, as demonstrated in the Eco Design pilot and TESPI gives the user an excellent knowledge base to build a better understanding of the issues relevant to eco-design. At the same time as educating the user, the tools are putting forward case study examples that could give advice that is directly relevant to the product under development.

Product-specific tools

It is necessary to prioritise design strategies to focus the designer on areas and issues that need improvement. In the strategy-specific tool the strategies are prioritised before advice or case studies are given. This is because these tools use strategies as a means of narrowing down the scope of the guidance they need to deliver. This mechanism can be very effective, and for some applications, such as educational resource tools, it is necessary as the designer often needs to search for inspiration on future projects as well as current ones. However, for LCA and prioritisation tools, there is an alternative output mechanism that could improve their performance.

d) Output mechanism 4

Output mechanism 4 is product-specific and customises its output dependent on information entered by the user on the individual product's category or function. This output mechanism, as illustrated in Figure 10 has the potential to improve the performance of these tools, as it can deliver advice and case studies tailored to the product.

Table 13 shows SortED was the only tool analysed that demonstrated this mechanism. Although this tool prioritises strategies in order to give strategy-specific advice, it does not do so until the user has chosen a product category. The user has to categorise their product into one of the 10 Waste Electrical and Electronic Equipment (WEEE) directive categories, and then is offered three to six relevant case studies. These case studies give specific advice on a product, and also recommend strategies to prioritise for that product. As well as prioritising, it also gives links to eco-design resources that better explain the strategies. The product categorisation led structure leading to product-specific advice results in a high performance rating of 4. It gives the user a means of assessing their product as well as assistance when generating solutions.

Table 13 - Output mechanism 4 breakdown by tool.

	Tool prioritised strategy	Strategy-specific advice	Specific case study	Specific product / problem	Performance rating
SortED	√	√	√	√	4

4.2.4 Paradigm shift – Strategy-specific tools to product-specific tools

These findings suggest that a paradigm shift in the way DfE tools structure their output mechanism could improve their performance. 19 tools demonstrate a strategy-specific output mechanism with performance ratings ranging from unsatisfactory to very good. All of the tools offer a structured method for assessing the environmental impact of a product. Many of them are very effective, however, the fact that they are strategy focused as opposed to product focused could be a hindrance to the usefulness of the guidance they provide. If a tool was able to categorise, as well as gather further information about the product such as function, it would result in the delivery of more accurately customised and reliable advice with case studies that could prove more useful to the designer.

The reported findings suggest that DfE tools have been developed as much as possible with the strategy-specific output mechanism but a common complaint is that the tools available do not demonstrate eco-design considerations. Lofthouse reported that many DfE tools only highlight the issues that need to be considered without the offer of any support to solve such issues (Lofthouse 2006).

This study provides evidence that many DfE functionality issues have been addressed, to varying degrees, in more recent tools. However, although designers can now get a better understanding of how generic eco-design is performed the information may not be relevant to the product they are developing. These incremental improvements to strategy-specific tools have resulted in some highly effective methods for equipping modern designers with eco-design knowledge. The next task is to give designers information and guidance that is customised to their specific needs. The product-specific mechanism is a viable method for achieving this aim, and is illustrated in Figure 11.

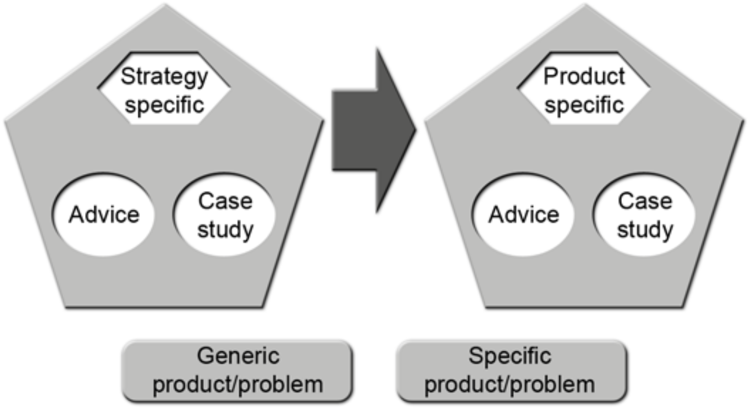


Figure 11 - Paradigm shift required in the way DfE tools output results.

There is also greater potential for development of better performing DfE tools using the product-specific output mechanism. By taking steps to reduce the scope of the guidance delivered to a particular product category, it becomes possible to tailor the case studies and advice to a more specific group of products. Categorisation of products is possible using many methods. Sousa and Wallace show a promising method for categorising products into environmentally driven categories (Sousa, Wallace 2006). SortED demonstrates categorisation using WEEE directive categories. Although these categories are quite broad and often the case studies are limited in variety and information, this form of output mechanism can be very effective at delivering guidance for a particular product or problem. The product-specific mechanism, demonstrated in SortED, has the potential to be built upon in order to develop a more advanced system for delivering tailored guidance to the user.

4.3 Link between *Phase 1* and *Phase 2*

As well as the identification of the four output mechanisms, *Phase 1* also began to identify four guidance components, strategy, advice, case studies and eco-resources. It became apparent that these components were important for the success of a DfE tool. How important though, was still unknown. It was inferred during *Phase 1* that the frequency of each component present in each tool could determine performance. Suggesting that the higher the frequency of each component in a tool then the better the corresponding performance. A second study, *Phase 2* was conceived in order to test this hypothesis. Testing this hypothesis required the investigation of tools with certain characteristics, specifically the tools from the *Phase 1* study which demonstrated advice in the output mechanism. Table 14 details the 10 tools applicable for the *Phase 2* study. It is important to note that additional tools could not be added during the *Phase 2* study because the 'performance rating', as defined in section 3.3.2 was integral in the assessment of the tools.

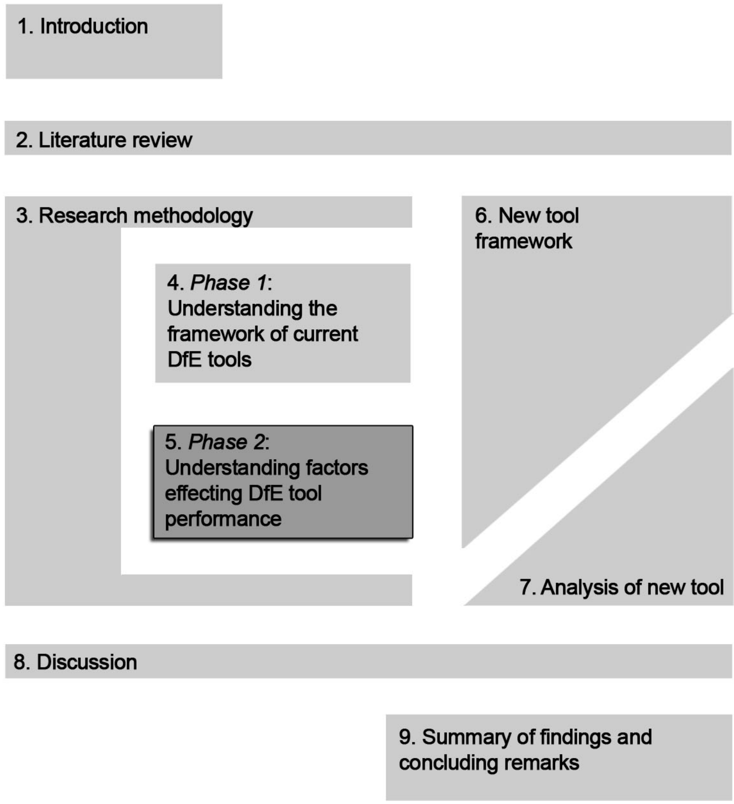
Table 14 - Basic information from the 10 DfE tools that demonstrated 'advice' in *Phase 1* and are applicable for *Phase 2*.

		Tool information				
Tools	Abbrev.	Category	Format	Price	Life cycle stages covered	Source
IDC LCA Calculator	LCA Calculator	Abridged LCA	Website	Free	All	Industrial Design Consultants
Eco-Design online Pilot	Eco Design Pilot	Abridged LCA	Website	Free	All	(Wimmer, Ostad-Ahmad-Ghorabi et al. 2008)
Envriz	Envirz	Prioritisation	Website	Free	All	(Fitzgerald, Herrmann et al. 2006)
Tool for Environmentally Sound Product Innovation	TESPI	Prioritisation	Website	Free	All	(Misceo, Bounamici et al. 2004)
IdeMAT '05	IdeMAT	Material selection	Software	Low	Materials	Faculty of Design, TU Delft
SortED	SortED	Prioritisation	Software	Low	End-of-Life	(Lofthouse, Bhamra 2005)
Information / Inspiration	Info / Insp	Educational resource	Website	Free	All	(Lofthouse 2006)
Lifecycle Design Strategy wheel	LiDS Wheel	Guidelines	Paper	Free	All	(Brezet, van Hemel 1997)
Sustainability Design-Orienting toolkit	SDO	Guidelines	Website	Free	All	(Vezzoli, Tishner 2009)
The Ten Golden Rules	10 Golden Rules	Guidelines	Paper	Free + cost of expert	All	(Luttropp, Lagerstedt 2006)

4.4 Initial conclusions

Four output mechanisms demonstrated by current DfE tools have been identified. These four mechanisms are linked to the performance of the tools they were identified in and a novel classification has been used to classify them as either strategy specific or product specific. Three strategy specific output mechanisms were identified in the majority of the tools. However it was the tool with the product-specific mechanism which performed the best. The product-specific mechanism has the capacity to allow for greater customisation of the outputs, and the effectiveness of product categorisation in order to tailor guidance was demonstrated. Refinement of the product specific output mechanism has a massive potential to improve the performance of DfE tool outputs and specifically make the designers job easier by reducing the effort required to find solutions.

The findings from this study have led to a *Phase 2* study involving the further assessment of 10 tools, in order to investigate performance related characteristics.



CHAPTER 5 – *Phase 2*: Understanding factors effecting DfE tools performance

5.1 General approach

Phase 2 further investigates and clarifies findings from *Phase 1*. It builds on the observation that of the 22 tools investigated during *Phase 1*, the 10 best performing tools have some form of design advice feature. This *Phase* attempts to understand how this feature works, and why it improves tool performance. The methodology set out in Chapter 3 describes the procedure taken during this study.

5.2 Findings from *Phase 2* study

5.2.1 Guidance components

The guidance components of a tools output mechanism are present in a variety of tools and in a variety of different forms. Many similarities between the types were observed, resulting in their categorisation into four groups:

a) Strategy

In the context of a DfE tool, a strategy is a phrase or short sentence that describes an aspect of a product's life cycle where attention should be focused in order to reduce environmental impacts. There is a lack of uniformity between the terminologies used in these tools, resulting in a variety of forms of strategy. The majority of tools present a strategy as either a subheading of a life cycle stage or as an individual issue for consideration. LCA Calculator uses the life cycle stage explicitly as a strategic focus, i.e. *extraction and manufacture, transport, use and disposal*. Six tools present strategies corresponding to a particular life cycle stage, i.e. Eco Design Pilot, TESPI, IdeMAT, SortED, Info/Insp and LiDS wheel. In this case the strategy in focus is associated with materials and manufacture, distribution, use, or end of life. An example is 'Reducing consumption at use phase', as demonstrated by the Eco Design Pilot (Wimmer, Ostad-Ahmad-Ghorabi et al. 2008). The three other tools, i.e. Envriz, SDO and 10 Golden Rules, present strategies that are not specific to individual life cycle stages. Instead they present strategies based on holistic factors, such as 'Energy intensity' and 'Dispersion of toxic materials', as demonstrated by Envriz (Fitzgerald, Herrmann et al. 2006). Other examples are present in Appendix 3.

b) Advice

A short sentence or paragraph giving a recommendation of action that could reduce environmental impact. Advice can be defined as either general or specific. A common mechanism within DfE tools involves establishing a strategy to narrow the scope of issues to consider, followed by delivering advice. Advice that is general can be relevant to any or all products or problems. An example is to recommend 'not using toxic substances and utilising closed loops for necessary but toxic ones', as demonstrated in 10 Golden Rules (Luttropp, Lagerstedt 2006). Advice that is specific requires a focus on a particular aspect, either strategy or product, where advice can be tailored in order to recommend action that is relevant to the situation. An example is 'improving the products energy efficiency' if the energy use phase of the product is dominant over its life time. Advice that is specific was identified in eight of the tools. Further examples of advice are presented in Appendix 3.

c) Case study

Case studies provide examples of products or solutions that have overcome a particular problem, informing the designer of what has previously been achieved. Examples usually consist of an image of the product and a description of its function, the problem encountered, and how it was overcome. Much of the advice from tools presenting case studies is delivered with reference to a particular example, contextualising the advice for better understanding. The case studies act as how-to instructions for how a designer can improve their product, and also aid the dissemination of knowledge. An example of this is using information about products that have previously exploited a certain technology to reduce energy consumption, as demonstrated in Info / Insp (Lofthouse 2006) and depicted in Figure 12.

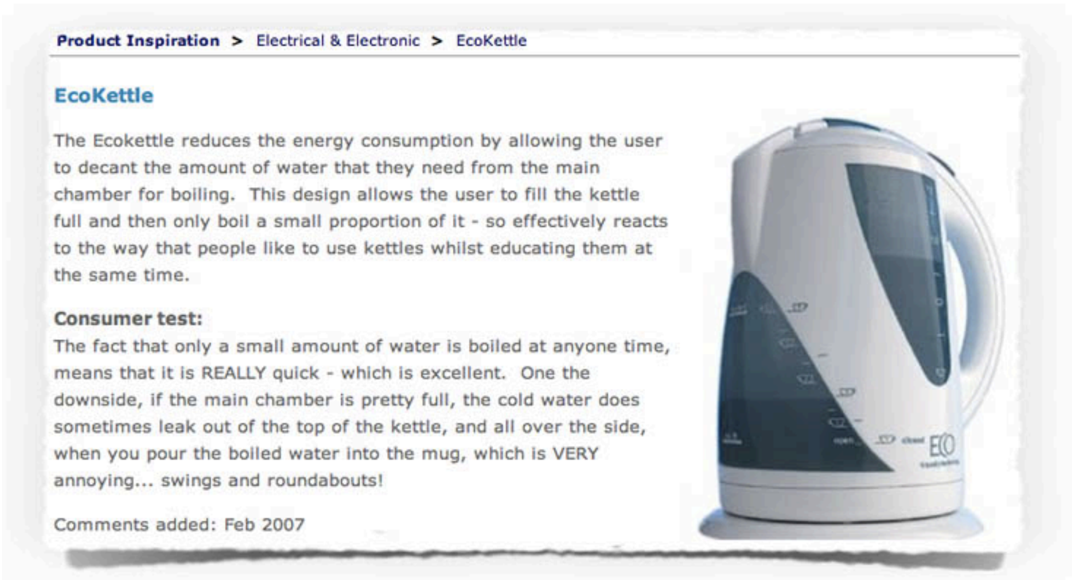


Figure 12 - Example of case study component taken from Info / Insp at www.informationinspiration.org.uk (Lofthouse 2006).

d) Eco-resource

An eco-resource comprises of any additional information that is supplied by a tool to aid the users' understanding of design strategy or a piece of advice. Though it is not a type of guidance, it is a means for delivering strategy and advice. Figure 13 depicts an example of eco-resources as demonstrated in Eco Design pilot (Wimmer, Ostad-Ahmad-Ghorabi et al. 2008).

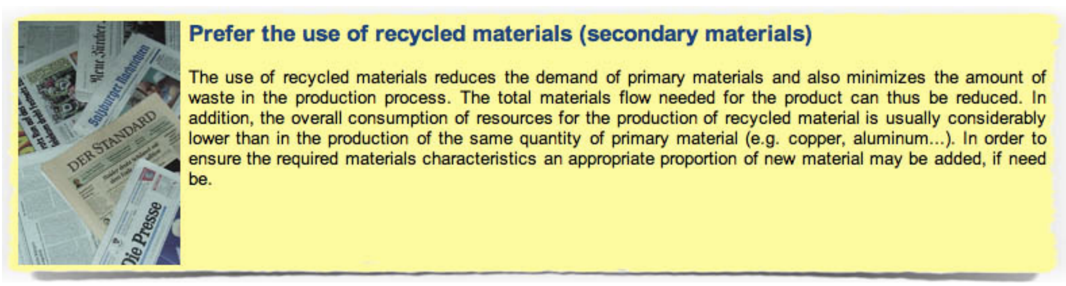


Figure 13 - Example of eco-resources taken from Eco Design pilot at www.ecodesign.at/pilot (Wimmer, Ostad-Ahmad-Ghorabi et al. 2008).

5.2.2 Component frequency

The frequencies of each component were determined and recorded in Table 15 and displayed in Figure 14, before they were assessed using the rating system and given a value. These values were then summed up to give an overall rating for that tool. This process was repeated for each tool.

Table 15 - The frequency of each guidance component recorded during the analysis and the corresponding overall rating.

Tool	Strategy	Rating 1	Advice	Rating 2	Case study	Rating 3	Eco-resource	Rating 4	Overall rating
10 Golden Rules	0	0	10	1	0	0	No	0	1
LCA Calculator	4	2	8	1	0	0	No	0	3
SDO	6	2	41	1	0	0	No	0	3
LiDS Wheel	8	3	33	1	0	0	No	0	4
IdeMAT	1	1	370	4	0	0	No	0	5
Envirz	6	2	90	2	131	4	No	0	8
TESPI	7	3	75	2	0	0	Yes	4	9
Eco Design Pilot	19	4	113	3	0	0	Yes	4	11
SortED	6	2	103	3	44	3	Yes	4	12
Info / Insp	35	4	165	4	143	4	Yes	4	16

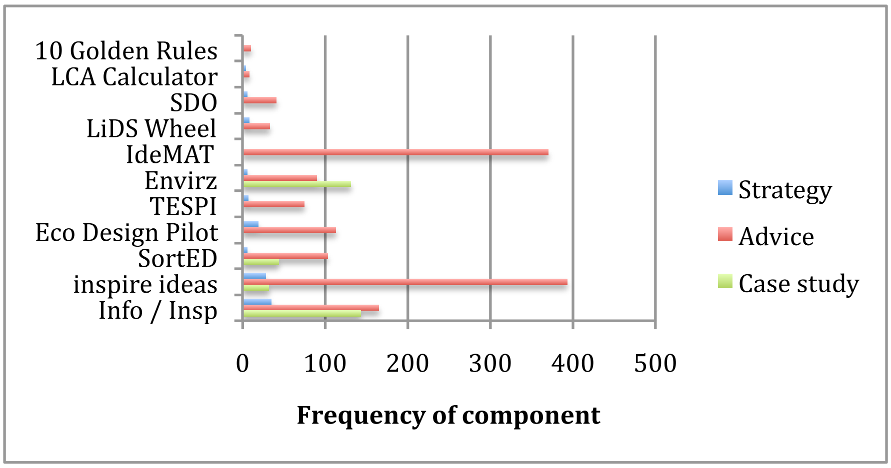


Figure 14 - Representation of the frequency of the guidance components found in each tool.

It is important to understand that the number of life-cycle stages that the tool accounts for has an impact on the results of the overall ratings of each tool. Eight of the tools cover all four life-cycle stages, however, two of the tools only cover one stage. As the results are concerned with the frequency of each guidance component observed in the tool, this puts the single stage tools at a disadvantage to the rest. Although this is an important consideration to keep in mind when viewing the results, its actual repercussions on the study are minimal.

5.3 Discussion of findings

This section discusses the resultant findings from the *Phase 2* study. The relationship between the overall rating of the tools and the performance of the tools are discussed, followed by clarification and discussion of the guidance components and the role they play in a tools performance.

5.3.1 Overall rating versus performance rating

Birch et al defined a subjective performance rating, from 0 to 4, by evaluating how well each tool satisfied a predefined metric, as defined in section 4.1.3. The performance metric was: *the capability of a tool's contents and output to assist the user towards a better understanding of environmental issues and improve their ability to generate viable solutions*. Comparison of the results showed a direct correlation between the overall rating of each tool generated in this study, shown in Figure 15, and their corresponding performance rating, shown in Figure 16.

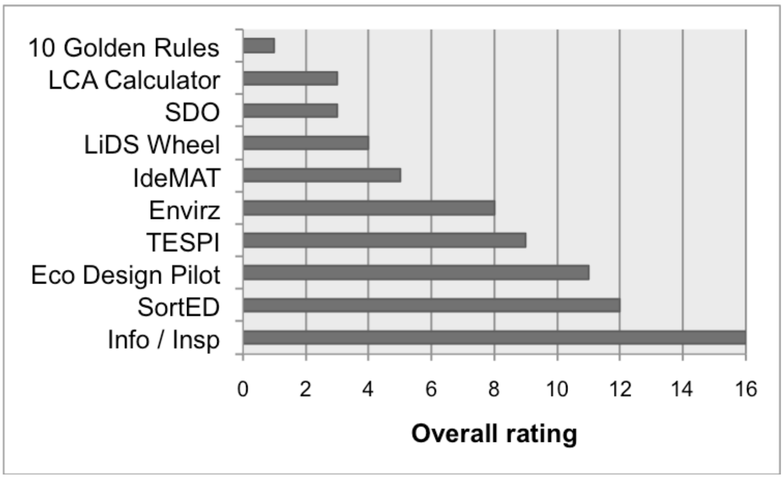


Figure 15 - The tools and their overall ratings.

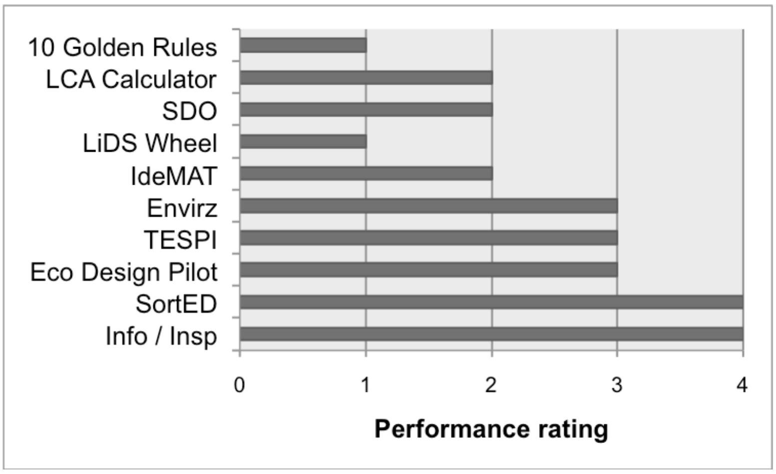


Figure 16 - The tools and their performance rating from Birch et al (Birch, Short et al. 2011)

This is encouraging as it links the contents of a tool to its performance. The LiDS wheel is the only exception, as its performance is not so closely linked to its overall rating as the other tools. This is due to the LiDS wheel having 'just tolerable' performance, whilst having an above average number of strategies and a below average frequency of advice.

5.3.2 Types of guidance

Analysis of the guidance components found in DfE tools led to the identification of two distinct categories: types of guidance, and delivery components. It was observed that case study examples and eco-resources are not types of guidance, they are a means of delivering the guidance, i.e. strategy and advice, within the context of an existing product or problem. The types of guidance: strategy and advice are defined in section 5.2.1. Table 16 gives examples of the way guidance is delivered to the user.

Table 16 - Examples of the way guidance is delivered to the user.

Type of guidance		Strategy	Advice
Delivery component	None	The use phase is the most detrimental stage during the products lifetime	Reduce the electricity consumed during the products usage stage
	Case study	Improving the insulation of your household kettle will reduce the energy required during its use	A similar product doubled the wall thickness in order to improve insulation, reducing energy required during use
	Eco-resource	Indicating the level of consumption during use to the user can avoid excessive consumption	Have a temperature read out that tells the user the heat of the water in the kettle

a) Frequency of strategy

Figure 14 shows how the number of strategies observed in each tool increases with the tools performance rating. This suggests that a tool is more beneficial to the user if it has a larger relative number of strategies to choose from. A larger choice of strategic guidance means the user is more likely to find a path that fits well with their constraints. There are two notable exceptions: IdeMAT and SortED. These tools showed a low frequency of strategic guidance relative to their performance rating. An explanation for this could be that both these tools cover a single life cycle stage only, and not all four life cycle stages like the other eight tools.

b) Frequency of advice

Figure 14 illustrates that generally as the performance rating increases, so does the frequency of advice observed in each tool, with the tool five best performing tools having a frequency of advice between 75 and 165 each. Though there is no clear-cut link between frequency of strategies and advice, it is suggested that a wider range of strategic options leads to a higher frequency of advice, increasing the tool's performance. A notable exception is IdeMAT as it has the highest frequency of advice, but an average performance rating of 2. Analysis suggests that the lack of strategic guidance and additional information limits the user's understanding of the advice, making it difficult to apply. This suggests that a large frequency of advice is not necessarily beneficial unless backed-up by strategic guidance and additional information.

The results show that strategy and advice are common components to all of the tools, with the exception of strategy in the 10 golden rules. This is no surprise as these tools were selected for their 'advice' component, however, it suggests that a tool with these components alone can have 'adequate' performance at best. Tools with better performance have additional delivery components in the form of case study examples and eco-resources.

5.3.3 Delivery components

These components are an additional way for a tool to deliver guidance to the user. Illustrated in Figure 17 is how the delivery components - case study examples and eco-resources - interact with the types of guidance in the tools. In the simplest form the strategic guidance and advice is presented straight to the user, as indicated by the central arrow. The more complex form involves either case study examples or eco-resources being used to assist the delivery of guidance. However, in the best performing tools there is a third form, where the guidance components are assisted by both case study examples and eco-resources.

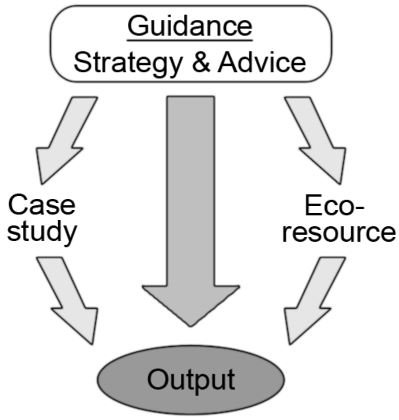


Figure 17 - Illustration of how the guidance and delivery components interact within the contents of a DfE tool.

c) Case study examples

Case study examples were present in three of the ten tools including the two best performing tools. Birch et al observed that the case study examples demonstrated by these tools operate in two different ways (Birch, Short et al. 2011). In Envriz and Information/inspiration the examples are used to link a strategy the user is investigating with relevant advice. SortED uses case study examples to link the user to similar products, where strategies are recommended, followed by advice.

Analysis suggests that case study examples have a definite benefit to the performance of a DfE tool, with tools achieving performance ratings of 3 or above. It is suggested that these examples contextualise the strategic guidance and advice giving the user a better ability to understand and apply the guidance to their design. It is important to note the limitations of case study examples. For advice to be of real use the case study example must be a close match to the product or problem in consideration. Given the variety of product types covered by DfE tools a better matching of example to product would demand a filtration or categorisation system.

d) Eco-resource

Table 15 illustrates that the four best performing tools in this study have eco-resources that backs up the guidance given by the tool, through strategy and advice, by giving additional information about a chosen eco-design issue, which aids the designer's understanding. As information relevant to eco-design is often dispersed and hard to find, the eco-resource brings information to the designer, either through information sheets or links to external material, delivering it in a manageable format with direct applicability. Analysis of the tools and the results suggest that in order for a tool to perform well there is the need for the guidance given to widen the picture with additional information, so that the advice is relevant and understood.

5.3.4 Initial conclusions

This study set out to investigate the interaction between the guidance components demonstrated in the studied DfE tools. By first identifying the four guidance components: strategy; advice; case study examples and eco-resources, it was possible to quantify the frequency of each present in each tool. These figures were collated together and rated giving each tool an overall rating. Using the established 'performance rating' the tools were ranked in order of performance and analysis of the components was conducted.

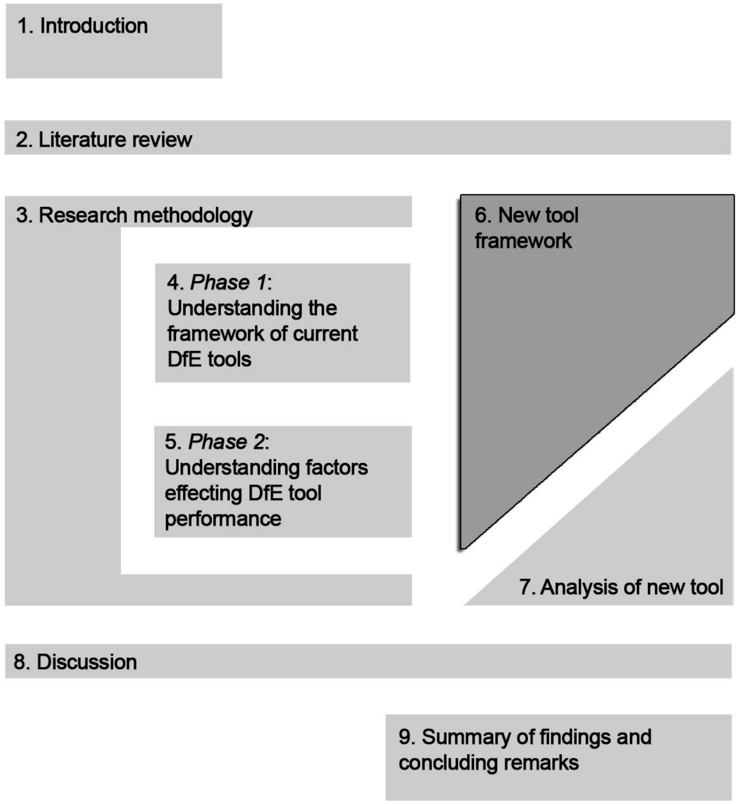
The results illustrate that the tools which performed best have four important characteristics:

- Eco-resources;
- A number of case study examples;
- More than 100 advice statements, and;
- More than 5 strategies per life cycle.

The results show that a DfE tool requires both types of guidance, as well as both delivery components for best performance. Analysis showed that as the frequency of strategies and advice per tool increased so did the tools' performance. The addition of case study examples, or eco-resources improved its performance, however, the tools that performed best had both case study examples and eco-resources, along with a high frequency of strategies and advice. The addition of case study examples and eco-resources when delivering guidance gives the user an excellent knowledge base to build a better understanding of the issues relevant to DfE. The best performing tools put forward case study examples that give advice directly relevant to the product under development, at the same time as educating the designer.

5.4 Issues with existing tools

The findings and discussion in Chapters 4 and 5 have highlighted a number of possible areas for improvement of current DfE tools. The current best performing framework has a significant potential for improvement. By enhancing the product type categorisation feature and increasing the focus on design guidance and its relevancy a new framework would be considerable more beneficial to the user. The identification of four common guidance components and the link between guidance frequency and a tools performance are also key findings. A new framework is needed because these findings have identified that the more favourable characteristics a tool has – advice, strategic guidance, case study examples and eco-resources - then the better the performance. The next chapter proposes a new framework that does exactly this. Research Objective 2 (**O2**) will be met by incorporating these design features and improvements into a new and innovative framework for DfE tools.



CHAPTER 6 – New tool framework

This chapter introduces a novel new framework that has the potential to improve the performance of DfE tools. This chapter discusses how the shortcomings identified during analysis of current tools and existing frameworks were used to develop a new DfE tool using the new framework. The purpose of the new tool is to apply the new knowledge gained during the research detailed in *Phase 1* and *Phase 2* to allow testing and verification of the new proposed framework and to test findings regarding guidance component frequency. The framework has been developed based on the investigation of the current best performing frameworks. The new tool, *Inspire Ideas*, was designed and developed in a web-based format using the software packages Adobe Flash, Dreamweaver and Photoshop.

The development of this new prototype tool consists of three stages. Section 6.1 presents the proposed framework. It brings together and clarifies the new knowledge while identifying how it can be used in a new framework. Section 6.2 discussed the key requirements of a new tool utilising this framework. Section 6.3 then documents and illustrates the development of a new tool prototype based on the novel framework.

6.1 Proposed new framework

The main aim of the new framework is to better match the information output with the user requirements. This framework assigns high priority to the information that is relevant to the product under development ensuring better relevance. This is achieved by combining user input data regarding product functions and the results of a simplified Life Cycle Assessment (SLCA) in order to guide its output.

6.1.1 Overview of new framework

The new framework differs from the existing - documented in Chapter 4 - by focusing on assisting the generation of solution, made possible by gathering user inputs, as shown in Figure 18. The framework consists of three sections. These sections are based around modified conclusions from *Phase 1 and Phase 2* studies.

The first is the Product Function Categorisation (PFC) section. This section results from the finding that a product-specific output mechanism has a large potential for improving tool performance. The purpose of this section is to ascertain the main functions of the product to assist categorisation.

In the next section, Simplified Life Cycle Assessment (SLCA), the user is asked to enter a series of values specific to the product under design. The information is then combined with pre-set eco-data and efficiency considerations, i.e. embodied energy used and CO_2 emitted per unit, in a series of algorithms to calculate the most detrimental life cycle stage or stages. This section builds on the *Phase 1* conclusions that useful information about the users product can be used to guide support in later stages of the tool.

The third section presents the three-way guidance matrix that displays the guidance relevant to the prioritised stages. These have been organised into three groups, i.e. strategy, function and TRIZ.

Strategy inspired – This section outputs strategies and advice based on the users inputs from the SLCA section.

Function inspired – This section uses inputs from the PFC section to determine alternative methods for generating a similar function to the users product by supporting suggestions with similar product examples and links to external resources, i.e. Creax's Function database and MoreInspiration.

TRIZ inspired – This section provides a knowledge structure for the interpretation of design progression, and the determination of Inventive Principles (IP) suitable to the users problem for further scrutiny and stimulation of alternative ideas. PFC and SLCA inputs are captured to guide outputs in the form of examples of IP's and advice suitable to the users product, along with similar product examples and case studies designed to facilitate Design by Analogy.

The intention with the guidance matrix is to assist the designer when generating and exploring possible solutions. Through the initial stages of gathering inputs and using them to inform the outputs, the framework ensures that the guidance delivered is relevant to the users requirements - as defined by Phase 1 conclusions - and in sufficient quantities to maximise performance, as concluded in *Phase 2* study.

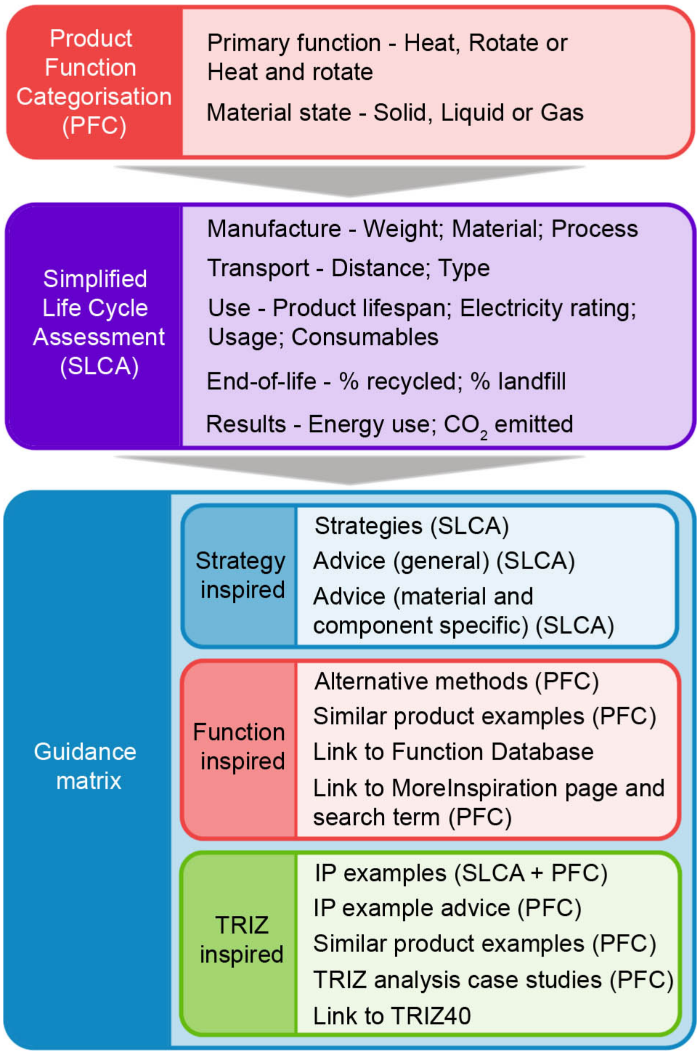


Figure 18 - A flowchart showing the main sections and features of the new framework, including the required inputs and where they are recalled to inform outputs.

6.1.2 Guidance capability of new framework

This section discusses how the guidance capability of the new framework has been enhanced. There is the capacity for eco-resources to be integrated into the fabric of the new framework. There is also space for additional information explaining specific aspects throughout the input sections, as well as throughout the output sections. The external links are also integral to this resource as they are able to link to additional useful information.

The new framework has the potential to include a high number of case study examples. For each of the possible 25 product categories there is space for up to nine case study examples. These case studies would be embedded in the framework. There is also the capacity for numerous relevant case study examples via a link to an external database, *MoreInspiration*, which boasts over 4000 case studies. This external resource returns a dynamic search of leading-edge innovations as inspiration for the user.

The framework supports a high frequency of advice, however, it is the way the advice is delivered which improves its performance. Instead of giving advice all at once in data sheets, or as a recommendation for a particular product, the advice is organised in the database into sections and therefore only revealed if the user selects a relevant trigger. This results in design support and guidance directly relevant to the product under development, improving DfE tool performance. The structure of the framework imposes no limitation on the amount of advice which can be included as the advice statements are stored in a database with no maximum size. There is the obvious limitation of time and resources required to populate the database further, however, the prototype tool includes 393 advice statements for user feedback and testing.

The framework also supports a high frequency of strategic guidance. Again, the structure of the framework does not limit the frequency, as it is contained in a database until triggered. Time and resource limitations are the only physical limit, resulting in the prototype tool including 28 strategies.

6.1.3 Guidance informed by both functional and strategic data

A key difference that sets aside the new framework from the previous and has the potential to lead to performance improvements is the way the inputs are used to inform the outputs. The new framework uses the input data generated during the Product Function Categorisation (PFC) step as well as data entered during the Simplified Life-Cycle Assessment (SLCA) section. This information is then stored and recalled from the ‘Guidance matrix’ section, as shown in Figure 19. The functional data is retrieved to inform both the 'function inspired' and 'TRIZ inspired' sections. The 'function inspired' section recalls only the functional data as a focusing mechanism. The 'TRIZ inspired' section interacts with both the functional data and the SLCA data.

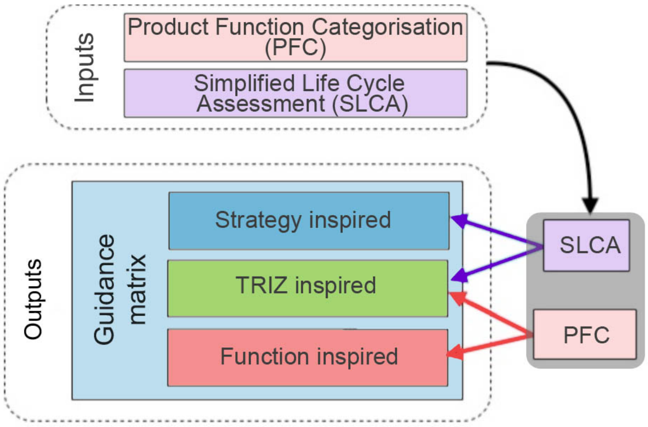


Figure 19 - How the user inputs inform the outputs.

6.1.4 Product Function Category (PFC)

A DfE tool framework is able to simplify the required user inputs and subsequent tool outputs if products with similar characteristics are grouped together (Sousa, Wallace 2006). As an example of testing and implementing the new framework, this approach has been adopted and developed to create a simple grouping system applicable to 'small household appliances', as previously discussed in section 6.1. As shown in Figure 19, the action is either heat, rotate or heat and rotate, and the state of material is either solid, liquid or gas. The PFC is the first mechanism of the framework that stores input information for subsequent retrieval to inform the guidance matrix.

6.1.5 Simplified Life Cycle Assessment (SLCA)

The second mechanism used to focus the user outputs are the results of a SLCA. This section of the framework is intended to give a quick environmental assessment of the users product. The user is requested to enter information relevant to three of their product's life cycle stages: materials and manufacture; transport; and use. Table 17 shows the life cycle stages and the corresponding area where user input data is required in order to evaluate the product. The information input by the user undergoes evaluation using algorithms (Appendix 4) to determine the most detrimental life cycle stage (Ashby 2009). This information will then be fed back to the user as a graphical output and it will be passed on to the guidance matrix to direct guidance.

Table 17 - A list of the proposed inputs used to gather product information during the SLCA section of the new framework.

Life cycle stage	Areas requiring user input data
Materials and manufacture	Part weight
	Materials type
	Primary process type
Transport	Distance traveled
	Transport type
Use	Product lifespan
	Electricity rating
	Usage
	Consumables used

6.1.6 Guidance matrix

The guidance matrix presents the applicable guidance as shown in Figure 18. It acts as a hub that funnels in user inputs combined with pre-programmed environmental data, and outputs propositions consisting of all four guidance components via three main sections shown in Figure 19. The segmentation of the output into three sections is integral to the framework. Not only does it help to break up the output information into more manageable and digestible chunks, it also improves the specificity of the guidance.

The three sections have been designed in such a way as to promote solution generation and exploration. Each section, as shown in Table 18, uses the four guidance components differently. The strategy inspired section delivers strategic guidance followed by general and specific advice; the function inspired section delivers advice followed by case study information and external resources to back them up; and the TRIZ inspired section delivers advice and case studies, backed up with demonstrations and eco-resources.

Table 18 - How guidance components are employed in the 'Guidance matrix'.

	Guidance components				
	Strategy	General advice	Specific advice	Case study	Eco-resources
Strategy inspired	√	√	√		
Function inspired			√	√	√
TRIZ inspired	√		√	√	√

a. Strategy Inspired Section

This section outputs the relevant strategies that have been triggered by the SLCA data results. Each strategy is linked to general advice relevant to that strategy. Dependant on the user inputs during the SLCA section the material and component specific links are displayed, which outputs the corresponding advice.

The advice retrieved by this section is informed by the results of the SLCA section. The advice database was built using the contents of current tools investigated by Birch et al (Birch, Short et al. 2011). The general advice refers to all advice that cannot be more accurately categorised under the specific advice categories. An examples of general advice is, *'look for synergies - can the product be linked into a system in a way which will save resources?'*.

The database organises all of the advice into categories in order to simplify the user's experience Eight specific-advice categories were identified: plastics; metal; glass; hazardous; PCB; motor; element; and consumables. These manageable packages of information are then made available in response to the user inputs, i.e. if a plastic and a metal are stipulated in the material and manufacture section of the inputs, then both plastic and metal specific advice will be provided. An example of this is, *'as ceramics generally have much lower embodied energy than plastics or metals, they can provide a more sustainable materials option for the right applications, such as knives and engine parts'*.

b. Function Inspired Section

This section intends to support the broadening of the designer solution exploration space, allowing the consideration of a wider range of feasible ideas. The main purpose is to allow the designer to consider alternate methods which are not commonly or habitually used. This offers an operational advantage to the designer who may overlook the best ideas due to time constraints, resulting in small iterative design improvements where larger improvements are possible.

In the similar products section, example products are displayed that share a similar function to the user's product. Each PFC has space for a number of example products. There is no physical limit within the framework to limit the number of examples. Every example will have an image and a link which opens a browser, loads the *MoreInspiration* database and searches a key term related to the product identified in the PFC section.

When the user is redirected to *MoreInspiration* database a key search terms relevant to the chosen product example will be loaded into the search engine. This will result in the dynamic generation of case study examples relevant to the user product. For example, if the PFC is heating a liquid, then an output similar product example could be a kettle. In this case the image link would search the *MoreInspiration* database using 'kettle' as a key word, and return up-to-date results. As the MoreInspiration database is externally managed and continuously improved it will give the user a dynamic experience, without the threat of out dated solutions and redundant information.

c. TRIZ Inspired Section

The TRIZ inspired section is designed to convey to the designer the possible opportunities made available through the use of the TRIZ contradiction matrix and the IP's. It is not intended to give or suggest possible specific improvements to the product, this would be unrealistic given the fast pace nature of technological progression, and almost impossible from a perspective of maintaining and keeping a tool up-to-date. Basically, it provides a knowledge structure for the interpretation of design progression and the determination of inventive principles suitable to that problem for further scrutiny and stimulation of alternative ideas.

This section will output example TRIZ Inventive Principle's (IP) applicable to the user chosen PFC as well as images of PFC similar product examples. For each PFC, the information from nine separate products - each with an apparent design variation – will be presented. IP's will be assigned to the apparent design variation found in each case study, and product specific advice will be generated to detail the solution. The intention of this section is to provide a structured approach for how to understand and interpret design progression, and then determine possible inventive principles suitable to that problem to further scrutinise and provoke alternative ideas.

6.2 Key requirements of new tool

The development of the new framework - which applies all the new knowledge gained from this study - represents a significant change for DfE tools. However, to ensure the completeness of this project, it is necessary to develop that framework into a working prototype tool to allow user and analytical testing. The framework defined in the previous section gives a detailed structure for how the processes direct the workflow through the required steps from inputs to outputs. When it came to developing a new tool there were a number of consideration that needed to be taken into account. These five subsections - which detail important characteristics and features of the new framework - are discussed in the following sections.

6.2.1 Small household appliance focus

The first consideration is the scope of the new tool. Researchers have commented that the fundamental failure of current DfE tools is their generic product focus (Knight, Jenkins 2009). This highlights the need for DfE tools that are specifically developed to deal with certain products, or certain categories of product. Lofthouse and Bhamra (2005) uses the grouping system demonstrated in the Waste Electrical Equipment and Electronics (WEEE) directive in order to apply product categorisation to the SortED tool. WEEE separates products into ten groups, or categories:

1. Large household appliances, including refrigerators, freezers, washing machines, etc;
2. Small household appliances, including vacuum cleaners, toasters, fryers, etc;
3. IT and telecommunications equipment, including personal computers, printer units, telephones, etc;
4. Consumer equipment, including televisions, hi-fi's, video cameras, musical equipment, etc;

5. Lighting equipment, including fluorescent lamps, discharge lamps, sodium lamps, etc;
6. Electrical and electronic tools, including drills, saws, lawnmowers, nail gun, etc;
7. Toys, leisure and sports equipment, including car racing sets, video games, electronic sports equipment;
8. Medical devices, including dialysis, radiotherapy, analysers, freezers, cardiology, etc;
9. Monitoring and control systems, including smoke detectors, heating regulators, etc;
10. Automatic dispensers, including automatic dispensers for hot drinks, cold drinks, money, etc.

Analysis of the products categorised as large household appliance showed that largely the performance and occasionally their design is discussed in many EU legislations. Refrigerator and freezers are discussed by EU 2003/66/EC; washing machines by EU 95/12/EC; clothes dryers by EU 95/13/EC; dishwashing machines by EU 97/17/EC; cooking apparatus and electric stoves by EU 02/40/EC; and, air conditioner appliances by EU 02/31/EC. With so much development and focus on these large appliances it seemed unnecessary to further investigate these areas.

The energy expenditure during use of small household appliances makes this group an obvious target for attention. Small household appliances have a significant energy requirement during use. It is common for small electrical appliances to require 80% of their lifetime energy during the usage stage (Stevels 2007). Despite this, none of the 22 tools studied in this research had a small appliance focus, opting for a more generic, blanket approach inferring use on any product both electrical and none electrical. This new tool therefore adopts a small electrical household appliances focus.

6.2.2 Manufacture and use phase focus

This second requirement considers the further narrowing of attention to known problem areas. As previously mentioned it is often the case that the use phase of small household appliances is responsible for >80% of the total energy expenditure and carbon dioxide emitted during a products life-time (Ashby 2009, Stevels 2007). Figure 20 illustrates the issue using information from an electric kettle and a coffee machine (Ashby 2009). A new tool aiming to improve the environmental performance of these products has to focus on the use and manufacturing phases as these are commonly an order of magnitude larger than that of transport and end-of-life. A small improvement to the energy use and CO_2 emission in these phases will dwarf even a large improvement in the transport or end-of-life phases. It therefore makes practical sense to focus improvement efforts on areas of use and manufacturing.

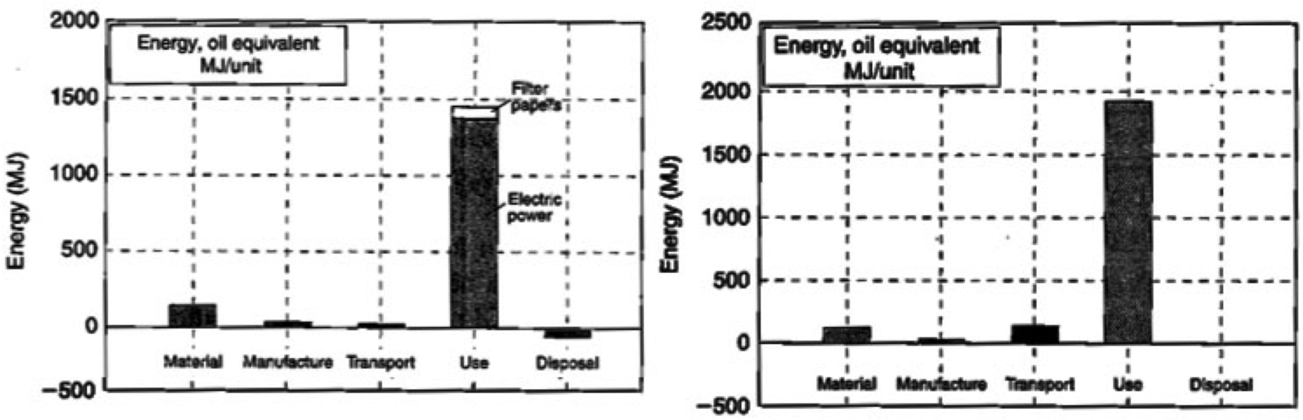


Figure 20 - The energy charts for a coffee machine, left, and an electric kettle, right (Ashby 2009)

6.2.3 Product categorisation

The description of the product has taken a more influential position in the way data is organised and delivered in the new tool. The product-specific output mechanism identified in chapter 4 has been enhanced and adopted in the new framework. A product description based on the function of the product is used to promote a mutual understanding of the requirements ensuring a relevancy of communication between the user and the tool. This product categorisation feature aims to makes sure that the tool has a product focus, and also tries to make certain that the output mechanism is product-specific. The guidance needs to be relevant to the product the user is enquiring about and therefore it should be informed by the users inputs. The introduction of a product categorisation feature, which categorises by product function, ensures that the guidance is as relevant to the users problem as possible.

Creax, a Belgium company specialising in innovation development, identified that the majority of the products - including those in the small household appliances category of the WEEE directive - could be further grouped by common functionality, i.e. heating a material, rotating a material, and, heating and rotating a material (Creax 2005). The material is the substance being acted upon during product use and exists in three states, solid, liquid and gas. This research builds upon this classification in order to develop an approach to further simplify product categories for simpler tools. Table 19 gives four potential example appliances, identifying their primary function, the functional component responsible for delivering that function, and the material acted upon during appliance use.

Table 19 - Examples of small appliances with primary function details.

Appliance	Example	Primary function	Functional component	Material acted upon
Vacuum cleaner		Suction	Motor (rotation)	Solid and liquid
Kettle		Heating	Element (heat)	Liquid
Food blender		Rotation	Motor (rotation)	Solid and liquid
Hair dryer		Heating and blowing	Motor (rotation) and element (heat)	Gas

As an example, vacuum cleaner's primary function is the suction of dirt and dust. The most common way of achieving this is through the rotation of a fan (or similar) by a motor (or similar) which results in the suction of solid and liquid material. A standard kettle has a single function, which is to boil a quantity of water. This is achieved using a heating element which heats the liquid. Rotation is commonly a food blenders primary function using a rotating blade to blend food and drinks. The motor rotates the blade that cuts and mixes the solid and liquid materials. The hair dryer has two primary functions, heating and blowing air. This is often achieved using a fan rotated by a motor, which blows a gas over a heating element.

For many appliances this over-simplifies their primary function. However, by simplifying the function it allows a large number of appliances to be categorised into nine groups using functional attributes common to each. This simple distinction allows for greater inclusion of products, where there is a direct linkage, i.e. function.

6.2.4 Guidance components

The findings from the *Phase 1* study resulted in a new understanding of what guidance components are and how they work. This improved understanding of the guidance components common to DfE tool, i.e. strategic guidance, advice, case studies and eco-resources, has enabled the framework to be developed to fully exploit the features. The new framework utilises the learned knowledge from the investigation to ensure the components are correctly incorporated into the new tool for best effects and optimum performance.

a) Emphasis on guidance

The new framework places a much greater emphasis on the importance of the guidance and support offered by a tool. A significant finding from the *Phase 1* study highlighted that only 10 of the 22 tool investigated had any form of guidance component, and that these 10 tools were among the best performing. The new tool has to be designed so that the guidance and support is prominent. It has to be ordered in a simple and logical way to avoid user confusion and reduce the time required for completion. The importance of these guidance components has been discussed in previous chapters and this proposed tool should have the capacity to facilitate their incorporation in high frequencies.

b) Delivery components

The new framework has been designed specifically to make best use of the delivery components. During *Phase 1* and *Phase 2* of this study these components were found to help clarify the strategic guidance and advice statements given by a tool. This clarification helps to encourage confidence and add context to problems and solutions to aid the users understanding. Case study examples should be used extensively to illustrate solutions through out the output section of the new tool.

6.2.5 Frequency of guidance

The frequency of guidance components required by a tool has been investigated and discussed in the *Phase 2* study in Chapter 5. The results clearly illustrate that the tools which performed best had four important characteristics:

- Eco-resources;
- A number of case study examples;
- More than 100 advice statements, and;
- More than 5 strategies per life cycle.

For the new tool to compete with the current best tools it has to be able to accommodate a minimum of these four characteristics. These figures should however not be seen as a limitation or a maximum figure. Nor should they be seen as infallible, as evidence in Section 5.3 shows, in the case of the IdeMAT tool, which boasts 370 advice statements but less than average performance, more is not necessarily better.

6.3 Development of the tool prototype

The author developed a working prototype tool, nicknamed *Inspire Ideas*, which exploits the novel framework. Its development required skills in graphic design, web development and software coding. A screenshot of the front page is presented in Figure 21, and a detailed walk through of the developed tool is available in Appendix 4. This section will document the main steps taken to develop the prototype tool and how content was added to make it ready for user testing and verification.

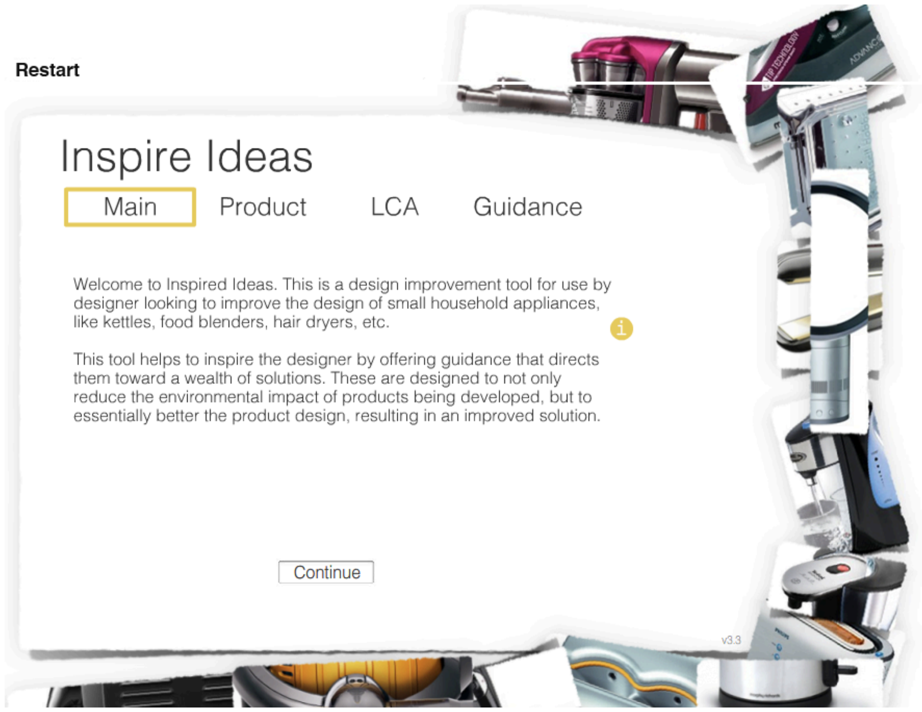


Figure 21 - Screenshot of the first page of the new tool, *Inspire Ideas*.

6.3.1 SLCA inputs required

The framework for the SLCA section has been set out in section 6.1.5, and this discusses where the inputs are required to allow product evaluation. In order to develop this empty framework into a workable tool, data had to be collected. Environmental data and information was collected from published sources including Granta Design's Eco Audit, and IDC's LCA Calculator. This data was stored in a database, a list of the types of data collected is shown in Table 20. The user inputs entered during tool use are combined with this stored data using algorithms. These algorithms (Appendix 4) determine the most detrimental life cycle stage. The results are then displayed as both relative to each other, and as absolute figure. While the units are both MJ of energy used and kg of CO_2 emitted, the energy used will be taken as the primary assessments results because this unit is better understood and more widely accepted (Stevels 2007).

Table 20 - A list of the inputs required to complete the SLCA section of the new tool.

Life cycle stage	Inputs required	Units	Options
Materials and manufacture	Part weight	Grams (g)	
	Materials type		ABS, PC, PP, PA, PS, Stainless steel, Medium steel, Aluminium, CFRP, Glass, Electronics
	Primary process type		Injection moulding, Polymer extrusion, Cast, Rolled, Metal powder formed, Autoclave moulded, Glass moulded, Electronic assembly
Transport	Distance traveled	Kilometre (km)	
	Transport type		Sea freight, Rail freight, 32T truck
Use	Product lifespan	Years (years)	
	Electricity rating	Kilowatt (kW)	
	Usage	Hours per day	
	Consumables used		Yes or no

6.3.2 Strategic guidance and advice databases

Table 21 shows the development structure used to arrive at the new tool ready for testing. The content that makes up the four guidance components, defined in Chapter 5, was a large part of the content that populates the proposed tool. The addition of the content to the framework results in a working prototype tool which was then ready for user and analytical testing.

Table 21 - Explanation of how the new tool was developed.

Framework	Content	New Tool
New	Current	New
Derived from analysis conducted in this study.	Taken from current tools.	Developed using the new framework, and populated with content, i.e. New framework + current content = New tool.

The content used to populate the tool is derived from the 10 tools investigated in the *Phase 2* study. For each tool, all of the strategic guidance and advice was transferred into an Excel spreadsheet. This content was then scrutinised to ensure there was no duplicated information. Additionally it was checked for copy-written material, and any trade names and specific references were removed. The information had to be organised into a database that the tool can use. The strategy data was organised relevant to the corresponding life cycle stage, as shown in Figure 22. The advice was then organised under each strategy, with more specific advice going under one or more of the eight specific advice categories defined in section 6.2.6.

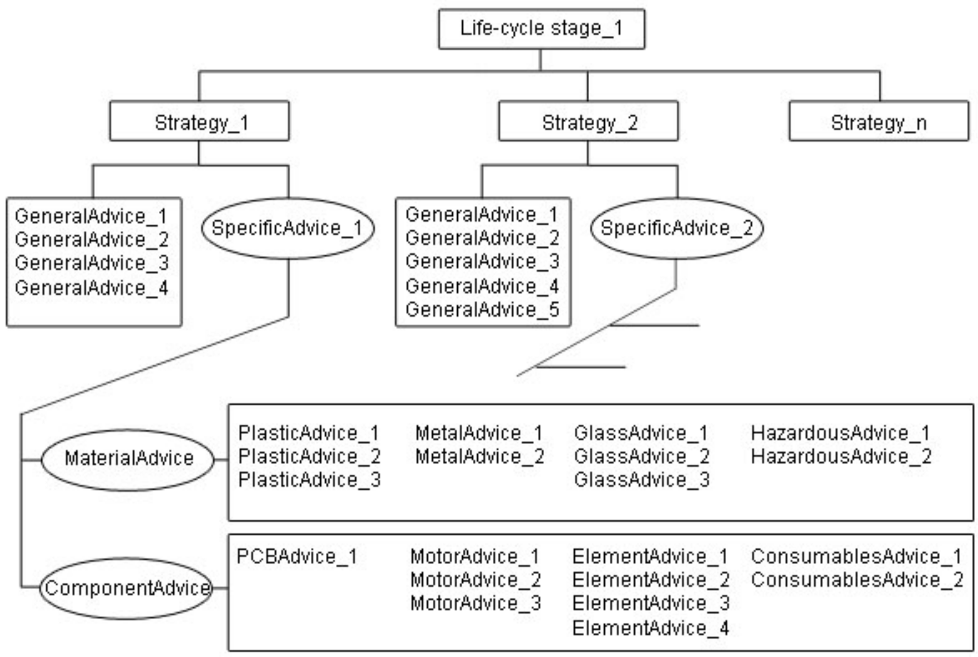


Figure 22 - A graphical representation of the database structure for each life cycle stage used in the strategy inspired section of the *Inspire Ideas* tool.

6.3.3 TRIZ examples database

Additional contents that needed to be added to the framework before testing was the analytical information derived from scrutiny of case study products against the TRIZ 'Inventive Principles'. An overview of how this process was completed is given in this section.

Three product function categories were chosen, i.e. *heat a liquid*, *rotate a solid* and *heat and rotate a gas*. Nine product examples were chosen for each category. For example, under the *heat a liquid* category nine kettles were chosen. Selection of the products was based on energy consumption during use and a visible contrast is design and technology used. For example, if a kettle was a different shape, i.e. a dome against a jug shape, and the energy consumption was different then it became of interest. This resulted in a varied range of products to best highlight potential improvements and negative factors.

Performance ability and other information was collected for each product. In the case of the kettle this information included water boiling time, element rating, water compartment size, etc. Resources such as the independent expert review website, which.co.uk and the products corresponding manufacturers website were consulted to built a complete picture of each product.

TRIZ analysis was then initiated. Any apparent innovation present in the design of the product were noted, followed by the identification of parameters associated with the innovation. The associated parameters were translated into TRIZ *characteristics*. For example, where the apparent innovation is to introduce an insulated layer into the walls to avoid heat loss, the associated parameters would be water temperature, material, heat loss. These resulted in a number of TRIZ *characteristics*, such as: loss of energy; temperature; loss of time; energy spent by stationary object; etc. The TRIZ Contradiction Matrix was then used to identify suitable TRIZ IP's which could have led to the innovation. Keeping with the insulated wall innovation, TRIZ IP's that could have resulted in that end result could be: composite materials, i.e. using a layer of insulating material as insulation; inert environment, i.e. using a layer of vacuum in the walls for insulation; partial or excessive action, i.e. keeping the water as warm as possible therefore it takes less time/energy to re-heat the next time; and cushion in advance, i.e. knowing that water will cool quicker if allowed to contact cold air, therefore insulating the walls contains the heat. Once compiled the information was structured and contents inserted into the tool, as the example illustrated in Figure 23.

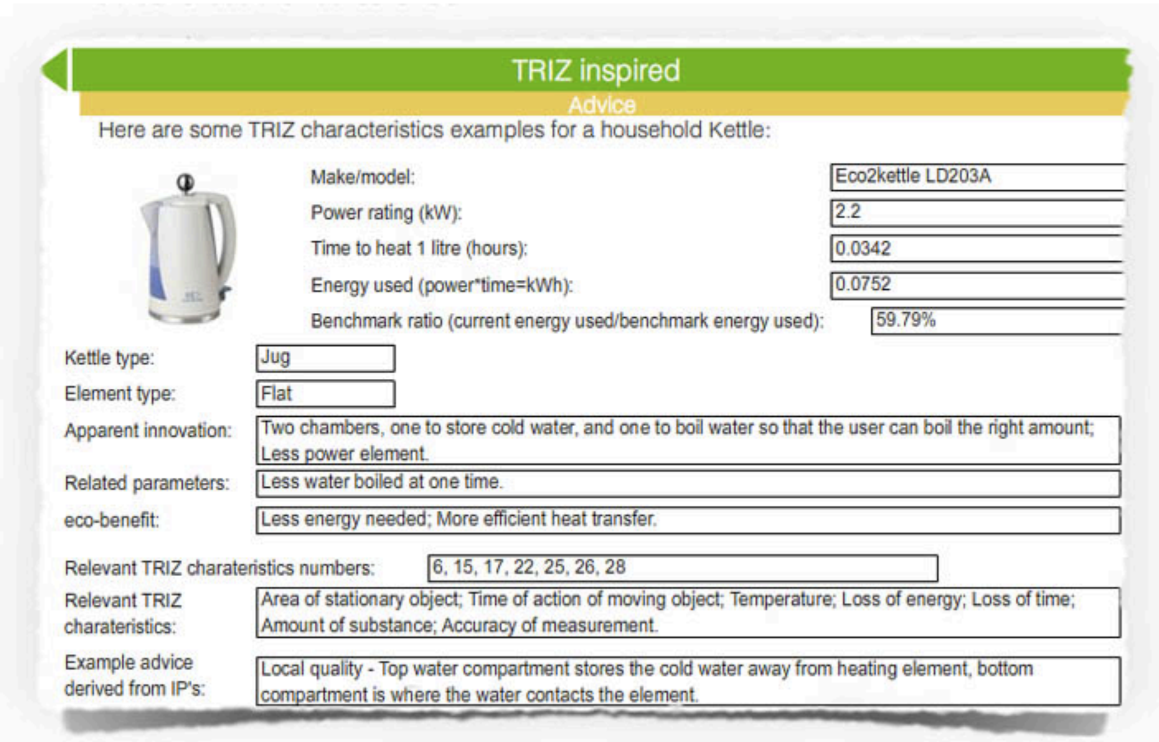
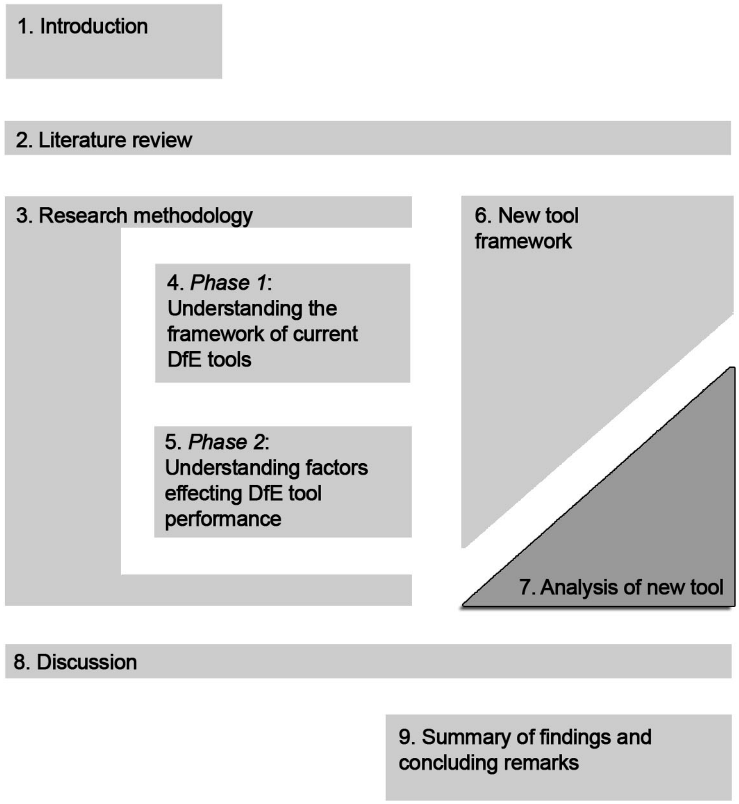


Figure 23 - Example of the way TRIZ data in structured in Inspire Ideas

6.4 Conclusions

A novel framework has been proposed. The sections have been described and explained to present how the new framework will set an improved structure for delivering tool outputs from user inputs. A prototype tool has been developed in an online software format, and has been populated with environmental data and information to allow both user and analytical testing. The next stage of the research is to assess the tool using two assessment methods. The first is to assess the performance of the new tool against the current best performing tools documented in Chapter 5. The second assessment let real designers use the tool to see how well they thought it worked.



CHAPTER 7 – Analysis of the new tool, *Inspire Ideas*.

This Chapter analyses the new tool and its framework in two steps. The first step highlights the potential performance enhancing capacity of the new framework through structured comparative analysis against current best performing tools. The new tool is quantitatively assessed relative to the 10 tools discussed in Chapter 5 to show that the framework has improved performance capability. Firstly, the new tool is scrutinised to reveal information about component type and frequency. This information is then added to the information gathered from the other ten tools during the *Phase 2* study. Tool analysis is conducted by the author and follows the structure set out in Chapter 5.

The second step aims to test the tool on real designers to let them use it to see how well they thought it operated. Feedback collected from the convenience sample groups described in

Chapter 3 is used to assess the usability and performance of the new tool. The data collected from the feedback are presented and findings are fully discussed.

The findings from these two steps are brought together and analysed in depth. Tool performance is noted for future work considerations and conclusions are drawn.

Step 1 – Quantitative analysis against current best

7.1 Determining new tool overall rating

This step assessed the performance of the new tool against the current best performing tools identified in Chapter 5. This analysis follows the same structure as that outlined and used in Chapter 5 to assess and determine an overall rating for the tools. To recount, the number of each guidance component was counted. The **overall rating** scale, shown in Table 4 (p. 54), was used to rate the individual component frequency giving five ratings from 0 – 4. These ratings were then summed to give a overall rating for the tool.

The study found that the new tool, *Inspire Ideas*, shown in Table 22 scored very well with an overall rating of 16 out of 16. This places it alongside the previously best-rated tool, Info / Insp. The new tool scored a maximum rating of four for the demonstration of strategy, advice, case studies and for the presence of eco-resources. Although the demonstration of strategy was slightly less in the new tool than that in Info / Insp, and the eco-resource rating was the same, there was a marked improvement in both the demonstration of advice and case study examples.

Table 22 – *Inspire Ideas* guidance component frequency against *only* the two previously best performing tools, SortED and Info / Insp.

Tool	Strategy	Rating 1 (0-4)	Advice	Rating 2 (0-4)	Case study	Rating 3 (0-4)	Eco-resource	Rating 4 (0-4)	Overall rating
SortED	6	2	103	3	44	3	Yes	4	12
Info / Insp	35	4	165	4	143	4	Yes	4	16
Inspire Ideas	28	4	393	4	4103	4	Yes	4	16

7.2 Overview of findings

This section gives an explanation as to why the new tool was awarded the ratings that it did using the **overall rating** scale, illustrated in Table 4. It will discuss each section individually and explain the rating given.

7.2.1 Strategy

The frequency of the guidance component 'strategy' demonstrated by the tool is a quantitative figure derived by counting the number of elements present in the tool, described in Chapter 5. With *Inspire Ideas*, the strategic guidance is contained in the strategy inspired section as discussed in Chapter 6. The strategic guidance is broken down into four categories corresponding to the relevant life cycle stages, as shown in Table 23.

Table 23 - Frequency of strategy-based guidance broken down by life cycle.

Life Cycle Stage	Frequency
Manufacturing	11
Transport	3
Use	5
End-of-life	9
Total	28

7.2.2 Advice

The advice component was not as simple to assess as the strategy component. This was because of the necessarily broad definition of 'advice', as defined in Chapter 5. Elements that fall under the definition of advice are given in many locations throughout the 'Guidance Matrix'. All three sections, strategy, function and TRIZ inspired, give advice to the user, as depicted in Table 24. The TRIZ inspired gives advice in the form of case studies, therefore it is difficult to separate and quantify. The function inspired section presents advice through internal and external eco-resources and is also therefore hard to separate. The strategy inspired section, however, has a definitive resource of structured advice organised relative to a corresponding life cycle stage and a user chosen strategy.

Table 24 - Frequency of advice broken down by life cycle.

Life Cycle Stage	Sub-category	Frequency
Manufacturing	All	99
	Plastic	12
	Metal	8
	Glass	5
	Hazardous	5
	PCB	2
Transport	All	40
Use	All	43
	PCB	10
	Element	19
	Motor	17
	Consumables	29
End-of-life	All	104
Total		393

7.2.3 Case study

The case studies presented by this tool in Table 25 are in two forms, internal and external. The internal case studies are embedded in the coding for the tool and therefore they are static, i.e. they will not change. Of this type there are 32. The external ones, however, are sourced from the *MoreInspiration* online database that returns a dynamic result based on key search terms. As this database is constantly being expanded the total number of relevant case studies is unknown, however, at date of tool testing [July 2012] the site boasted 4071 examples. This ability to search through such a large number of examples increases the probability of finding relevant case studies that fit the users requirements. This is a significant benefit over previous best-rated tool.

Table 25 - Frequency and type of case study components.

Case study location	Nature	Frequency
Internal, i.e. embedded in tool	Static	32
External, i.e. sourced from *MoreInspiration*	Dynamic	4071

7.2.4 Eco-resource

Defined as "any additional information that is supplied by a tool to aid the users' understanding of strategic guidance and advice" it was clear that there were sufficient eco-resources present in the tool. Though much of this is found in the external features that the tool makes use of, i.e. the *Creax Function* database and the *MoreInspiration* database, there was a definite presence throughout the guidance matrix as well. The resources found in the external resources are accessed via a link from the tool to the relevant website.

7.3 Discussions of step 1 findings

These findings suggest that the new framework in the *Inspire Ideas* tool has the capacity to accommodate sufficient guidance and delivery components to ensure its performance is competitive with current best performing tools. These findings confirm theoretically that the new framework is as good as the current best. The added capacity of this framework to expand and make use of external resources has the potential to further improve its performance, paving the way for the next generation of tools with improved performance.

It is necessary to note that this new tool has many limitations resulting from its immature status as a prototype tool. This prototype is intended to assess the potential benefits of the new framework developed during this research. As such there are many issues, which arose during feedback gathering that would not have been present if the tool was more mature and in later stages of development.

There was no additional instructional material available with the tool, only that embedded in the tool. A common complaint regarding existing DfE tools was the time consuming manuals and instructions that often accompanied them. The intention with this tool was to make it self-explanatory, and to include any instructional material in the contents of the tool to facilitate fluidity, and keep completion time to a minimum.

Step 2 – User feedback

The following section will detail and discuss the feedback acquired from both feedback sessions, using both self-administered questionnaires and semi-structured interviews. The feedback was based on the designers' hands-on experience of the tool, and was relevant to how the tool operated.

7.4 Student designer group

This section will present the important findings resulting from the user feedback data from the student designer group. The initial overview of the questionnaire results is very convincing. All ten questions achieved a satisfactory response rate.

7.4.1 Overview of feedback data

Q1 - Have you used an environmental design tool before?
Q2 - If Yes, please rate how useful you found that tool?
Q3 - How useful did you find the new tool?
Q4 - How easy did you find the new tool to use?
Q5 - How well did the new tool help you generate ideas/solutions?
Q6 - How well did the new tool help you explore ideas/solutions?
Q7 - How relevant was the content of the "Guidance" pages (i.e. Strategy inspired, Function inspired, TRIZ inspired) to the product you were developing?
Q8 - What, in your opinion, are the strengths of the new tool?

Q9 - What, in your opinion, are the weaknesses of the new tool?
Q10 - Would you consider using the new tool in future projects?

Q1 and Q2 gave some background about the use of DfE tools. The responses to Q1 show that 95.1% of the respondents had not previously used an environmental design tool. Two respondents stated that they had used a tool. However, as the responses to Q2 illustrate, there must have been some confusion. Q2 asked for the respondents who had previously used a tool to rate their experiences. Table 26 illustrates a discrepancy between the results that is discussed in the following section, i.e. only two people claimed to have used an environmental tool before in Q1, however, 11 respondents answered Q2.

Table 26 – Overview of responses to Q1 and Q2.

Questions	Rating	Rating definition	Responses %	Rating 4+5 as %
Q1. Have you used an environmental design tool before? (n = 42)				
	Yes	2	4.9%	
	No	39	95.1%	
Q2. If Yes, please rate how useful you found the tool? (n = 11)				
	1	Very useless	9.1%	
	2	Useless	9.1%	
	3	Neutral	18.2%	
	4	Useful	54.5%	
	5	Very useful	9.1%	63.6%

Of the five questions relevant to assessing the qualitative performance of the tool, i.e. Q3, Q4, Q5, Q6, Q7, they all achieved a very high number of positive responses, i.e. choosing a "4 = Easy" or "5 = Very easy", or equivalent, option, as shown in Tables 27-31.

Q3 is of immediate interest as it asked how useful the respondent found the tool. A considerable 56.7% of the respondents said they found it either 'useful' or 'very useful', as shown in Figure 24.

Table 27 - Overview of responses to Q3, showing response % for rating 4 and 5 for each question.

Questions	Rating	Rating definition	Responses (%)	Rating 4+5 (%)
Q3. How useful did you find the tool? (n = 37)				
	1	Very useless	0.0%	
	2	Useless	5.4%	
	3	Neutral	37.8%	
	4	Useful	45.9%	
	5	Very useful	10.8%	56.8%

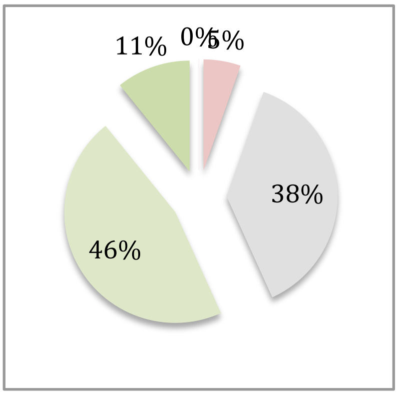


Figure 24 - Responses to Q3 presented as a proportionality diagram. Legend corresponds to adjacent Table.

This trend is also true about the other four questions. Skipping over Q4 for a second, Q5 and Q6 will be discussed. The respondents gave very satisfactory results to both questions, with 54.1% of users giving positive feedback to both, i.e. choosing “4 = Well” or “5 = Very well” as shown in Table 28 and 29. Figures 25 and 26 illustrate the results, showing the larger proportion (11%) of “5 = Very well” responses to Q6, against only 5% to Q5. This suggests that the respondents found the tool’s ability to explore idea’s stronger than its ability to generate them.

Table 28 - Overview of responses to Q5, showing response % for rating 4 and 5 for each question.

Questions	Rating	Rating definition	Responses (%)	Rating 4+5 (%)
Q5. How well did the tool help you generate ideas/solutions? (n = 37)				
	1	Very poor	0.0%	
	2	Poor	10.8%	
	3	Neutral	35.1%	
	4	Well	48.6%	
	5	Very well	5.4%	54.1%

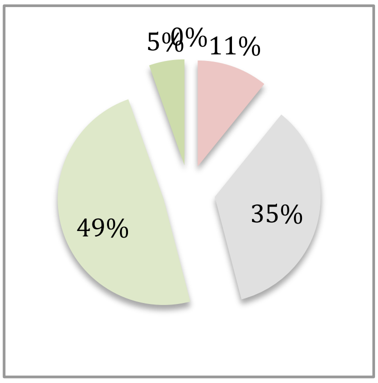


Figure 25 - Responses to Q6 presented as a proportionality diagram. Legend corresponds to adjacent Table.

Table 29 - Overview of responses to Q6, showing response % for rating 4 and 5 for each question.

Questions	Rating	Rating definition	Responses (%)	Rating 4+5 (%)
Q6. How well did the tool help you explore ideas/solutions? (n = 37)				
	1	Very poor	0.0%	
	2	Poor	16.2%	
	3	Neutral	29.7%	
	4	Well	43.2%	
	5	Very well	10.8%	54.1%

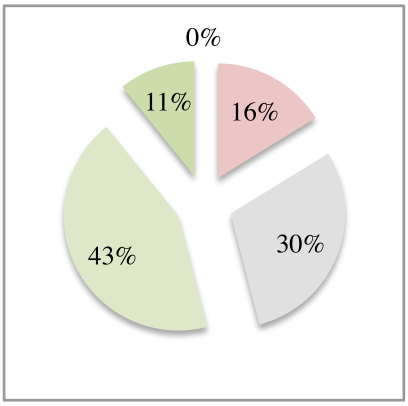


Figure 26 - Responses to Q4 presented as a proportionality diagram. Legend corresponds to adjacent Table.

Tables 30 and 31 show that Q4 and Q7 had a less substantial result, however, it is still noteworthy. Q4 asked the users how easy they found the use of the tool. Figure 27 shows that

45.9% of respondents stated that they found the tool either 'easy' or 'very easy' to use. A similar result came from Q7 which asked the users how relevant the content of the 'guidance' pages were to the product they were developing. To which 43.2% of respondents said that they found it either 'relevant' or 'very relevant' as illustrated in Figure 28. Notably, the "5 = Very well" option received the largest proportion of responses in Q4 (22%), twice that of Q3 (11%), Q5 (11%), Q6 (11%) and Q7 (5%). The observation suggests a more unified opinion among respondents than other questions, that the tool is indeed very easy to use.

Table 30 – Overview of responses to Q4, showing response % for rating 4 and 5 for each question.

Questions	Rating	Rating definition	Responses (%)	Rating 4+5 (%)
Q4. How easy did you find the tool to use? (n = 37)				
	1	Very hard	2.7%	
	2	Hard	5.4%	
	3	Neutral	45.9%	
	4	Easy	24.3%	
	5	Very Easy	21.6%	45.9%

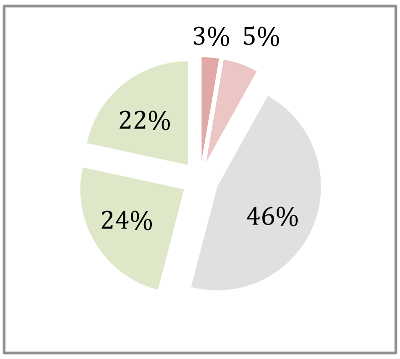


Figure 27 - Responses to Q4 presented as a proportionality diagram. Legend corresponds to adjacent Table.

Table 31 - Overview of responses to Q7, showing response % for rating 4 and 5 for each question.

Questions	Rating	Rating definition	Responses (%)	Rating 4+5 (%)
Q7. How relevant was the content of the "Guidance" pages (i.e. Strategy inspired, Function inspired, TRIZ inspired) to the product you were developing? (n = 37)				
	1	Very irrelevant	0.0%	
	2	Irrelevant	8.1%	
	3	Neutral	48.6%	
	4	Relevant	32.4%	
	5	Very relevant	10.8%	43.2%

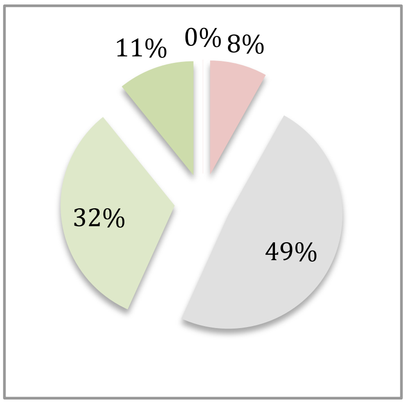


Figure 28 - Responses to Q7 presented as a proportionality diagram. Legend corresponds to adjacent Table.

Q8 and Q9 also introduced some interesting results. Q8 asks what were the strengths of the tool. As shown in Table 32 there was an excellent response rate to this question. The respondents where told to choose as many strengths as they like, resulting in the 37 respondents choosing on average three strengths each. The top scorers were 'Simplicity' and 'Interface' with 62.2% of the respondents. The *inspired section's* follow closely behind, 'The 'strategy inspired' section' with 48.7%, 'The 'function inspired' section' with 45.6% and 'The 'TRIZ inspired' section' with 37.8%.

Table 32 - Overview of responses to Q8.

Question	Response count, a^s	Respondents, a^s/n (%)
Q8. What, in your opinion, are the strengths of the tool? Please choose as many as you like. (n = 37)		
Simplicity	23	62.2%
Interface	23	62.2%
The ‘strategy inspired’ section	18	48.7%
The ‘function inspired’ section	17	45.6%
The ‘TRIZ inspired’ section	14	37.8%
The support offered	11	29.8%
External links	6	16.2%
No strengths	0	0%
Other… (free text box)	0	0%
Total responses	112	

Q9 asked what were the weaknesses of the tool. Again the respondents were told to choose as many weaknesses as they liked, however, the response rate for this question was not as strong as the previous question. There were only 62 responses from 37 respondents. Table 33 illustrates the most chosen weakness was the ‘Lack of case studies’ with 46.0%. This was followed by ‘Lack of information’, ‘Complexity’, ‘Navigation’, and ‘Lack of support’ with 29.7%, 24.3%, 21.6% and 18.9%, respectively. Also worth mentioning is that the ‘No weaknesses’ and ‘Other…’ choices received 13.5% of respondents each. Weaknesses suggested under the ‘Other…’ option included issues with tool complexity, navigation and clarity of tool instructions.

Table 33 - Overview of responses to Q9.

Question	Response count, b^s	Respondents, b^s/n (%)
Q9. What, in your opinion, are the weaknesses of the tool? Please choose as many as you like. (n = 37)		
Lack of case studies	17	46.0%
Lack of information	11	29.7%
Complexity	9	24.3%
Navigation	8	21.6%
Lack of support	7	18.9%
No weaknesses	5	13.5%
Other… (free text box)	5	13.5%
Total responses	62	

Q10 is of particular interest. Q10 asks whether the respondent would consider using the tool in future projects. The responses to this were very reassuring with 91.9% of the respondents saying "Yes", as shown in Table 34.

Table 34 - Overview of responses to Q10.

Question	Response count	Responses %
Q10. Would you consider using the tool in future projects? (n = 37)		
Yes	34	91.9%
No	3	8.1%

7.4.2 Discussions of feedback analysis

This section analyses the feedback from the student designer group. It will identify any major trends and discussion points, and give a break down of the significant results.

Pivot tables and χ^2 testing were used to verify that the results of the questions were significant and not due to chance. For a result to be significant with this series of analysis, $p \leq 0.05$.

Initial analysis involved identifying questions which would be suitable to reference against in a Pivot table in order to assess the statistical significance of the responses to other questions. Q1 and Q10 (Have you used an environmental design tool before, and, would you consider using the tool in future projects?) were the obvious choice as they were simple yes/no questions. Using pivot tables to test the χ^2 values using Q10 proved useful as it established that the responses to Q5 and Q7 were significant. However, χ^2 testing using Q1 returned no significant results. Therefore, other questions had to be considered. Q3 (state question) appeared during analysis as the most appropriate as it confirmed the statistical significance of Q4, Q5, Q6 and Q7. Analysis was also conducted to assess Q8 against Q3.

Solution generation and relevance

Shown by 54% of respondents, the results of the Q5 versus Q10 analysis supported the hypothesis that the tool helped them to generated solutions “Well” or “Very well” ($p = 0.011$). This was further backed up by the resultant analysis of Q7 versus Q10, which showed that 43% of people agreed that the content of the guidance matrix was relevant to the product they were developing was also highly significant ($p = 0.002$).

These results are important as they confirm that over half of the users thought that the tool had a positive effect on their ability to generate solutions. It also confirms that the tool was delivering guidance that was relevant to the user’s product.

Assessing tool usefulness against other factors

Analysis of the Q3 results, which asks the respondent to specify how useful they found the tool, determines how many respondents found the tool positive, i.e. either “4 = Useful” or “5 = Very useful”. All respondents who answered positively to Q3, referred to as the “*Q3 filter*”, where then further analysed against Q4-Q7 individually.

The *Q3 filter* was applied to the responses to Q4 ($n = 37$). After scrutinising the remaining 21 respondents it was revealed that 37.1% found the tool either “Useful” or “Very useful” and also either “Easy” or “Very easy” to use, with a large percentage of the reminder choosing a neutral response. This suggests that for those who found the tool useful, over a third of them also found the tool easy to use, with very few finding it hard to use ($p = 0.027$).

The *Q3 filter* was applied to the responses to Q5, Q6 and Q7. The analysis revealed:

- 40.5% of respondents to Q5 found the tool useful and also found it helped them generate solutions either “Well” or “Very well” ($n = 37$; $p = 0.02$);
- 37.8% of respondents to Q6 found the tool both useful and also found it helpful in exploring solutions “Well” or “Very well” ($n = 37$; $p = 0.00002$), and;
- 35.1% of respondents to Q7 also found the tool useful, and agreed that the content of the tool was either “Relevant” or “Very relevant” to the product they were developing ($n = 37$; $p = 0.046$).

These results clearly illustrate that the respondents who found the tool useful, also found that the content in the guidance matrix helped them generate and explore solutions.

How tool strengths vary depending on tool usefulness.

Another interesting result is related to Q3 and Q8. Initial observation of the results suggests that the order of importance of the tool strengths is illustrated in Table 35. This analysis works on the basis that these are the responses from people answering 4-5 on Q3, and therefore found the tool ‘useful’ to ‘very useful’.

Table 35 - Responses to tool strengths (Q8) against how useful the tool is (Q3), showing how the order of strengths differs depending on whether all, or only positive responses are considered.

Q8 – What are the strengths of the tool?	Q3 - How useful did you find the tool?			
	All respondent's with rating of 1-5 [A] (n = 37)	All respondent's with rating of 4-5 [B] (n = 21)	Difference (%) [A vs B]	+ive = pass -ive = fail
Simplicity	23	12		
Responses / Total	20.5%	18.2%	-11.2%	fail
Interface	23	14		
Responses / Total	20.5%	21.2%	3.4%	pass
The 'strategy inspired' section	18	12		
Responses / Total	16.1%	18.2%	13.0%	pass
The 'function inspired' section	17	10		
Responses / Total	15.2%	15.2%	0%	fail
The 'TRIZ inspired' section	14	8		
Responses / Total	12.5%	12.1%	-3.2%	fail
The support offered	11	6		
Responses / Total	9.8%	9.1%	-7.1%	fail
External links	6	4		
Responses / Total	5.4%	6.1%	13.0%	pass
No strengths	0	0	0%	fail
Other	0	0	0%	fail
Total responses, C.	112	66		

Table 35 shows the percentage difference between the full 37 respondents results and the positive 21 respondents. There are two strengths which were chosen more often by the positive respondents than by all respondents. "The 'strategy inspired' section" and "The external links" proved to be a more successful strength to those respondents who found the tool useful.

This analysis shows that there is a different emphasis with regards to the tools strengths depending on how useful the tool was. When considering all 37 respondents, "Simplicity" and "Interface" are the highest frequency strengths, followed by "The 'strategy inspired' section".

However, when only the positive responses are considered, “Interface” becomes the most chosen strength followed by “The ‘strategy inspired' section” and “Simplicity”, as illustrated in Figure 29. This is interesting at it suggests that the respondents who found the tool useful also found “The ‘strategy inspired’ section” of more value, than did the rest of the respondents.

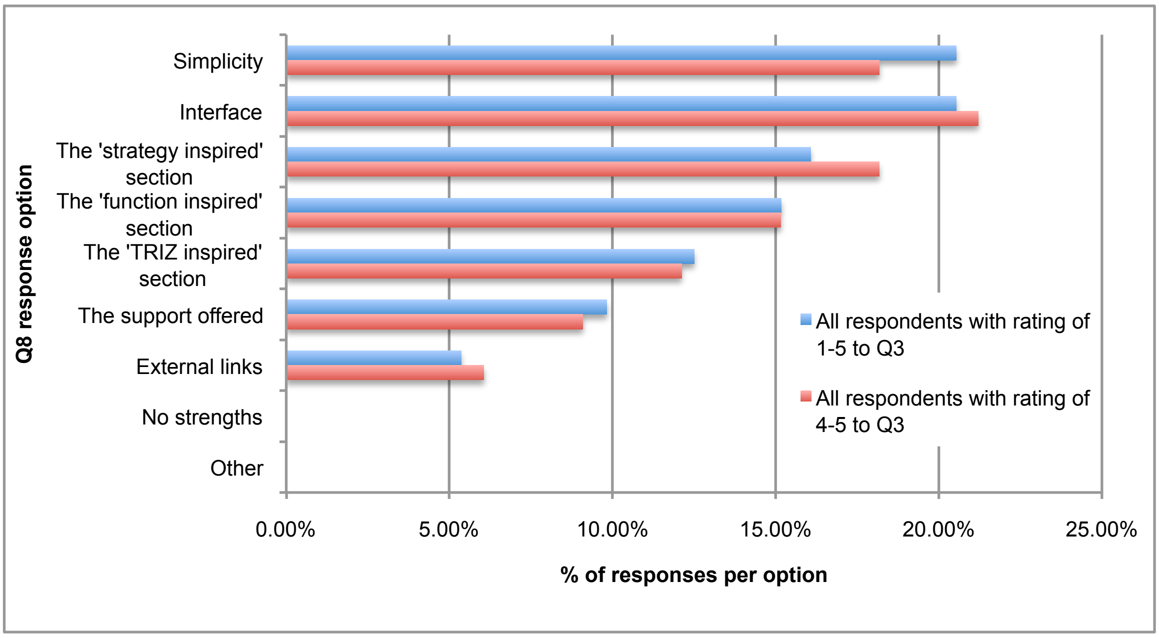


Figure 29 - The responses to Q8, showing how the relative % of responses per option varies depending on respondents’ response to Q3.

Lack of content

A disappointing finding was that of the responses to Q9 where the participants where asked to identify the weaknesses of the tool. The response with highest frequency is “Lack of case studies” followed by “Lack of information”. This is disappointing because these are the two areas where the new features of this tool intended to improve. Step 1 of this analysis highlights that the new tool accesses 32 internal case studies and over 4000 external ones via the *MoreInspiration* database. This is far more than any other tool analysed in this study. The problem could have arisen due to a number of reasons. One reason could be that the tested tool is not complete, i.e. it is a prototype tool created for demonstration purposes. The lack of case studies and information is understandable given that this tool is only intended to demonstrate the capability of the framework, and therefore it is only populated with case study examples for three types of product.

An additional reason could have resulted from the *MoreInspiration* database. Though there are a large number of case study examples present, they cover many fields and many types of product. Therefore, there are only a limited number of examples which might be relevant to the users product type. However, for the internal case study examples, three have been fully populated each with nine examples, so if all 25 product types were completed there could be as many as 225 cases for reference.

There is still the issue of a lack of information, which could be related to the minimal eco-resources present in this prototype. The framework has the potential to be better filled. However, this was not achievable due to time constraints.

Confusion in responses

Other questions that are of lesser relevance are Q1 and Q2. Q1 asked whether the respondent had used an environmental design tool before. An initial glance at the results could suggest a significant result with 41 respondents, and two saying “Yes” they had. A closer scrutiny revealed that these two respondents claimed to have used the *Inspire Ideas* tool, i.e. the tool under development in this project, before and therefore their result is of no use. This issue of confusion was further compounded in Q2, where the respondents who had answered “Yes” to the previous question had to rate the usefulness of the tool they had used. Confusion occurred as there were 11 respondents, which considering only two respondents confessed to using another tool in Q1, invalidate the results.

7.5 Professional designer group

This section presents the feedback results from the professional designer group.

7.5.1 Overview of feedback data

11 designers gave feedback on the *Inspire Ideas* tool. Q1 shows that 18.2% of the respondents had used an environmental design tool before. These respondents then listed up to 15 various tools. Again, there must have been some confusion among respondents as six respondents went on to answer Q2. Table 36 illustrated the discrepancy.

Table 36 – Overview to responses to Q1 and Q2.

Questions	Rating	Rating definition	Responses %
Q1. Have you used an environmental design tool before? (n = 11)			
	Yes	2	18.2%
	No	9	81.8%
Q2. If Yes, please rate how useful you found the tool? (n = 6)			
	1	Very useless	16.7%
	2	Useless	16.7%
	3	Neutral	33.3%
	4	Useful	33.3%
	5	Very useful	0.0%

The results for Q3 shown in Table 37 and illustrated in Figure 30 show a disappointingly low positive result, with only 18.2% of respondents finding the tools "4 = Useful" or "5 = Very useful". The majority of respondents (63.6%) rated the tool "3 = Neutral".

Table 37 - Overview of responses to Q3.

Questions	Rating	Rating definition	Responses (%)
Q3. How useful did you find the tool? (n = 11)			
	1	Very useless	0.0%
	2	Useless	18.2%
	3	Neutral	63.6%
	4	Useful	18.2%
	5	Very useful	0.0%

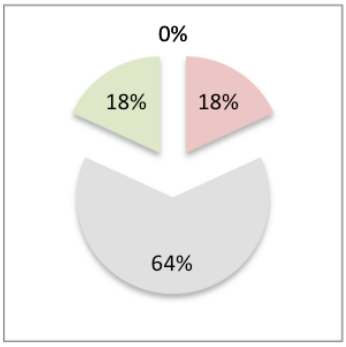


Figure 30 - Reponses to Q3 as a proportionality diagram. Legend corresponds to adjacent Table.

Q4 is of considerable interest as it shows that a huge majority of respondents (72.8%) found the tool either "4 = Easy" or "5 = Very easy" to use. This is further emphasised by the lack of negative responses, i.e. "1 = Very hard" and "2 = Hard", detailed in Table 38 and Figure 31.

Table 38 - Overview of responses to Q4.

Questions	Rating	Rating definition	Responses (%)
Q4. How easy did you find the tool to use? (n = 11)			
	1	Very hard	0.0%
	2	Hard	0.0%
	3	Neutral	27.3%
	4	Easy	45.5%
	5	Very easy	27.3%

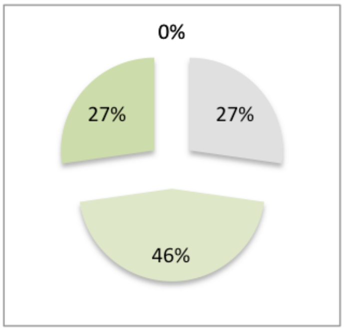


Figure 31 - Responses to Q4 as a proportionality diagram. Legend corresponds to adjacent Table.

Table 39 shows that Q5 gave disappointing result with only 18.2% positive results, and a large 27.3% negative, i.e. "1 = Very poor" or "2 = Poor". This left a significant 54.5% of the responses as "3 = Neutral" as shown in Figure 32.

Table 39 - Overview of responses to Q5.

Questions	Rating	Rating definition	Responses (%)
Q5. How well did the tool help you generate ideas/solutions? (n = 11)			
	1	Very poor	9.1%
	2	Poor	18.2%
	3	Neutral	54.5%
	4	Well	18.2%
	5	Very well	0.0%

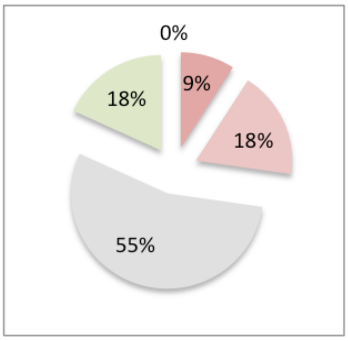


Figure 32 - Responses to Q5 as a proportionality diagram. Legend corresponds to adjacent Table.

The responses to Q6 show some promise, as illustrated in Figure 33. 27.3% of respondents thought the tool helped them explore ideas 'well', but no one thought it helped 'very well'. Only 18.2% of responses were negative, as shown in Table 40.

Table 40 - Overview of responses to Q6.

Questions	Rating	Rating definition	Responses (%)
Q6. How well did the tool help you explore ideas/solutions? (n = 11)			
	1	Very poor	9.1%
	2	Poor	9.1%
	3	Neutral	54.5%
	4	Well	27.3%
	5	Very well	0.0%

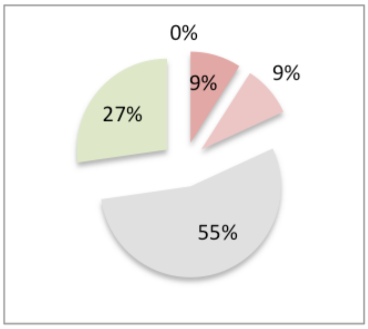


Figure 33 - Responses to Q6 as a proportionality diagram. Legend corresponds to adjacent Table.

Table 41 shows that 36.4% of respondents to Q7 found that the content of the "Guidance" pages were 'relevant' to the product they were developing, with only 9.1% negative responses. Figure 34 show that 54.5% of respondents gave a 'Neutral' results.

Table 41 - Overview of responses to Q7.

Questions	Rating	Rating definition	Responses (%)
Q7. How relevant was the content of the "Guidance" pages (i.e. Strategy inspired, Function inspired, TRIZ inspired) to the product you were developing? (n = 11)			
	1	Very irrelevant	9.1%
	2	Irrelevant	0.0%
	3	Neutral	54.5%
	4	Relevant	36.4%
	5	Very relevant	0.0%

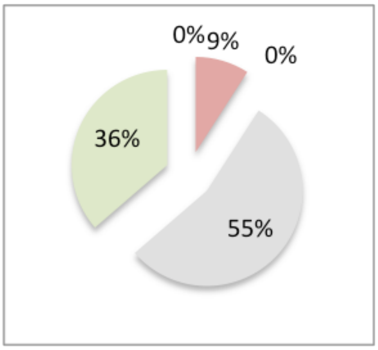


Figure 34 – Responses to Q7 as a proportionality diagram. Legend corresponds to adjacent Table.

Q8 allowed multiple answers and received a total of 20 responses from 11 respondents. The most prominent strength was 'Simplicity', chosen by 63.4% of the respondents. 'Interface' and 'The 'strategy inspired' section' were also popular being chosen by 27.4% of respondents. Interestingly, the 'No strengths' option and 'Other…' free box achieve 18.2% of respondents each. The remaining four options, shown in Table 42, received 9.1% of respondents' votes, except from 'The 'TRIZ inspired' section' which received none.

Table 42 - Overview of responses to Q8.

Question	Response count, a^P	Responses a^P/n (%)
Q8. What, in your opinion, are the strengths of the tool? Please choose as many as you like. (n = 11)		
Simplicity	7	63.4%
Interface	3	27.4%
The 'strategy inspired' section	3	27.4%
No strengths	2	18.2%
Other… (free text box)	2	18.2%
The 'function inspired' section	1	9.1%
The support offered	1	9.1%
External links	1	9.1%
The 'TRIZ inspired' section	0	0%
Total responses	20	

17 responses were received from 11 respondents to the multiple answer, Q9. 45.5% of them further explained their views of the tools weaknesses using the 'Other…' box as shown in Table 43. Table 44 shows that 'Lack of information' followed by 'Lack of case studies' and 'Navigation' were identified as other weaknesses, including a 'Lack of support'. 'Complexity' was not identified as an issue.

Table 43 - Comments from the 'Other…' option to Q9.

Comments from the 'Other…' free box option to Q9
lack of process and materials
No breakdown of components hotspots; hard to examine sensitivity of inputs (eg product lifespan)
A little over simple? I tried a simple 5 product input and could see numerous input variants with an impact on end of life power usage that were not considered.
too broad/general, misses targets

Table 44 - Overview of responses to Q9.

Question	Response count, b^p	Responses b^p/n (%)
Q9. What, in your opinion, are the weaknesses of the tool? Please choose as many as you like. (n = 11)		
Other… (free text box)	5	45.5%
Lack of information	4	36.4%
Lack of case studies	3	27.3%
Navigation	3	27.3%
Lack of support	2	18.2%
Complexity	0	0%
No weaknesses	0	0%
Total responses	17	

Table 45 illustrates that 40% of the respondents would actively consider using the *Inspire Ideas* tool in future projects. It is noted that only 10 of the possible 11 respondents answered this questions.

Table 45 - Overview of responses to Q10.

Question	Response count	Responses %
Q10. Would you consider using the tool in future projects? (n = 10)		
Yes	4	40%
No	6	60%

7.5.2 Discussions of feedback analysis

This section will now discuss the results from the professional designer group. On the whole the results were positive.

Simplicity is the key

A significant finding was that the respondents found the tool easy to use, and that the tool's simplicity was a strength. This is stated in Q4 where 72.8% of respondents found the tool either "4 = Easy" or "5 = Very easy" to use, and it is further stated in Q8 where 63.4% of the 11 respondents chose it as a strength. Due to the relatively low number of respondents (n = 11) it was not possible to conduct statistical analysis for all responses to the questions. However, the responses to Q4 were found to be statistically significant.

Content relevancy

The results to Q7 showed that a large proportion of the group found the tools contents relevant to their project. Further to this only one respondent found the content irrelevant or less, with the majority of respondents opting for a neutral stance. This suggests that the framework has successfully delivered relevant content and guidance to the user through the process of function categorisation, input collection and output specificity, a structure that is unique to this framework.

Usefulness and ability to help

Q3, Q5 and Q6 on the whole gave quite inconclusive results about the ability of the tool to help designers to generate and explore solutions and on general usefulness. Q3 had as many positive responses as negative ones with the majority of them being neutral. However, none of the negatives or positives were at the top of the range, i.e. “1 = Very useless” or “5 = Very useful”. This middle of the road opinion could have resulted from a balance between the tool strengths and its identified weaknesses, i.e. its simplicity of use, interface and strategy inspired section against its lack of information and others weaknesses.

Q5 had slightly more negative responses than positives, but again the majority of responses were neutral. In this case there were both negative responses, i.e. “1 = Very poor” and “2 = Poor” suggesting a slightly more prominent view that helping designers to generate solutions may not be this tool’s strong point. Contrasting this view is the apparent opinion of responses to

Q6, which suggests a positive response towards the tool's ability to help designers explore solutions and ideas.

Low previous use of tools

The responses to Q1 are quite revealing. These state that only two out of a possible 11 designers recruited for this study due to their product development expertise had used an environmental design tool before. This low result is disappointing which reflects the priority given to DfE within the industry. Potentially the benefits of the *Inspire Ideas* tool could improve this situation.

Potential for future use

Just under half of the respondents said that they would consider using the *Inspire Ideas* tool on future projects. Given that only two of the designers had previously used an environmental design tool before this study, it is encouraging that four designers have decided to consider further use of this tool.

7.6 Discussions of step 2 findings

This section will bring together the results from the student and the professional designer groups, as well as the qualitative feedback recorded during the designer interviews in order to identify and highlight any common trends and make visible any contrasting results.

On the whole the student designer group responses were much more positive than that given by the professional designer group. All questions asking about tool performance given certain tasks, i.e. Q3, Q4, Q5, Q6 and Q7, showed a large positive response from the students (often >50%) with a very small negative response in each case (often <10%). This can be contrasted against the significantly more balanced responses presented by the professional designers, where in most cases a neutral response was prominent (often >50%).

The first common finding is that only a small percentage of each group had previously used an environmental design tool. Although this was fully expected with the student group given their lack of experience, it came as some surprise that so few of the professional group had, given their eligibility for inclusion as a BDI member. It could perhaps be inferred that environmental design tool use in the UK is probably very low, however, this would have to be confirmed with a wider survey.

The issue of tool simplicity is acknowledged as a significant positive and a strength by both the student and the professional designer groups. These results can be further linked to the interview responses. A comment from one professional designer was that due to the tool's ease of use and simplicity it would be suited for use in education, to train and educate designers in DfE practices. This undeniable strength suggests that a pedagogical future for this tool could have many educational benefits.

An interesting result is the commonality between the two groups regarding the tool's strengths. Both groups identified 'Simplicity', 'Interface' and 'The 'strategy inspired' section' as the three main strengths. 'Simplicity' has already been discussed, and to some degree so has the 'Interface'. The acknowledgement of 'The 'strategy inspired' section' as the third key strength is very encouraging. If this result is coupled with the responses to Q7 from both groups, i.e. showing that both groups have a large positive response rate (positive >35%), it can be inferred that the categorisation feature and input/output management of the new framework has been a success. It suggests that the content and guidance given in 'The 'strategy inspired' section' is sufficiently relevant to their product for it to be deemed a strength.

Both groups inferred that the ability of the tool to help explore solutions (Q6) was better than its ability to help generate them (Q5). This finding suggests that the content and structure of the tool is more suited to idea exploration than idea generation. The professional designers who were interviewed further back up the findings. A significant feedback comment was the ability of the tool to promote alternative thinking during the design concept generation phase. Examples that were given included linking together similar methods of producing a function which a designer may have overlooked or may not be familiar with, i.e. using the 'function inspired' section, and overcoming company inertia by highlighting alternative processes. Both interviewees agreed that this was a definite benefit of the tool, and this is hinted towards through identification of the 'function inspired' section as a strength by the student group.

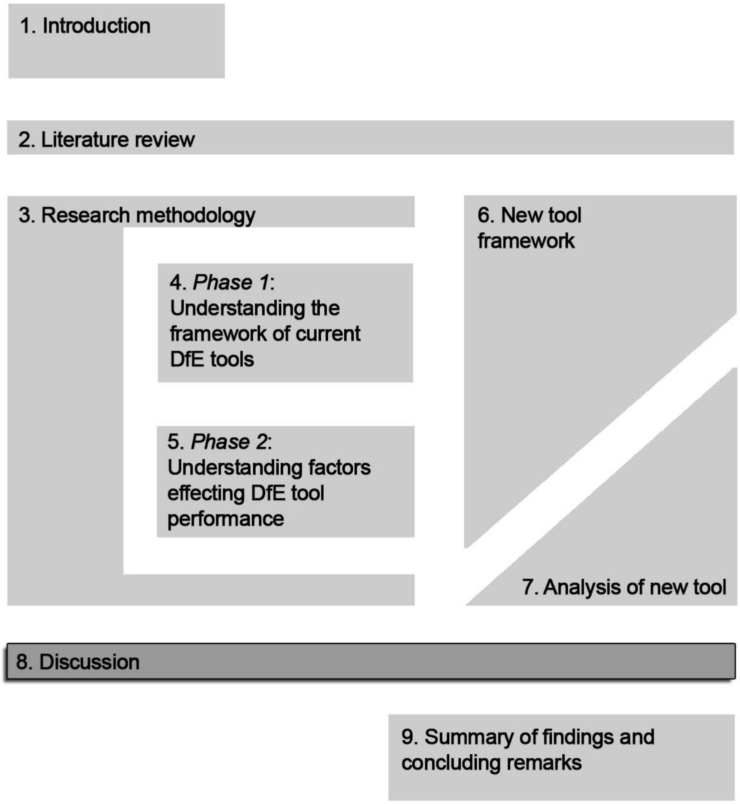
The contrasting view between the two groups responses to Q3, Q5 and Q6, i.e. the student group were mainly significantly more positive than the professional group, could suggest that the tool is best suited to use by students and inexperienced designers for training purposes as opposed to by professional designers on commercial projects. This outcome could have stemmed from the author's strong academic and educational background and a lack of commercial experience. If this were the case it would be an inherent flaw in the project, and would need to be rectified through closer contact and better inclusion of industrial partners throughout the development and execution of the project.

7.7 Conclusions

As the feedback regarding the performance of the new tool shows, it has many positive attributes. The main findings from Step 1 of the tool analysis found that the new framework, which the *Inspire Ideas* tool is built upon, can accommodate a higher level of guidance making it out perform the best performing tools. These results confirm that the new framework has improved performance due to its ability to maximise known beneficial characteristics, such as the guidance components - strategic guidance and advice. These characteristics improve the user's ability to generate and explore solutions by giving them the necessary cues. Assessment of the required frequency of guidance components is crude as it favours only the highest frequency and does not consider quality or whether there is a maximum frequency limit. There is, however, a clear trend identified that tool performance improves with increase in component frequency concluding the new framework's large capacity will be a definite benefit as opposed to a hindrance.

Step 2 has a number of findings, of which the overall outcome is a significant contrast between the two groups of respondents. The majority of student designer group found the tool useful, and said it helped them to generate and explore solutions with guidance relevant to their project. The professional designer group were inconclusive about the tool's usefulness and its ability to help generate and explore solutions. However, they definitively confirmed the relevance of the content and guidance, and concluded that the tool is easy to use.

The results have verified that the proposed framework has a number of benefits to a designer. The most intriguing results common to both test groups were regarding the tool's ease of use and its simplicity. Also significant is the strong acknowledgement by both the student and the professional designer group that the content delivered by the tool in the guidance matrix was relevant to the product being developed. This issue of redundancy of information was highlighted in Chapter 2 as one of the main downfalls of current DfE tools, therefore this verification of the tool's ability is important. These improvements give the tool a real benefit over current tools as it gives the designer a setting to be able to generate and to explore ideas confidently, knowing that the information and case studies presented will be relevant to their product.



CHAPTER 8 – Discussion

This chapter compares and contrasts the research findings put forward in this thesis with work by other authors in the field. It also discusses the relevance of this research to the current body of knowledge and identifies how it can be applied to bring about palpable improvements in the design and functionality of Design for Environment tools of the future.

8.1 Contrasting approach and applicability

The work in this thesis has set about understanding how DfE tools can better fit the requirements of the designer. Understanding the barriers to the adoption of Design for

Environment tools has been a subject of multiple works (Knight, Jenkins 2009, Byggeth, Hochschorner 2006, Lindahl 2006, O'Hare 2009).

We know that we need more user-friendly, effective DfE tools with beneficial performance that designers will readily use in their day to day work.

Lindahl (2006) found that designer would use a DfE tool if:

- it had been found to be useful;
- a customer required it;
- the tool covered issues handled on daily basis;
- it were not complicated to use.

A number of external pressures impact on the adoption of tools (O'Hare 2009), however, we have focused on DfE tool performance as a driver to adoption.

The key to a successful DfE tool is to give the user what they require. A number of researchers have indentified that current tools fail to offer sufficient support to the designer when attempting eco-design (Byggeth, Hochschorner 2006, Bhamra, Lofthouse 2003, Vallet 2012). **By putting forward a framework that overcomes this issue, while structuring and making sense of the components responsible for its delivery, the work completed in preparation of this thesis has closed the gap between what users what and what they get.**

It makes their job of environmental assessment and impact reduction as rewarding as possible, by allowing them maximum return from minimum input. In the context of DfE tools, this means assisting the designer towards lower impact solutions relevant to their development project. They use these tools to assess their products and find solutions to improve them. They are looking for something in return for using the tools.

Too many current tools are focused on environmental assessment, i.e. finding the problem, and not enough are focused on doing anything about it (Vallet 2012). This is due to the poor understanding of the framework that underly these tools, and more specifically the output mechanisms that take the input from the user and deliver the return.

This research has taken what was previously known about DfE tools – e.g. early use, designer operated, product focused – and added a considerable amount of knowledge about how tools work and perform.

A novel method for assessment was devised leading to the identification of four common frameworks that describe how DfE tools work:

1. The user or tool priorities the strategy to focus on, with little to no design guidance.

2. The user or tool priorities the strategy to focus on, before strategy-specific design guidance is delivered.

3. The user prioritises the strategy to focus on, before the strategic guidance and advice is delivered using case study examples as reference.

4. The tool requires user inputs to categorise their product before delivering guidance based on their inputs.

Drawbacks were discovered - relating to performance and appeal - with all four frameworks, which led to the development and verification of an innovative, new framework with improved performance. The new framework finally developed from the four previously details – uses user-inputs to control and determine tool-outputs – gives the user the guidance and assistance that many researchers have called for by taking more detailed inputs about function and characteristics, before structuring the design guidance and assisting information in a design matrix with approaches proven to be beneficial. (Byggeth, Hochschorner 2006, Lofthouse 2006, Vallet 2012, Knight 2009). Performance is improved, the user gets the assistance they want - products get more environmentally benign.

The research outcomes have similarities with Lindahl (2005). Lindahl set about identifying the reasons why the designer was not using tools. His approach was to interview designers to understand their habits to get an idea of what affected their decision to use a tool or not. A significant difference between this research and Lindahl's is the approach taken to achieve the results. While Lindahl adopted a more interpretive approach, i.e. interviewing designers and interpreting their responses into hypotheses to test, the approach taken in this research is to interrogate the tools themselves in a positivistic manner, in order to identify characteristics which effect performance. The approaches are complimentary to each other as they overlap with common ground. Findings from Lindahl’s thesis have influenced this work by understanding how a designer uses a tool and it begins to identify what they need. However, this work has then built on the findings and has added considerably more knowledge about how the tools themselves work and what criteria affect their performance.

An important legacy of this research is to bring together and organise the many formats and types of design support and guidance offered by current DfE tools for the first time ever, to the author's knowledge. This standardisation gives future research projects grounding on which to base continued work and development within the field.

In addition to the major structural enhancements to DfE tools shown in this study, are the function and characteristic improvements brought about by a novel approach to tool

assessment. As well as structural rethinks, this research isolated characteristics proven to be beneficial to tool performance and developed guidelines for their use in future tools.

The novel method for assessing tools has wide applicability as an approach for identifying the functional characteristics of a range of tools. Its focus could be redirected towards other groups of tools with an aim of improving output performance using identifiable stages.

The output mechanisms discovered link in to the understanding of the structures of tools and how they should be structured to maximise performance. This novel distinction of structure has wide applicability throughout industry and academia when developing tools for design or other disciplines.

The new guidelines for the use of characteristics proven to be beneficial to tool performance also have applicability. **Future projects attempting to generate commercially viable tools will find the guidelines constructed here when deciding specific tool details, such as how much detail should a tool present.** The guidelines would assist with decision making, facilitating better tool development.

8.2 Taking findings forward

This work links in with both academic projects aiming to progress DfE practices and commercial efforts to exploit the techniques. **The main area for future work on the project should involve developing the framework into a fully developed tool for commercial release. As the majority of the groundwork has been completed in this study, future work will involve refinement and enhancement of the current proposals.** The main steps anticipated from this successful commercialisation of a tool from this research are discussed in these following sections.

8.2.1 Guidance components

The first requirement is to investigate further the guidance components found in DfE tools. It is necessary to widen the scope of testing, including a larger quantity of DfE tools and more general design tools to determine whether commonality found in this study can be identified in more general groups. This study should aim to identify further groups of common components. The Design by Analogy approach should be used to identify potential tool improvements. Researchers should evaluate function and performance improving features and characteristics in established productivity tools such as Microsoft Office, and social media tools, such as Facebook and Twitter. Quick response and assistance has been identified as a desired characteristic of DfE tools, these consumer tools exploit similar characteristics and potential analogies can be made to enhance performance.

8.2.2 Framework refinement

The use of PRODCOM codes as a universal method for powering the Product Function Categorisation (PFC) feature of the framework should be further investigated. This would facilitate the inclusion of other product groups also included in the universal method. The aim should be to include all major product groups with the initial steps of the tool narrowing the scope appropriately so that the output remains relevant. This beneficial feature would widen the applicability of the next generation of DfE framework, without succumbing to the pitfall of giving assistance that is too generic.

A further study should specifically assess each of the features of the guidance matrix in the new framework to determine their success at improving guidance relevancy and assisting the designer. A testing protocol should be devised to ensure thorough comparison of the three guidance matrix sections. User testing is likely to be required to gather sufficient opinions to verify any findings and therefore a metric will be required to ensure research validity.

8.2.3 Testing and refinement

A process of significant beta testing would be required to refine tool functionality, eliminate bugs and improve performance. A large test group would need to be generated to ensure a significant response rate. A workshop day at the University could include designers and industrial players to assess the effectiveness of the new tools. Seminars could be arranged to allow local businesses to discuss and share practices, followed by a workshop session where the attendees can use the tool on practical problems. This event would serve to draw awareness to work being carried out by the University, and would also help to develop contacts with local businesses to facilitate future projects and the participation of designers to continue development of the DfE tool framework.

A summary table of the anticipated steps necessary to develop the current framework and tool into a commercially viable offering are outlined in Table 46.

Table 46. The 61 steps required to turn the current prototype tool into a commercially ready software tool

Step	Description	Outcome
1. Wider assessment of guidance components	Widen scope of tools included for assessment to verify current groups and generate further common groups	Further enhancements to component groups and understanding
2. Wider inclusion of product groups	Develop an advanced product categorisation method for including all main product groups	More inclusive product groups
3. Optimisation of guidance matrix features	Identify and optimise the most beneficial features of the guidance matrix to improve performance	Improved understanding of tool requirements
4. Development of appropriate tool interface	Create and employ an interface design appropriate for commercial environment, utilising intuitive usability including Tablet and smart phone availability	A tool interface that encourages designers to use it
5. Enhancement of guidance database	Expand the guidance database to include up to date guidance covering all the main product groups	A more applicable database of information
6. Testing and verification	Thorough testing and feedback sessions required to optimise performance and eliminate system bugs and	A software tool ready for commercial release

	maximise functionality	

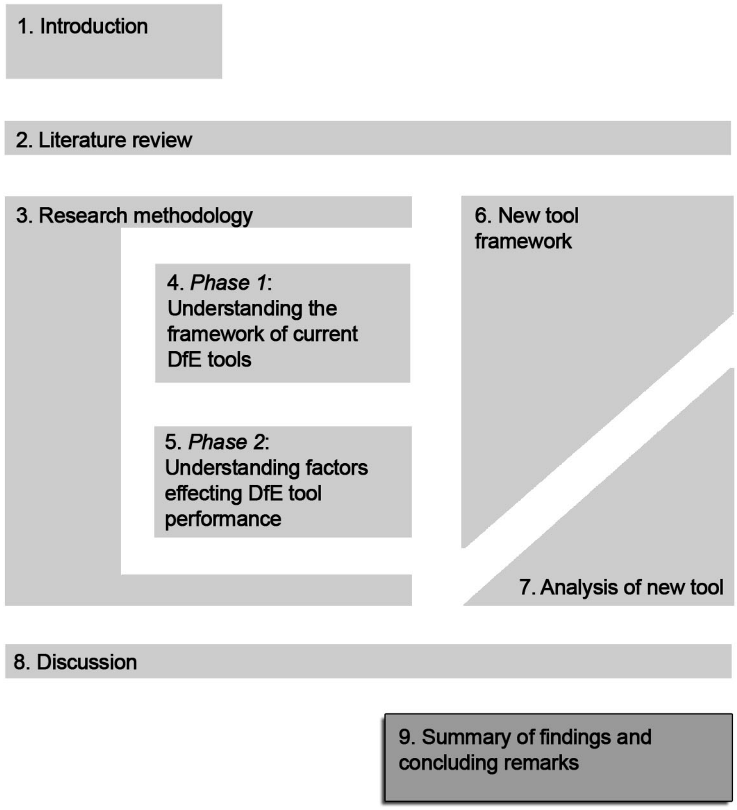
8.2.4 Educate future designers

Another avenue for investigation is the assessment of the tools suitability within a pedagogical environment. Evident from the results is the students' acknowledgement of the tools performance. At the time of publishing this thesis (Nov 2012) it was confirmed that the tool would remain part of the MSc Product Design program as a design assistant tool for the students. Further research could consist of assessing the tools performance in this guise against the other tools available to them.

The understanding brought by this research should be influential in the way students are taught DfE in the future. The framework presented here should be investigated to assess its applicability as a learning tool for young designers. Not only this, a better understanding of the way DfE tools work and which characteristics improve performance will be essential when they enter industry and have to make decisions about the tools they use. This research could prove valuable for years to come.

And certainly the author's hope is that this work can play a key role in helping to gain an important step forward in the utilisation of Design for Environment methodologies across the commercial design sector.

Not only will this help to ensure a better future for the environment, but by reducing costs and increasing profits for manufacturing industry and reduced running costs and longer product life for consumers.



CHAPTER 9 – Summary of findings and concluding remarks

The purpose of this chapter is to summarise the findings of this research and ensure that the two research objectives are fully addressed. A critical review will assess the contribution of the research findings to scientific knowledge. Limitations of the study are discussed, and recommendations for the development of the next generation of DfE tools using the new framework proposed in this report are offered.

9.1 Critical review

This project comprised of two studies, which were completed in order to answer the four research questions that address the two research objectives. The two-phased first study used quantitative and qualitative data derived from a sample of current DfE tools to establish areas for improvement. The new knowledge was then used to create a working prototype tool for testing and verification.

This thesis makes the following contribution to scientific understanding:

- It establishes a novel framework configuration within the context of the research findings, which has been verified through testing.
- It establishes an improved understanding of a DfE tools output mechanism. It identifies four output mechanisms common to all tools, and determines two distinct approaches, strategy-specific and product-specific, which have a performance contrast.
- It identifies and defines a series of guidance components that are common to all tools. It establishes that the guidance delivered by all DfE tools is of two types, strategic guidance and advice. It also establishes that these two types of guidance can be delivered straight to the user or using the delivery components, case studies and eco-resources.
- It establishes that there is a link between the frequency of the guidance components found in a tool and the tools performance. For optimum performance a tool requires:
    - Eco-resources;
    - A number of case study examples;
    - More than 100 advice statements, and;
    - More than 5 strategies per life cycle.

This thesis makes the following contribution to industry:

- The new framework can be used directly by tool developers to improve the performance of DfE tools and meet the designers' requirements better.
- The recommendations made during this research can be used to enhance DfE tool design and to further match the requirements of designers to new design tools.

9.2 Limitations

There are some limitations to the research that need to be discussed. The first limitation relates to tool investigation study in Chapters 4 and 5. Although a significant number, i.e. 22 DfE tools were included in the investigatory study, issues arise with the potentially biased random selection and the relatively low representation of the overall number of current DfE tools. The results from this study can therefore not be said to represent the whole population of DfE tools. However, the tool selection was intentionally as broad as possible in order to give a decent approximation.

The second limitation relates to the user testing study. This covers issues such as convenience method of sampling user groups; the research reliability; and validity of the results as discussed in Chapter 3.

Thirdly, limitations were identified due to the prototype nature of the tested tool. This explains the lack of information and case studies identified as a weakness by both groups, and hence should be eliminated with a fully developed and populated tool.

It is apparent from the results from both groups that the framework has many beneficial characteristics. The issues that need rectifying have been highlighted and discussed above.

9.3 Reaching objectives

The purpose of this research was to address the two objectives set-out in Chapter 1: **O1 – To explore and develop recommendations for how Design for Environment tools can better fit the requirement of the designer**, and, **O2 – To develop and evaluate an innovative Design for Environment tool with a next generation framework.**

To fully address these objectives, four research questions had to be answered:

Q1 – Are current Design for Environment tools letting the designer down?

This research has thoroughly investigated current tools in both literature and through hands-on testing to determine that there is much scope for improvement. It has found that a gap still exists between the documented literature and the tools available to designers. A lack of understanding of designer requirements regarding performance and capability still exists within DfE tools. Many of the current shortcomings of DfE tools are related to a lack of appropriate knowledge and assistance offered during their use. A number of areas where identified where these shortcomings can be improved in order to improve tool performance.

Q2 – What changes need to be made to a Design for Environment tool to improve performance?

The thorough investigation of current DfE tools gave the answer to **Q2**. The study identified that DfE tools with a product-specific mechanism have the capacity to allow for greater customisation of outputs, resulting in greater output relevancy. Along with this, an emphasis should be placed on design guidance and support utilising the four guidance components. Changes to the framework underlying a DfE tool to utilise these features would improve performance.

Q3 – What specification does the next generation framework include?

The next generation framework includes many specification enhancements (**Q3**). A narrowed scope to focus on small household appliances during the manufacture and use phase reduces the required complexity. A product categorisation step at the start of the tool ensures greater outputs relevancy for designers' tasks. Guidance components are at the heart of the next generation framework. This research has determined desired frequencies for all four components. The new framework utilises these characteristics to maximum potential.

Q4 – Can a framework with increased design support improve a Design for Environment tool's performance?

A working prototype tool was developed using the next generation framework and specification. Quantitative analysis and user testing techniques were used to assess the success and performance of the new framework (**Q4**). The quantitative study (Step 1) determined that the framework does have the capacity to accommodate a larger frequency of characteristics known to improve performance, i.e. guidance components, than current tools. The user testing study (Step 2) verified that the new framework also has significant benefits to a designer. Major findings from the study confirmed that the test groups found the guidance given by the prototype tool was directly relevant to their product, enhancing the users experience, and it also remained quick and easy to use.

9.4 Concluding remarks

The intention of this project was to investigate current DfE tools, and use the new knowledge to develop a new, novel tool. It is only through the application of useful methods, such as design and DfE tools - which have been proven to improve productivity and awareness of the issues - that sustainable solutions to worldwide design and manufacture problems can be met before it is too late. New knowledge in this area is essential to help shape and direct future efforts. This dissertation has documented a successful knowledge building journey, from a brief beginning through to an accomplished end.

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APPENDICES

Appendix 1

A1.1 Self-administered questionnaire used to assess the performance of the new tool, Inspire Ideas.

1. Have you used an environmental design tool before?

Yes
No

2. If Yes, please rate how useful you found the tool?

Very unuseful - 1
2
3
4
Very useful - 5

3. How useful did you find the Inspire Ideas tool?

Very unuseful - 1
2
3
4
Very useful - 5

4. How easy did you find this tool to use?

Very hard - 1
2
3
4
Very easy - 5

5. How well did the tool help you generate ideas/solutions?

Very poor - 1
2
3
4
Very well - 5

6. How well did the tool help you explore different ideas/solutions?

Very poor - 1
2
3
4
Very well - 5

7. How relevant was the content on the 'Guidance' pages (i.e. Strategy inspired, Function inspired, and TRIZ inspired) to the product you were developing?

Very irrelevant - 1

2
3
4
Very relevant - 5

8. What, in your opinion, are the strengths of the tool? Please choose as many as you like.

Simplicity
Interface
The support offered
The 'strategy inspired' section
The 'function inspired' section
The 'TRIZ inspired' section
External links
No strengths
Other…

9. What, in your opinion, are the weaknesses of the tool? Please choose as many as you like.

Complexity
Navigation
Lack of information
Lack of support
Lack of case studies
No weaknesses
Other…

10. Would you consider using the tool in future projects?

Yes
No

How, in your opinion, can the tool be improved?

A1.2 Notes from the semi-structured interviews with two professional designers.

Interview 1

Background: Senior product designer developing many products

Comments:

Supply breakdown – many location – transport

Subsets – subassemblies – adds complexity

Considerations for addition in advice section:

Packaging

Currency fluctuation – raw materials cost fluctuation, shipping costs, time of year

Housekeeping – reduce packaging size to maximise no. of units per distribution unit

Use assembly – semi assembled parts

Optimisation of design through allowing weight removal

Transport packaging – logistics of distribution

Optimisation of components for manufacture

Use of standard components

Assembly consideration

Interface: (a lot of importance placed on interface)

Contemporary design needed

Time line at top

Consider negative issues of materials, processes, suggested advice decisions

Challenge pre-set opinions of professional designers

More functional criteria

What is most important criteria – allow prioritisation of criteria – price, aesthetics

Open sourced tool – proposed idea from designers

Exploration:

Visually interesting – interactive

School students – engrossing for young designers

Examples – case studies – more examples, make them better visible

User centered:
Current processes + fabrication processes
>> tool suggests >>
Tool then links to similar or alternative processes
*with context of overcoming company inertia, ie a outdoor company mainly designs with tarpaulin and steel poles may have a lack of expertise to comfortably design an Injection Moulding plastic part.

**Prototyping tool – ie for development of prototype products

Interview 2

Background:
Industrial designer at large household appliances producer producing complex products, such as Dishwashers, Washing machines, etc.

Comments:
Easy going tool
Functions are a bit oversimplified
Far too few parts in LCA section
Weights – possibly a range of weights, eg 1-2Kg, 3-4kg, etc.
Transport – approximate distances for direction, maybe notes to better explain, eg ASIA – 120000km
Include air transport
Use – Cycle time of dishwasher etc varies
Cycle usage
Results – energy mix
Manufacturing energy mix, eg made in China, used in UK

Good Idea – general suggestions at end – guidance matrix
However the designer often has little say over many of the issues covered.

Emphasis educating the user – main aspects – behaviour

Designer has little say in where product is made

Energy used – little effect

Interviewee liked the guidance matrix

- reminds the designer of possible overlooked ideas and solutions
- prompts alternative thoughts

Appendix 2

A2.1 Product information generation structure

The structured method used to gather the product information required to complete the DfE tools in section 3.2 is displayed below. In order to collect the required information it was necessary to:

1. Complete a Bill of Materials (BOM) for all main assemblies for the product, including the packaging, with tooling requirements clearly identified*;
2. Complete an Assembly Operations sheet for all main assemblies for the product, with tooling and fixtures requirements identified*;
3. Estimate transport distances and method of transport for all assemblies;
4. Measure the product and packaging dimensions;
5. Infer approximate frequency of use figures**, including number of times used per year and product life length.
6. Determine the functional unit of the product.

* These steps were adopted from Shane Bathurst's reverse engineering method used as a DFMA challenge exercise for undergraduate Engineering students at the University of Liverpool.
** Frequency of use figures derived from which.co.uk analysis of products

A2.2 The generated Bill of materials and additional product information for the blender.

PRODUCT	Breville Blender 800W
ASSEMBLY	
SHEET NUMBER	1 OF 1

Part No.	Description	No. of	Component weight (grams)	material weight (grams)	Material	Primary Manufacturing Process	Other Manufac. Process + Comment
1	Lid	1	48.98	48.98	Polypropylene	Injection Moulding	
2	Lid seal	1	52.96	52.96	Polyurethane	Over moulding	overmoulded over the lid
3	Lid plug	1	42.66	42.66	Styrene-acrylonitrile	Injection Moulding	
4	Handle cover	1	14.88	14.88	ABS	Injection Moulding	
5	Main body	1	401.26	401.26	Styrene-acrylonitrile	Injection Moulding	
6	Rotation unit seal	1	4.48	4.48	Silicon rubber	Injection Moulding	
7	Base bottom screws	4	0.54	2.16	Medium carbon steel	Rolled	Threaded
8	Base bottom	1	63.16	63.16	ABS	Injection Moulding	
9	Base bottom foot	1	8.1	8.1	Polyurethane	Extruded	then trimmed
10	Internal base screw	4	0.74	2.96	Medium carbon steel	Rolled	Threaded
11	Internal base	1	192	192	ABS	Injection Moulding	
12	Internal base sheild	1	3.12	3.12	Low carbon steel	Rolled	Stamped
13	Mains cable clamp	1	0.46	0.46	Polypropylene	Injection Moulding	
14	Mains cable clamp screw	2	0.72	1.44	Medium carbon steel	Rolled	Threaded
15	Outer shell	1	211.3	211.3	ABS	Injection Moulding	
16	Button frame	1	12.74	12.74	ABS	Injection Moulding	
17	Button main (green)	1	20.28	20.28	ABS	Injection Moulding	
18	Button cover	1	1.4	1.4	Polystyrene	Extruded	Printed, then glued to button

19	Button PCB	1	28.48	23.92	Electrical components		
20	LED's	12	0.12	1.44	Electrical components		Soldered into place
21	Button's	12	0.26	3.12	Electrical components		Soldered into place
22	Assorted	39		0	Electrical components		
23	Button PCB screws	4	0.38	1.52	Medium carbon steel	Rolled	Threaded
24	Main PCB	1	55.48	55.48	Electrical components		
25	Large components	24		0	Electrical components		
26	Small components	9		0	Electrical components		
27	Override mech screw	2	0.38	0.76	Medium carbon steel	Rolled	Threaded
28	Override mech arm	1	1.88	1.88	Polycarbonate	Injection Moulding	
29	Override mech master	1	3.4	3.4	Polycarbonate	Injection Moulding	
30	Override mech spring	1	0.14	0.14	Low alloy steel	Rolled	
31	Override mech switch body 1	1	0.36	0.36	Polycarbonate	Injection Moulding	
32	Override mech switch body 2	1	0.8	0.8	Polycarbonate	Injection Moulding	
33	Override mech switch innards	1	0.96	0.96	Stainless steel	Rolled	
34	Top Internal	1	98.54	98.54	ABS	Injection Moulding	
35	Top internal seal	1	4.9	4.9	Polyurethane	Injection Moulding	
36	Rotation connector female	1	9.04	9.04	Polyamide	Injection Moulding	
37	Rotation connector female plug	1	0.68	0.68	Polyamide	Injection Moulding	Glued in place
38	Rotation connector male	1	4.54	4.54	Polyamide	Injection Moulding	
39	Rotation unit	1	52.32	52.32	Polyamide	Injection Moulding	
40	Rotation unit internal mount	1	4.8	4.8	Polyamide	Injection Moulding	
41	Rotation unit internal seal	1	0.4	0.4	Silicon rubber	Injection Moulding	
42	Rotation unit blade + bearing	1	55.24	55.24	Stainless steel	Rolled	

43	Motor fan	1	11.58	11.58	ABS	Injection Moulding	
44	Motor				Electrical components		
	copper wire	1	326.41	326.41	Electrical component		
	steel	1	652.83	652.83	Electrical component		
45	Motor connector bolt	2	6.1	12.2	Medium carbon steel	Rolled	Threaded
46	Motor bottom mount	1	64.1	64.1	Low carbon steel	Rolled	Stamped
47	Motor PCB screws	2	0.12	0.24	Medium carbon steel	Rolled	Threaded
48	Motor PCB	1	1.14	1.14	Polyamide	Injection Moulding	
49	Small components	2		0	Electrical components		
50	Wires	6	15.6	15.6	Electrical components		
51	Motor rubber	1	17.08	17.08	Polyurethane	Injection Moulding	
52	Zip ties	7	1.12	1.12	Polypropylene	Injection Moulding	
53	Mains cable	1	136.6	136.6	Electrical components		
	No. of components	170	2635.56	2647.48			

Total weight of ABS	624.48	23.59%		
Total weight of Polyamide	72.52	2.74%		
Total weight of Polycarbonate	6.44	0.24%		
Total weight of Polypropylene	50.56	1.91%		
Total weight of Polystyrene	1.4	0.05%		
Total weight of Polyurethane	83.04	3.14%		
Total weight of Silicon rubber	4.88	0.18%		
Total weight of Styrene-acrylonitrile	443.92	16.77%		
			total weight of plastics	1282.36
Total weight of Stainless steel	56.2	2.12%		
Total weight of Low alloy steel	0.14	0.01%		

Total weight of Electrical components	873.4	32.99%
Total weight of Copper	342.01	12.92%
Total weight of Low Carbon Steel	67.22	2.54%
Total weight of Medium carbon steel	21.28	0.80%

total weight of steel	144.84

Total weight	2647.48

No. of IM parts	33
No. of rolled parts	4
No. of Overmoulded parts	1
No. of extruded parts	2
No. of screws + bolts	20
No. of springs	1

Packaging						
Recycled pulp card	1	297.6	297.6	Recycled card pulp	Stamped	
Plastic bag	1	13.3	13.3	Polyethylene	Blown	
Bubblewrap	1	30.1	30.1	Polyethylene	Blown	Stamped
Manual	1	59.4	59.4	Card/paper		
Cardboard box	1	260.1	260.1	Recycled corregated cardboard		

Total packaging weight	660.5
Overall product weight	3307.98

Transport		
Transport of PCB's to assembly factory	32 tonne truck	1000km
Transport of Motor to assembly factory	32 tonne truck	1000km
Transport of product to EU	Sea freight	5000km

Dimensions (m)

L	0.29	
W	0.35	
D	0.19	
	0.019285	

Frequency of Use

5	years	
5	days per week	
1/8	hours per day	based on the unit being used once through out the day
162.5	No. of hours per year	

Maintenance

Water for cleaning (L)	1300	
		based on 1L of water being used to clean after use once a day for 260 days over 5 years

Functional Unit

To blend 1 litre of solid and liquid food

A2.3 The generated Bill of materials and additional product information for the kettle.

PRODUCT	Russell Hobbs 3kW 240V Kettle
ASSEMBLY	
SHEET NUMBER	1 OF 1

Part No.	Description	No. of	Component weight (grams)	material weight (grams)	Material	Primary Manufacturing Process	Other Manufac. Process + Comment
	Base power unit						
1	Base cover - under base	1	32.4	32.4	Polypropylene	Injection Moulding	
2	Base screw - triangle head	3	0.54	1.62	Medium carbon steel		
3	Base Body	1	65.22	65.22	Polypropylene	Injection Moulding	
4	Power unit - female plug	1	8.82	8.82	Polyamide	Injection Moulding	
5	Rubber feet	3	0.9	2.7	Polyurethane	Injection Moulding	
	Main body						
6	Silver screws	2	0.54	1.08	Medium carbon steel		
7	Cap cover	1	31.26	31.26	Polypropylene	Injection Moulding	
8	Cap cover seal	1	1.26	1.26	Polyurethane	Injection Moulding	
9	Cap base	1	16.58	16.58	Polypropylene	Injection Moulding	
10	Cap lock mech master	1	3.46	3.46	Polyphenlene Oxide	Injection Moulding	
11	Cap lock mech arm L	1	1.92	1.92	Polyphenlene Oxide	Injection Moulding	
12	Cap lock mech arm R	1	1.96	1.96	Polyphenlene Oxide	Injection Moulding	
13	Cap lock mech spring	1	1.38	1.38	Low alloy steel	Extruded	Coiled
14	Water filter	1	6.72	6.72	Polypropylene	Injection Moulding	over steel gorse
15	Water filter mount	1	19.02	19.02	Polypropylene	Injection Moulding	
16	Black screws	4	0.34	1.36	Medium carbon steel		coating
17	Handle cover	1	23.4	23.4	Polypropylene	Injection Moulding	
18	Thumb lever - locking mech	1	3.92	3.92	Polypropylene	Injection Moulding	
19	Middle arm - locking mech	1	1.36	1.36	Polyphenlene Oxide	Injection Moulding	
20	End arm - locking mech	1	0.96	0.96	Polyphenlene Oxide	Injection Moulding	
21	Spring - locking mech	1	0.42	0.42	Low alloy steel		
22	Master lock mech	1	3.44	3.44	Polyphenlene Oxide	Injection Moulding	
23	Cap spring arm	1	3.32	3.32	Polyphenlene Oxide	Injection Moulding	
24	Cap arm	2	0.14	0.28	Low alloy steel		

	spring						
25	Handle base	1	52.76	52.76	Polypropylene	Injection Moulding	
26	Silicon rings	2	0.13	0.26	Silicon rubber	Injection Moulding	
27	Black rubber seal	1	0.5	0.5	Polyurethane	Injection Moulding	
28	Handle bolts 1	1	1.66	1.66	Medium carbon steel		
29	Handle bolts 2	1	1.02	1.02	Medium carbon steel		
30	Plastic spacer	1	0.36	0.36	Polyphenlene Oxide	Injection Moulding	
31	Base screw	3	1.12	3.36	Medium carbon steel		
32	Body base	1	71.94	71.94	Polypropylene	Injection Moulding	
33	Element mech screws	3	0.6	1.8	Medium carbon steel		
34	LED covers	4	1.84	7.36	Polycarbonate	Injection Moulding	silicon rubber sealed in place
35	LED cover nuts	4	0.8	3.2	Medium carbon steel		
36	LED cover seals	4	0.18	0.72	Silicon rubber	Injection Moulding	
37	Steam catcher	1	1.2	1.2	Polypropylene	Injection Moulding	placed on end
38	Main shell	1	504.36	504.36	Stainless Steel	Rolled	Stamped
	spout	1			Stainless Steel	Rolled	Spot welded
	handle connectors	2			Stainless Steel	Rolled	Spot welded - 6 welds top, 4 welds bottom
	element	1				Cast	Welded to shell base
	shell base	1			Stainless Steel	Rolled	Stamped, then spot weled to shell base
	LED cover bolts	4			Stainless Steel		Welded into place on shell base
	Power unit base of kettle						
39	Top	1	21.46	21.46	Low Carbon Steel	Rolled	Stamped
40	Element overheat shutoff	2	0.5	1	Shape Memory Alloy	Rolled	Stamped, then Trained
41	On/Off switch	1	6.26	6.26	Polycarbonate	Injection Moulding	Sliding cores
42	On/Off switch flat spring	1	0.14	0.14	Low alloy steel		

43	On/Off switch mech arm	1	5	5	Polycarbonate	Injection Moulding	
44	On/Off switch SMA spring	1	0.44	0.44	Shape Memory Alloy		
45	Base extension	1	1.58	1.58	Polypropylene	Injection Moulding	
46	Base (Kettle)	1	16.12	16.12	Polyamide	Injection Moulding	
47	Copper connections (Kettle body)	3	0.88	2.64	Copper (electical)	Rolled	Stamped
48	Brass connections	2	0.52	1.04	Copper (electical)	Rolled	Stamped
49	Large circle connection	1	2.44	2.44	Copper (electical)	Rolled	Stamped
50	Small circle connection	1	1.68	1.68	Copper (electical)	Rolled	Stamped
51	Central pin connection	1	0.5	0.5	Copper (electical)	Extruded	
52	Anti-burn control pin	1	0.06	0.06	Polycarbonate	Injection Moulding	
53	Anti-burn control pin spring	1	0.16	0.16	Low alloy steel		
54	Overheat pins	2	0.03	0.06	Polycarbonate	Injection Moulding	
55	Steam path rubber seal	1	0.6	0.6	Silicon rubber	Injection Moulding	
56	Copper connections (base body)	1	1.64	1.64	Copper (electical)	Rolled	Stamped
57	Zip ties	8	0.14	1.12	Polypropylene	Injection Moulding	
58	LED lights	4					
59	Wires	11					
60	Assorted						
	total		30.62	30.62			
61	Standard mains cable	1	136.6	136.6			
	No of components	117	1095.12	1115.52			

Total weight of Polyamide	24.94	2.24%		
Total weight of Polycarbonate	18.74	1.68%		
Total weight of Polyphenlene Oxide	16.78	1.50%		
Total weight of Polypropylene	327.12	29.32%		
Total weight of Polyurethane	4.46	0.40%		
Total weight of Silicon rubber	1.58	0.14%		
			total weight of plastics	392.04
Total weight of Stainless steel	504.36	45.21%		
Total weight of Low alloy steel	2.38	0.21%		

		Total weight of Medium carbon steel		15.1	1.35%		
		Total weight of Electrical components		177.16	15.88%	total weight of copper	40.56
		Total weight of Low Carbon Steel		21.46	1.92%		
		Total weight of SMA		1.44	0.13%		
						total weight of steel	544.74
					38.94		1.6
		Total weight		1115.52	39.98		0.256
		No. of IM parts		38			
		No. of rolled parts		5			
		No. of cast parts		1			
		No. of screws + bolts		21			
		No. of springs		6			
Packaging							
Recycled pulp card		1	209.6	209.6	Recycled card pulp	Stamped	
Plastic bag		1	12.5	12.5	High Density Polyetherlyne	Blown	
Manual		1	15	15	Card/paper		
Cardboard box		1	216.7	216.7	Recycled corregated cardboard		
		Total packaging weight		453.8			
		Overall product weight		1569.32			
Transport							
Transport of Strix components to assembly factory			32 tonne truck	1000km	1.56932	tkm	
Transport product to the EU			Sea freight	5000km	7.8466	tkm	
Dimensions (m)							
L	0.28						
W	0.22						

D	0.22	
	0.013552	

Frequency of Use

5	years	
7	days a week	
1/6	hours a day	based on the unit being used 4 times through out the day
303.3333333	No. of hours a year	

Energy consumption per use (average according to Which? Review)

0.114	kWh

Functional Unit

To heat 1 litre of water to boiling point

Appendix 3

Table A3.1 – Examples of strategies from DfE tools.

	Strategies
Eco Audit	Materials and manufacture; Transport; Use; Report
ECO-it	Production; Use; Disposal
EuP Profiler	Production; Distribution; Use; End of life
LCA Calculator	Extraction and manufacture; Transport; Use; Disposal
LCALight	Manufacture; Operation; Recycling
Eco Design Pilot	Reducing consumption at use phase; Optimizing product functionality; Improving maintenance; Avoiding waste in the production process; Reduction of packaging
MET	Production; Use; Disposal
ERPA	Materials choice; Energy use; Solid residue; Liquid residue; Gaseous residue
MECO	Material; Manufacture; Use; Disposal; Transport
SimaPro	Unavailable
GaBi	Valuable substances; Resources; Production residues in life cycle; Emissions to sea water; Deposited goods
DFMA	Materials, End of life
Envriz	Material intensity; Energy intensity; Dispersion of toxic materials; Recyclability; Renewable resource use; Product durability
TESPI	Selection of Low-impact materials; Material minimisation; Techniques for production optimisation; Optimisation of distribution; Reduction of impact during use; Optimisation of initial lifetime; Optimisation of end of life management
EFM	Function related strategies: Physical lifetime; Use-time; Reliability; Safety; Human/machine interaction; Economy; Technical flexibility; Environmental demand. Environment related strategies: Number of products produced per year; Size; Number of different materials; Material mix; Scarce materials; Toxic materials; Energy; Energy source.
DFEM	Raw material extraction and processing; Manufacturing; Packaging and distribution; Product use; End of life
IdeMAT	Materials
SortED	Manual disassembly; Granulating; Recycling; Brute force disassembly; Energy recovery; Shredding
Info / Insp	Materials, Distribution, Use, Optimal life, End of life strategies, such as Materials selection; Mainstream materials; Materials reduction; Compatibility; Bio-degradable materials; Types of energy; Efficiency; Energy reduction Alternative energy; Take back; Design for disassembly.
LiDS wheel	Reduction of environmental impact in the use stage; Selection of low-impact materials; Phasing out of hazardous substances.
SDO	System life optimization; Transportation/distribution reduction; Resources reduction; Waste minimization/valorization; Conservation/bio-compatibility; Toxicity reduction.
10 Golden rules	Exclude or account for toxis substances; Minimise energy and resource consumption in production, transport and use; Minimise weight; Promote repair and upgrading; Promote long life; Reduce maintenance; Prearrange upgrading, repair and recycling.

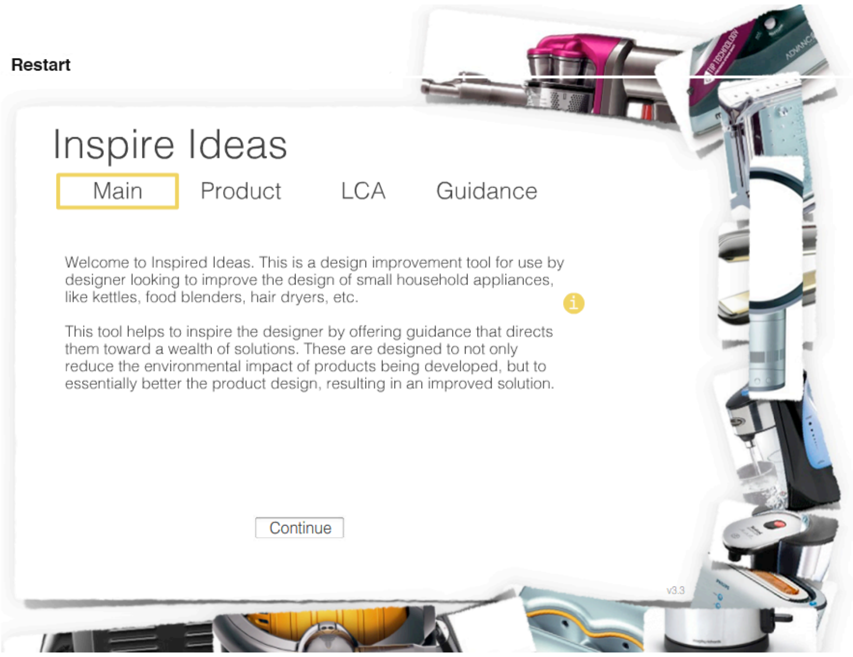
Table A3.2 – Examples of advice from DfE tools.

	Advice
LCA Calculator	Manufacture and extraction is the largest use of energy in your products life cycle. Value engineering would help to remove any unnecessary components reducing product impact; The use phase is the largest use of energy and you should make improvements here to make the biggest impact on environmental performance.
Eco Design Pilot	In order to avoid excessive consumption at use stage the level of consumption should be indicated to the user; Avoiding conventional auxiliary and process materials can be realised by using renewable raw materials; Indicate consumption of product along use phase; Recycle process materials whenever possible; Ensure reversibility of assembly procedure.
Envriz	Divide an object into independent parts; Replace symmetrical forms with asymmetrical forms; Instead of direct action dictated by a problem, implement an opposite action.
TESPI	Instead of making a product too big, ensue rigidity and strength through construction types and good design; Use the lowest energy-consuming components available; If heating or cooling occurs, ensure that components are well insulated where necessary.
IdeMAT	If the designer is looking for product casing, then they can set a filter to 'housings for electronic equipment', and the tool filters out inappropriate materials, and advises them of appropriate ones.
SortED	Granulating is a good approach for small household products; Make sure you are aware which hazardous materials are contained in your product.
Info / Insp	Avoid using adhesives which may require chemical processing to dissolve; Material choices can affect the environmental impact of product throughout its life cycle; Recycled materials help to close the loop and put nutrients back into the cycle; Provide feedback to consumers on how much energy they are using.
LiDS wheel	Use the lowest energy consuming components available; Make use of the default power-down mode; The less energy it costs to process a material, the better for the environment, especially if non-renewable energy sources are used.
SDO	Complement product or infrastructure with services for their maintenance, reparability, substitution; Complement product or infrastructure with services for their technological up-grade ability.
10 Golden Rules	Do not use toxic substances and utilise closed loops for necessary but toxic ones; Promote long life, especially for products with significant environmental aspects outside of the usage phase; Transporting energy can be saved if the product is given a space saving structure and shape. See plastic cups or "knock down" furniture the IKEA-model.

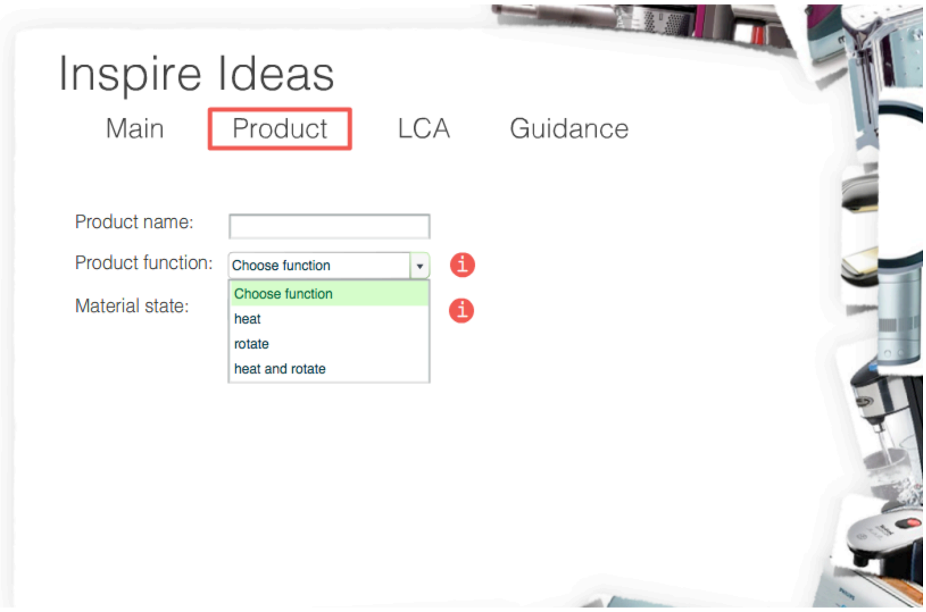
Appendix 4

A4.1 A detailed walk through of the new tool, *Inspire Ideas*.

This appendix consists of a walk-through of the new DfE tool, Inspire Ideas. It comprises of a detailed step-by-step approach to the tool with screenshots at every major stage.

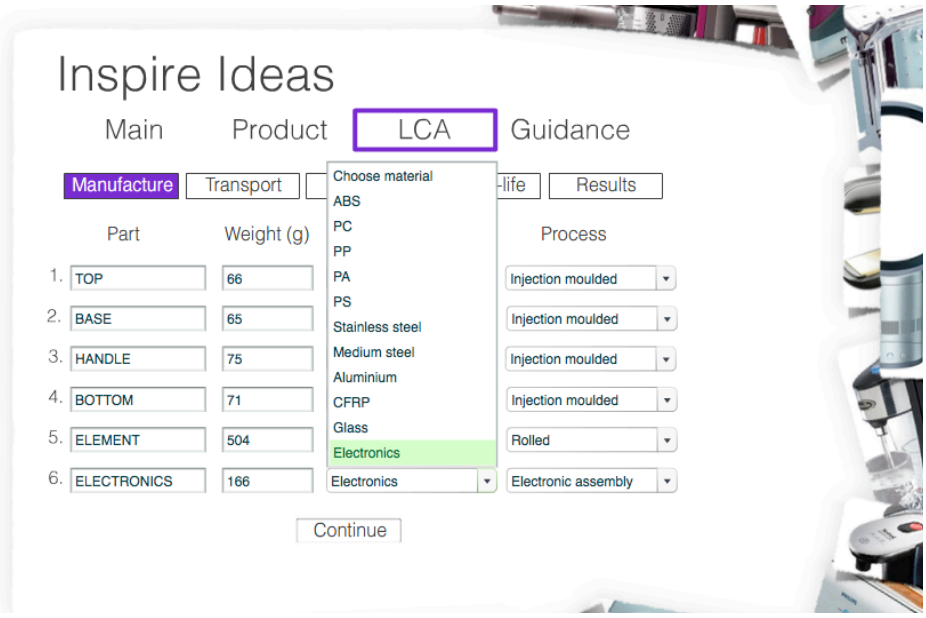


1. The 'Main' page introduces the tool, giving some background to the tool and information regarding which products are applicable. Holding the mouse over the yellow 'i' button gives examples of applicable products. Note that the whole border is included in the first image only, after that the images have been cropped to save space.

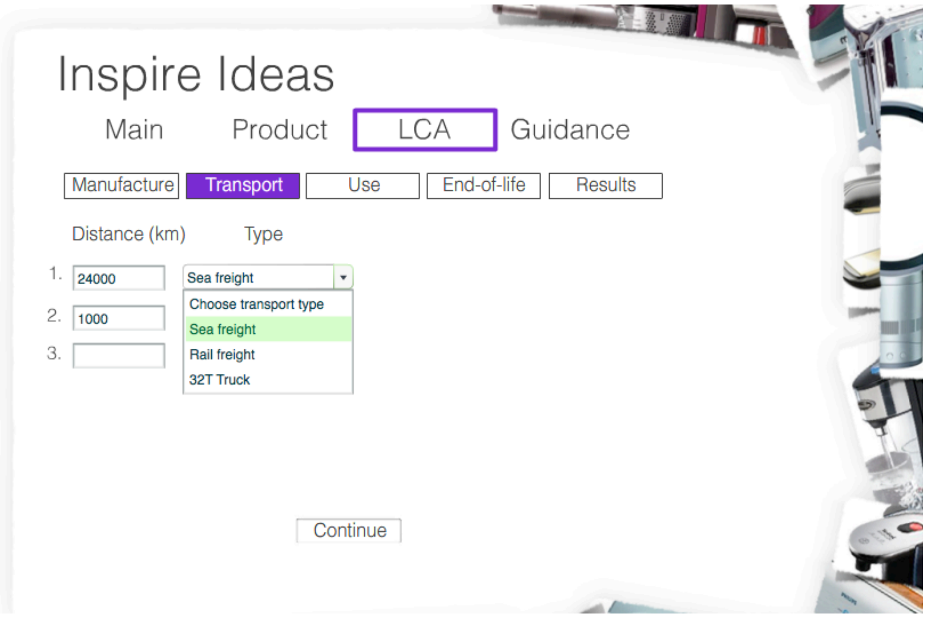


2. The 'product' tab denotes the Product Function Categorisation (PFC) step. Here the user is asked to name their product, followed by stating their products function. This is done by choosing a

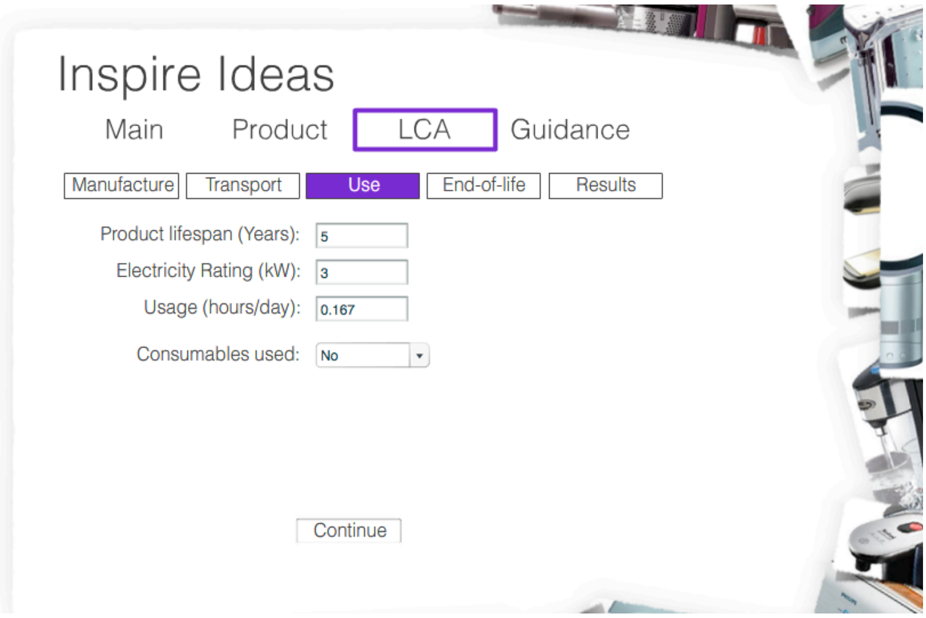
product function, i.e. either heat, rotate of heat and rotate, and by choosing a material state, i.e. solid, liquid or gas. The red 'i' buttons give examples to clarify this process.



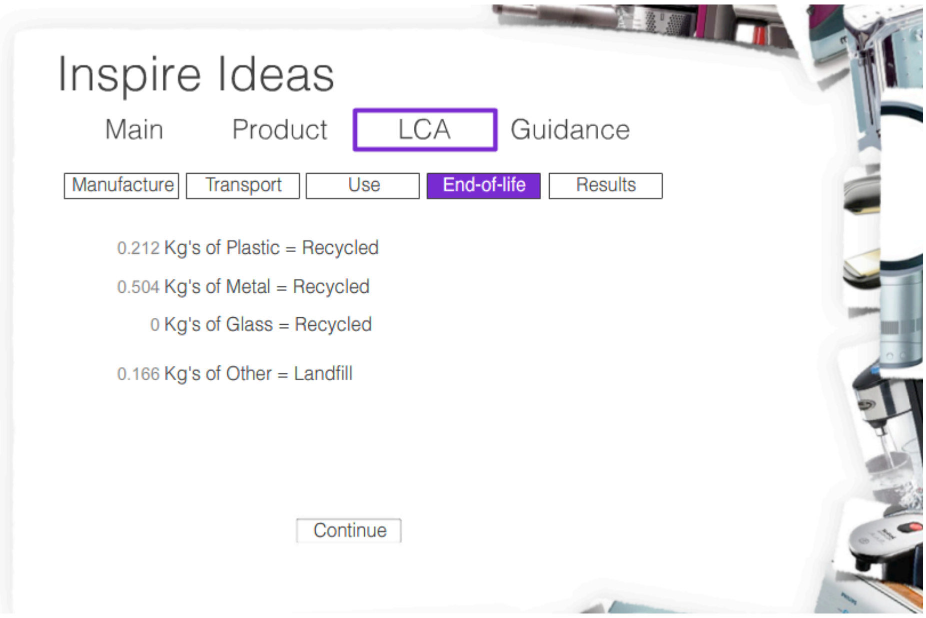
3. The next section is the Simplified Life-Cycle Assessment section denoted by the 'LCA' tab. The first step is to assess the manufacturing stage of the product concept. Part name, weight, material type and primary processing type are required for this section.



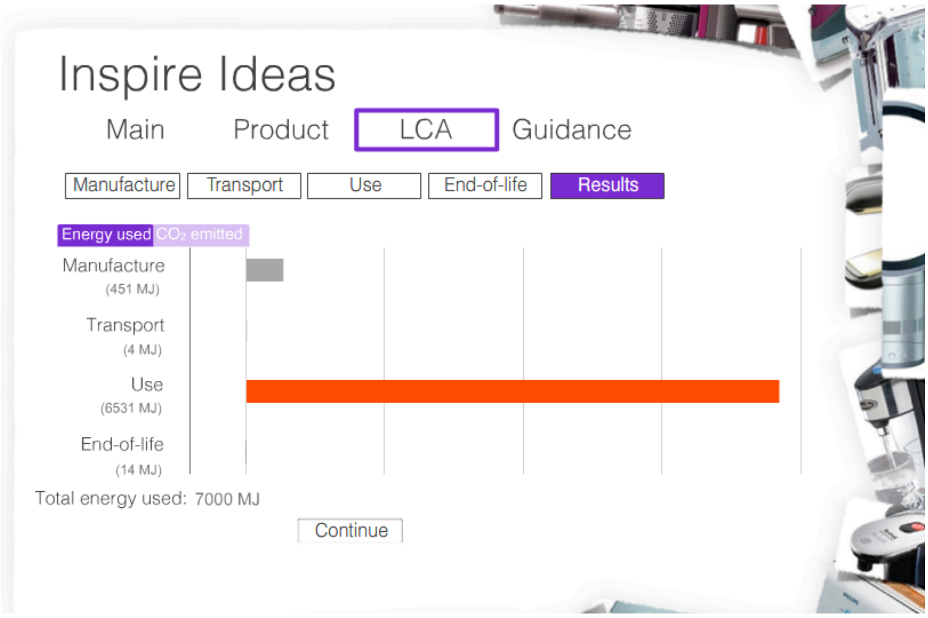
4. Next the transport stage is assessed. The distance travelled and the transport type are needed for each journey.



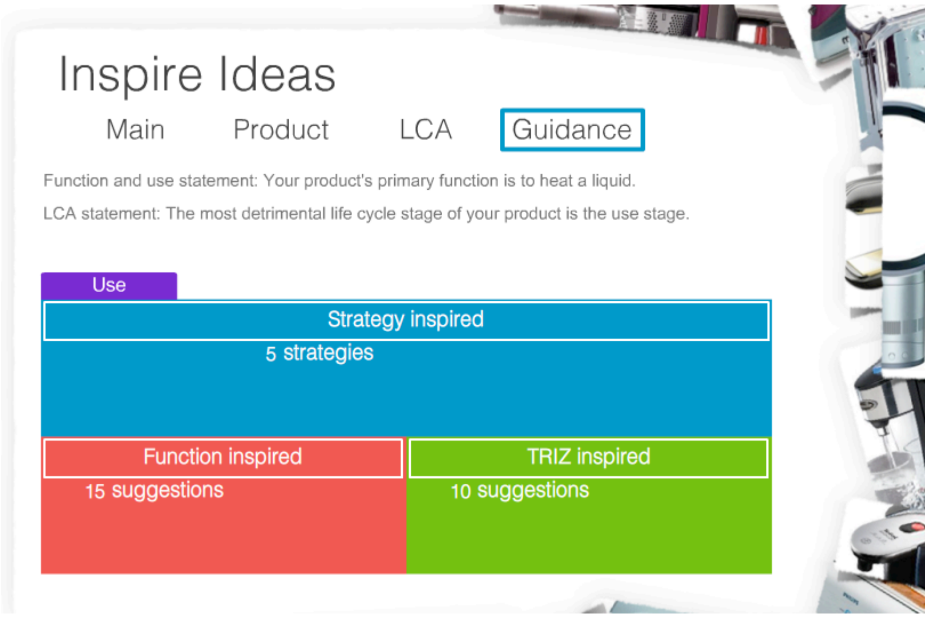
5. Next the user is asked to enter information about the products lifespan, electricity rating, usage and whether there are consumables needed or not.



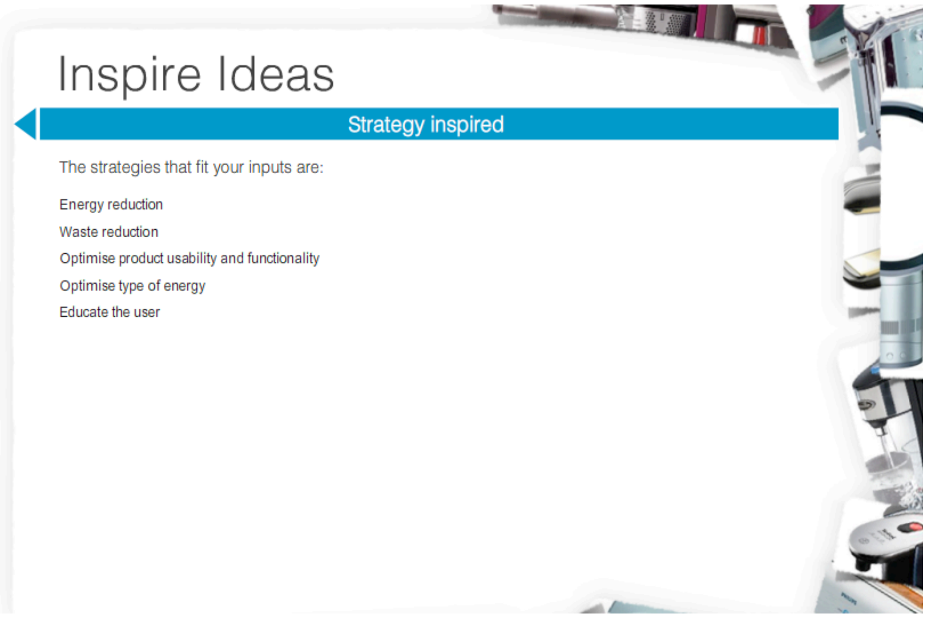
6. The end-of-life section gives a brief recap on the quantity of materials used and possible E-o-L strategies for the material.



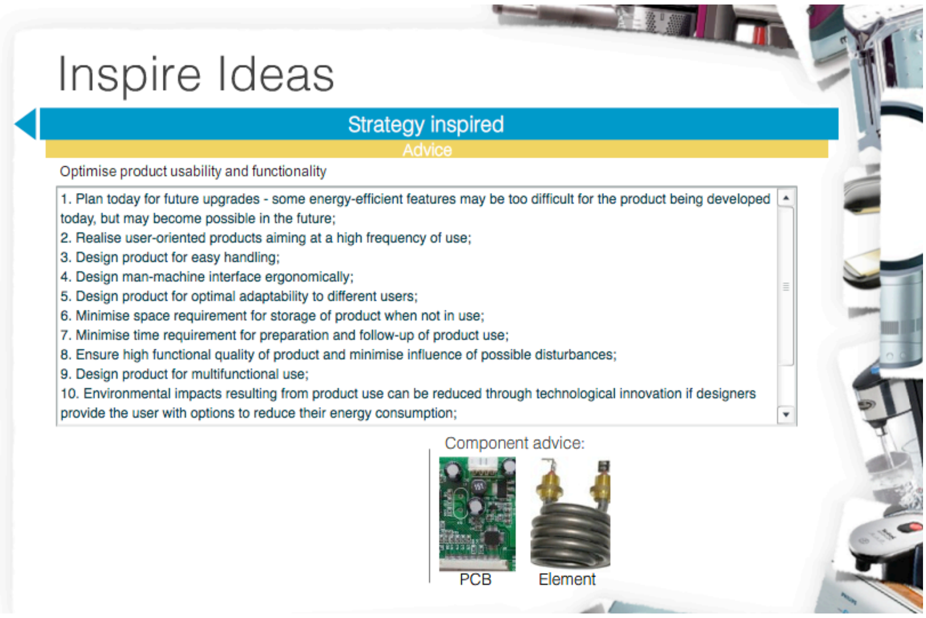
7. The results section displays the quantified results achieved by combining the user entered data with pre-set eco-data stored in a database. The tool uses in-built equations to derive a value for the energy used and the CO2 emitted from each life cycle stage, over the products lifetime.



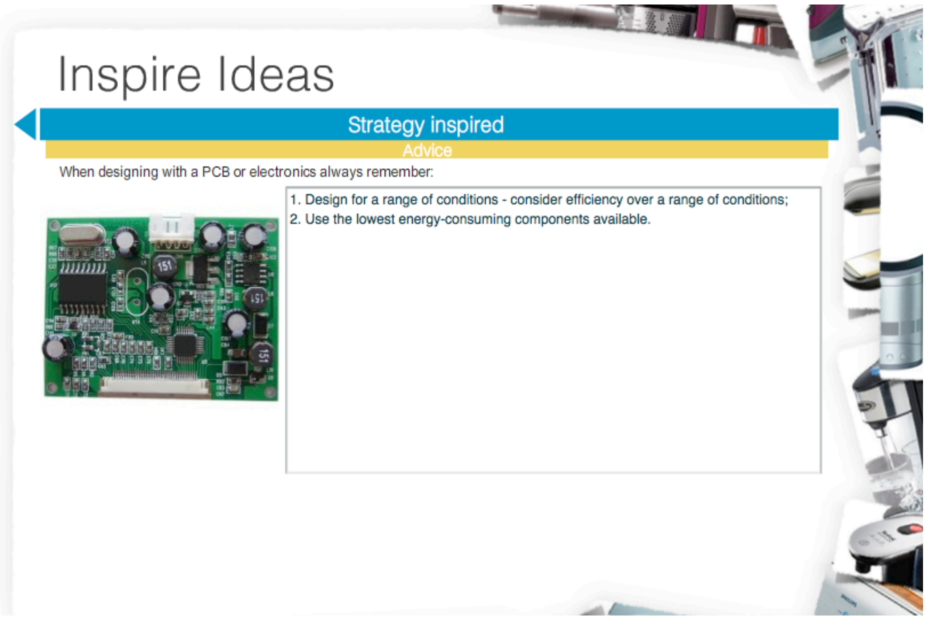
8. The results from the previous section are then fed into the 'Guidance matrix' section denoted by the 'guidance' tab. Firstly, at the top of the page the 'function and use statement' recaps the user entered product function. The 'LCA statement' then recaps which life-cycle stage was the most detrimental. Next, the outputs are split into 3 sections, i.e. 'strategy inspired', 'function inspired' and 'TRIZ inspired'.



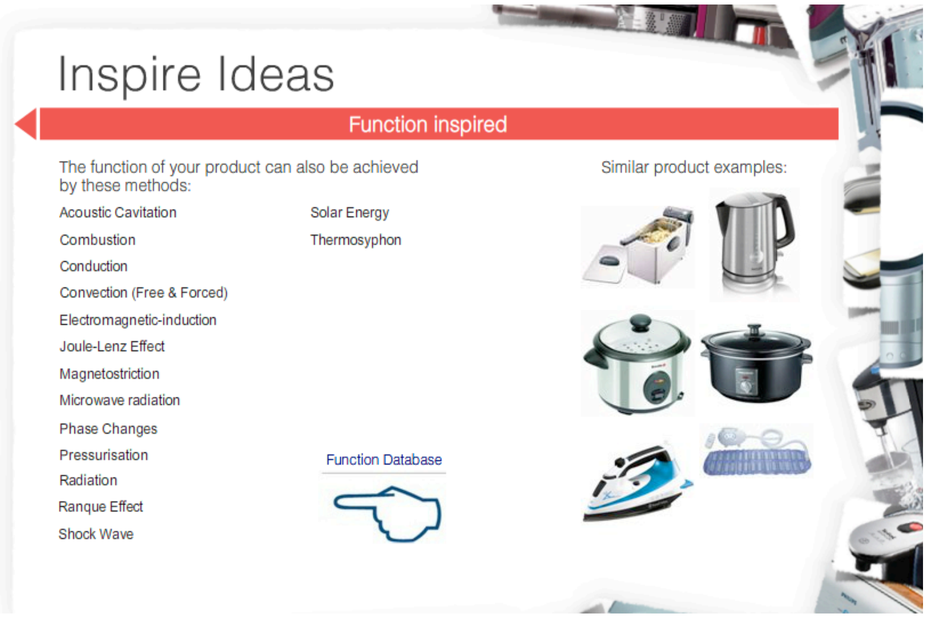
9. Upon clicking on the ‘strategy inspired’ button, all of the strategic guidance relevant to the users product function and LCA results are displayed. In this case study there are five relevant strategies to choose from.



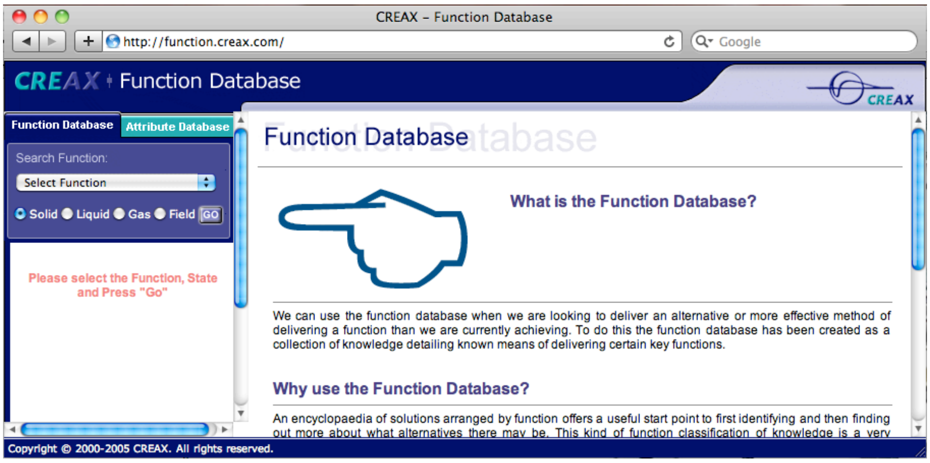
10. By selecting a strategy all the relevant advice is then displayed. From some products additional subheadings will become available. In this case study, where we have described our products function as ‘heating a liquid’, and included ‘electronics’ in out part list we are given the ‘PCB’ and ‘Element’ sub-sections.



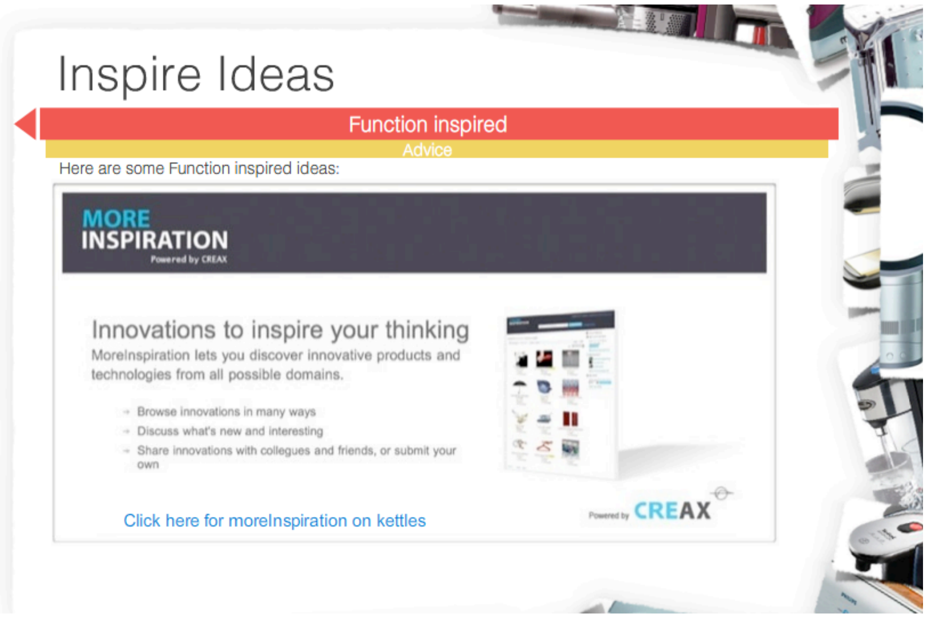
11. Under the 'PCB' sub-section we are given all the advice which is relevant to the users product if circuit boards or other electronics are included in the design.



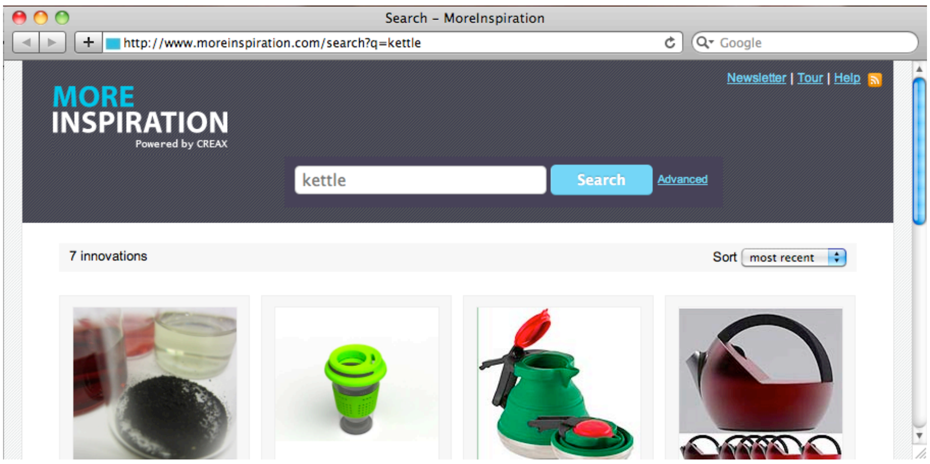
12. Branching off the 'Guidance matrix' to the 'Function inspired' section displays functional inspired guidance. On the left a list is generated displaying alternative methods for achieving the same function as the users product function. For more information, the user can choose to follow the 'Function Database' button. On the right there are a number of 'Similar product examples' which have a similar function to the users product. For this case study we are interested in kettles so if we choose to click on the picture of a kettle we will follow that product to step 14.



13. The 'Function Database' button opens up a new window and loads the *Function Database* developed by *Creax*. Here the user can further explore alternative functions.



14. This page gives some background information about the *MoreInspiration* database, and also gives a link to the database.



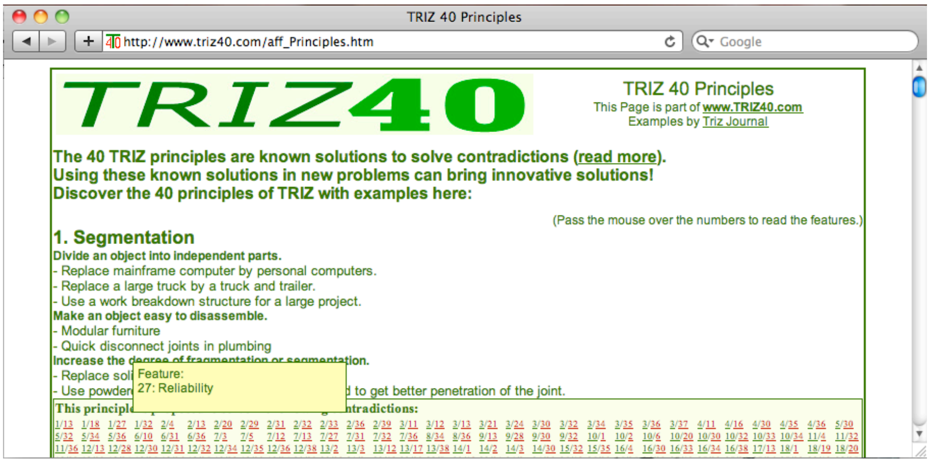
15. Following the link opens up a new window, loads the *MoreInspiration* database and then enters a keyword relevant to the users product choice into the search bar. It then loads all the relevant

innovation examples currently in the database, giving a truly dynamic search. For example with this case study the keyword is 'kettle', and it returns 7 innovations related to that term. The user is the free to further explore the database.

16. Branching off the 'Guidance matrix' into the 'TRIZ inspired' section displays all of the TRIZ related guidance. On the left side of the page there is an example of TRIZ IP's which have the potential to fit with the users product function. Selecting an IP from the list gives more detail as in step 17. On the right hand side there a product examples with a similar function to the users product. Clicking on of these links to further information about the chosen product. For this example where we are using the kettle case study example, if we select the kettle image the tool takes us to step 20.

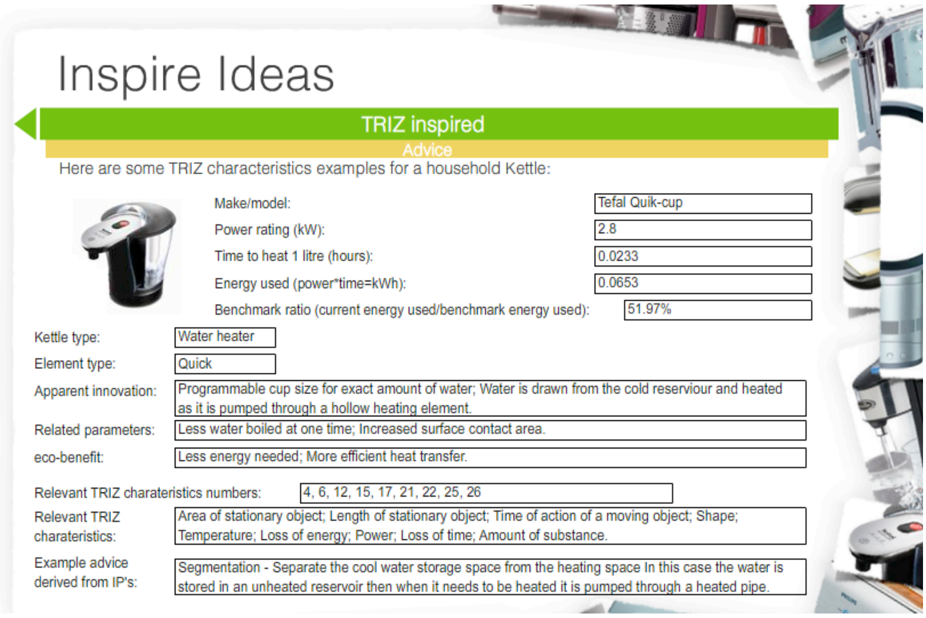
17. On this page each TRIZ IP is better explained. However, if this is not enough information or if the user requires background to TRIZ they can follow the link to more information by clicking the '*TRIZ40'* button, and background by clicking the 'What is TRIZ?' link at the bottom of the page.

18. Following the 'What is TRIZ?' link loads a brief introduction to the concept of TRIZ by '*The TRIZJournal'* into a new window. The user is then free to explore this well-respected network.



19. Clicking the '*TRIZ40'* button takes the user to the 'triz40.com' web resource. This website explains the 'TRIZ 40 Inventive Principles' in greater depth, and also gives examples.

20. Here nine product examples are displayed. A benchmark product has been chosen. For this product some details are displayed. For this case study energy use is used to assess each of the products performance against the benchmark. This ratio is displayed for each product.



21. By selecting an example product the tool displays further information. This section derives relevant TRIZ IP's which could have led to the apparent innovations exploited by the example product. This template is intended to inspire the user to explore other product examples.

A4.2 Equations required in LCA section of *Inspire Ideas*

Materials and processes

User defined inputs: *partWeight* = weight of a part

$$energyUsed = (partWeight * materialEnergy) + (partWeight * processEnergy) \quad (1)$$

$$carbonEmitted = (partWeight * materialCarbon) + (partWeight * processCarbon) \quad (2)$$

Table A3.2a – Values predefined in the database for materials and processes.

Material	Energy (kJ/kg)	Carbon (kg/kg)
ABS	96	3.4
PA	128	5.5
PC	110	5.6
PP	94	2.7
Stainless steel	81	5.1
Electrical components	300	20
Low carbon steel	32	2.5
Process		
IM ABS	24	1.9
IM PA	9.6	0.78
IM PC	23	1.9
IM PP	19	1.5
R SS	3.4	0.27
E E	1974	1135
R LCS	3	0.24

Transport

User defined inputs: *dist* = distance travelled to customer

Values brought forward: *prodWeight = combined weight of partWeight's*

$$energyUsed = transEnergy * prodWeight * dist \quad (3)$$

$$carbonEmitted = transCarbon * prodWeight * dist \quad (4)$$

Table A3.2b – Values predefined in database for transport

Transport type	energy used (kJ/kg)	Carbon (kg/kg)
sea	0.16	0.07
rail	0.31	0.07
truck	0.46	0.07

Use phase

Use defined inputs: *useLength* = average amount of time product is used for each time

elecRating = rating of the electrical device

lifeSpan = number of years product is active for

$$useValue = ((useLength * elecRating) * 365) * lifeSpan \quad (5)$$

$$energyUse = ((useValue * conEff) / elecConE) * energyEquiv \quad (6)$$

$$carbonEmitted = ((useValue * conEff) / elecConC) * carbonEquiv \quad (7)$$

Table A3.2c – Values predefined for use phase

Shorthand	Explanation	Value
conEff (element)	Conversion efficiency from electricity to heat (element)	1
conEff (motor)	Conversion efficiency from electricity to rotation (motor)	0.89
energyEquiv	Energy equivalence factor for electricity	2
carbonEquiv	CO_2 equivalence factor for electricity	0.11
elecConE	Electricity conversion factor from kWh to MJ	0.28
elecConC	Electricity conversion factor from kWh to kg of CO_2	0.27