Effective Practices for the Concept Design of Electromechanical Systems

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Abstract:

Purpose

Concept design practices in engineering are not common across industry or academia. There are a number of well-known tools and methods acknowledged as useful in facilitating concept designing, that is, to assist idea generation, aid evaluation and final selection of one winning concept from many. Combinations of these popular concept design tools and methods provide various systematic methodologies by which practitioners propose to conduct or teach concept designing. In this paper, effective practices and trends are observed through the application of a specific concept design methodology over a range of different projects in electromechanical systems design.

Design/methodology/approach

The concept design methodology utilised in this study has been developed through the adoption of various tools and methods shown to be beneficial to concept designing, supported by previous positive experiences and successful utilisation associated with electromechanical systems research projects in academia. Each stage of the methodology is discussed and six case studies are presented, which are used to explore effective practices for concept designing.

Findings

Analysis of the case study data reveals the most popular criteria for the selection of concepts in electromechanical systems design, the number of selection criteria and number of initial concepts ideally required to converge on a final winning concept more efficiently, that is without the need for a more detailed second stage of selection using performance metrics

Originality/value

Rarely are detailed studies undertaken in concept design, first, to address the justification for the concept design methodology adopted and, second, to show how effective practices emerge through the analysis of non-subjective data over a number of concept design projects. Although the paper uses only six case studies in electromechanical systems design, it is hoped that the approach presented promotes the possible future development of a framework for verification of concept design methodologies across different products, sectors and user groups.

Keywords: Case studies, Design strategies, Concept design, Electromechanical system design and analysis

1. INTRODUCTION

The first time the requirements of a product are translated into a form whereby their satisfaction can be gauged is at the concept design phase. The designer needs to source a single solution quickly to a specific problem when in fact many alternatives could exist. It is a phase of product development where important decisions are made by designers and engineers; decisions which subsequently impact on later stages of product development and ultimately the performance and success of the product in service with the customer, and its ultimate fate in the marketplace (Reich & Ziv Av, 2005). There are a number of approaches, tools and methods which can assist concept designing, the process of conceiving and generating ideas, evaluating these ideas and selecting one winning concept for further development, although none are standard, universally accepted or used consistently.

Given the level of subjectivity and high level of qualitative information driving the process of concept design, industry has shied away from it (Rosenman, 1993). Furthering this argument, Nikander *et al.* (2013) claims that structured design approaches are often not used properly or at all in industrial practice. Kihlander (2011) suggests that the concept selection methods proposed in the literature might be of little or no use in design. When setting out to design a new product, some designers will tend to pursue preferred solutions based primarily on prior experience or intuition, but without any formal justification as to why it is the most appropriate one. A lack of rigour or methodology in these early phases of design often lead to unexpected problems later in the process, typically after expending a great deal of resource, only to realise that the preferred solution has no further potential for design progression or that choosing a different concept would have mitigated these problems. In order to avoid this, the academic discipline of engineering design has for many decades tried to formalise and systematise the process of concept design generation, evaluation and selection, trying to make it as guided but as non-inhibitory as possible, whilst suppressing uncertainty and subjectivity. Ideally, an effective concept selection methodology should be holistic, structured, traceable, transparent, objective, reasoned, supporting, systematic, and have general applicability.

Ultimately though the concept design approach adopted may have been informed by the education and/or experiences of the individuals involved (through both successes and failings), rather than taken entirely from the literature. There may be many reasons for this, but a major contradiction and argument is the suggestion that structure and procedure can be brought to concept design when in fact conceiving ideas can be quite an emotional and absorbing experience. Designers are more likely to be accepting of strange ideas drawn from odd and unfamiliar sources and are less likely to conform to standard rules and preconceptions. They should have a certain freedom to explore potential solutions without excessive prescription it is argued. Ultimately, they have the freedom to adapt and adopt any combination of approaches which they deem facilitate their own concept designing (López-Mesa & Bylund, 2011). However, with an ever increasing need for transparency in decision making, the process should at least be justified and clear to all stakeholders. The use of a systematic approach is required in order to manage the process of converging on a concept design solution resulting from the assessment of a number of potential concepts (Pahl *et al.*, 2007).

Any final 'winning' concept design, by virtue of its weak definition of geometry, material choice and service conditions is never going to be optimal resulting from the application of a concept design methodology. A great deal of work is still required in order to provide design definition and assess final performance through embodiment design, and finally the detailed design phases. With the absence of any verification of concept design methodologies, there are no guarantees in the adoption of any approach (Pahl *et al.*, 2007). As commented on by Reich (2010), there is a great deal of debate on which approach is most suitable and what needs to be done in terms of verification in order to have more confidence in the results. Verification of concept design methodologies is a very different undertaking from, say, that of DFX tools and techniques (Huang & Mak, 1997). This is mainly due to lack of tangible characteristics to measure and evaluate (Kajtaz *et al.*, 2013). The outcomes reflecting design decisions are therefore regarded as subjective when related to the potential performance of concept designs and satisfaction of the requirements. It also is difficult to compare intangible measures with previous results e.g. bench-mark solutions. The observations of a single concept design methodology applied systematically over a number of case studies would be useful in the context of verification. Potentially, observations of good practice and analysis of tangible case study data could also be used as the basic foundations of a verification approach to gauge the usefulness of the concept design methodology adopted. Huang & Mak (1997) suggest verification tests should be carried out using a sufficient number and wide spectrum of case studies in terms of research in design tools and techniques. No such recommendation is provided for the verification of concept design methodologies in the literature.

This paper will explore the various effective practices resulting from the use and observation of a specific concept design methodology developed by the authors, and applied consistently to six case studies in electromechanical system design. Initially an overview is provided for the case studies before the paper addresses the reasons for adoption of certain approaches incorporated into the methodology. Discussion centres about the key stages of idea generation, evaluation and final selection. An analysis of the case studies is then presented, including some trends and observations. Finally, a number of recommendations are made for the implementation of the concept design methodology devised.

2. CONCEPT DESIGN CASE STUDIES

The complexity of engineered products has increased substantially over the last two decades in response to the demand for higher performance products by the customer. Many products have become heavily reliant on the integration of electrical and mechanical disciplines in order to satisfy these demands. The EEMG Group at the University of Bristol conducts interdisciplinary research and development into high efficiency, power dense and highly controllable electromechanical systems for actuation, energy generation and conversion. The projects undertaken, termed case studies in this paper, are used for the application of a common concept design methodology, discussed in Section 3.

Six case studies are selected covering a range of topics within electromechanical systems research representing a variety of technology readiness levels (achieved or targeted) and size of project, in terms of funding and staff allocated. Some of these projects are commercially sensitive and therefore some detail is not in the public domain. All but one project had high involvement from industrial partners, with the ‘energy source for a nuclear waste monitor’ project being part of an academic consortium. All projects were of the order of several months in duration for the concept design phase. Table 1 provides an overview of the six case studies and includes information about the number of concepts generated, number and type of evaluation criteria, supporting design and experimental tools used and the convergence process to one winning concept, which will be useful in the discussions that follow. Here we are limited to six case studies only, although the case studies comprise sufficient richness of detail as to warrant inclusion in a reflective assessment of a methodology.

3. CONCEPT DESIGN METHODOLOGY

3.1 Introduction

There are many design methodologies presented in the literature (Evbuomwan *et al*., 1996; Cross, 2000; Otto & Wood, 2001; Pahl *et al.*, 2007; Ullman (2009; Tomiyama *et al.*, 2009). Understandably, many of these methodologies also describe a process to aid the conception, evaluation and selection of new design solutions (King & Sivaloganathan, 1999). In this section, the key components of the concept design methodology used are overviewed, shown in Figure 1.

Convergence on a final winning concept is achieved through a staged approach: first, a concept generation stage; second, decisions on the relevant criteria for selection; third, an evaluation of the concepts and down selection stage to minimise candidate solutions, and finally, if needed, a fourth and final quantitative assessment of remaining candidate solutions using key performance metrics through detailed analyses. This fourth stage is only effective if the third stage does not yield a clear winning concept, and supports the situation where definite performance measures are needed to aid final selection in some cases (Kajtaz *et al.*, 2013). As Kihlander (2011) indicates, there has been a ‘blurring’ of the concept design phase with later activities in design making it longer, so the potential to accommodate more detailed analyses has increased, together with the design tools needed to facilitate these analyses being more rapidly executed.

Table 1 Overview of Case Studies
(DBT = Design Build Test, FEA = Finite Element Analysis, RP = Rapid Prototyping)

Case Study (in chronological order of research conducted)	Target Technology Readiness Level (TRL)	PDS Researched and Developed on Project	Number of Evaluation Criteria Used	Number of Initial Quantitative Evaluation Criteria	Supporting Tools Used at Concept Stage	Number of Initial Concepts → Number of Concepts Progressed to Next Stage	% Satisfaction of Top Ranked Concept (preferred weighting)	% Satisfaction of Bottom Ranked Concept (preferred weighting)	Number of Performance Metrics used for Second Stage (when applicable)	Supporting Tools used for Final Concept Selection
Actuated Shaving Head	3	No	12	0	CAD	6 → 3	73	49	3	Analytical Modelling +CAD +FEA +DBT
Energy Source for a Nuclear Waste Monitor ***(reference omitted)***	4	Yes	5	1	Analytical Modelling	12 → 1	90	43	0	DBT
Pico-hydro System ***(reference omitted)***	6	Yes	6	3	Analytical Modelling	11 → 1	74	50	0	DBT
Regenerative Braking System ***(reference omitted)***	5	No	6	0	CAD	6 → 2	78	60	4	Analytical Modelling +CAD +FEA +RP +DBT
Stop and Hold Device ***(reference omitted)***	5	No	8	0	CAD	9 → 1	71	51	0	DBT
Active Gurney Flap ***(reference omitted)***	6	No	8	0	CAD	6 → 2	76	31	5	CAD +FEA +DBT

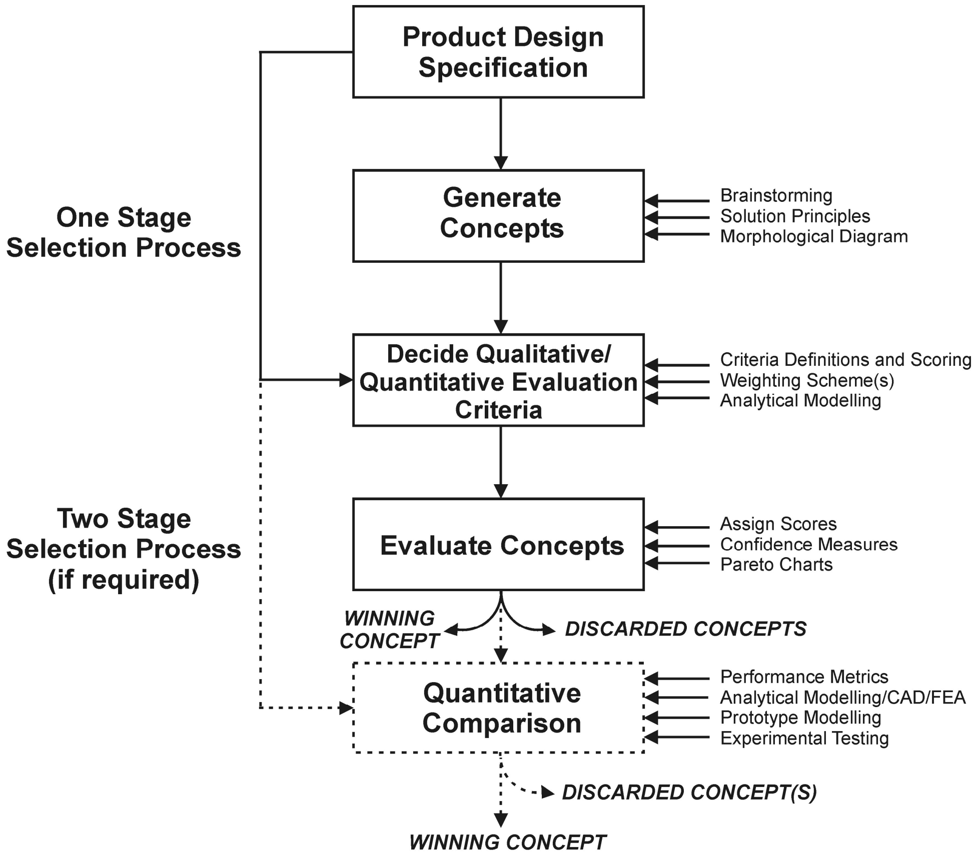


Figure 1 Concept Selection Methodology

3.2 Concept Generation

A PDS, or just specification, is a prerequisite before concept designing (Cross, 2000). It defines a set of requirements which naturally provides targets to aim for and measures of the design to compare to. Fricke (1996) suggested that under-defined problems produce fewer concepts, highlighting need for an adequate PDS. This is partially supported by the information shown in Table 1, where it is evident that establishing the PDS as part of the project was beneficial to generating more concepts than in the cases where it was simply given to the team (see Table 1). On some projects, specifications are complex documents informed heavily by internal company requirements and other constraints, tending to over-define the problem as far as the concept generation stage is concerned. Rationalising the content of specifications into a quickly absorbed document, literally a 'brief', is recommended in these situations, to develop a mind-set focussed on helping idea creation (Gomez *et al*., 2013). Conversely, other projects may be under-defined to such a degree that focus groups and Quality Function Deployment (QFD) may have to be used in order to construct sufficient boundaries to the problem and translate loose needs into engineering requirements before conceiving ideas can even take place.

Time is rarely invested in carrying out a review of the technical literature in order to construct as comprehensive as possible a ‘catalogue’ of existing or possible solution principles embodying concepts ideas, many of which might have been overlooked or simply ignored when setting out the design task. Such a research exercise, which would enable the designer to take into consideration a wider range of the options available, is often regarded as wasted time by some designers, rather than as a risk mitigating step that decreases the chance of problems later in the design process. The generation of prior art, lessons learned and, of course, experience should all be utilised in generating solution principles. More typically a brainstorming exercise is advocated (for example see Straker, 1995), although there are many other approaches which can be used aid the generation of ideas (Bluemner, 2008).

Morphological diagrams provide a more structured approach to generate ideas. First developed by Zwicky & Wilson (1967) for general ‘life’ problems, it has subsequently found wide application in engineering design. It can be used to help generate concept ideas by synthesising sub-function solution principles, with a large volume of ideas generated in a short time (Otto & Wood, 2001; Higgins, 2006). Still common sense and experience is required in order to judge which solutions principles combine to create viable solutions. Adapting and merging concepts is also likely using this approach – ‘cherry picking’ elements of successful designs to arrive at different concept ideas. Two examples are shown in Figure 2, where traditional sketches (a) and more often CAD sketching (b) is used to produce solution principle representations to populate the sub-function rows. The lines passing from top to bottom show the selection of sub-function solution principles which combined to generate a single concept idea.

Developing more than one concept idea is also a key issue for this process to work effectively. The aim should be to select the technically 'perfect' concept design from a number of alternative solutions that have been arrived at systematically, and not just select the first satisfactory solution (Braunsperger, 1996). Andersson (1994) found that some companies that do utilise a concept design methodology conceive very few candidate solutions. Fricke (1993, 1996) concluded from studies with designers that generated only a few concepts, or conversely many concepts, that both were unsuccessful strategies. Although an ideal number was not defined, Fricke stated that a 'moderate' number of concepts assist designers to 'explore the solution space without becoming bogged down in excessive evaluation'. Frey *et al.* (2007) suggest that generating 15 concepts as typical. Kudrowitza & Wallace (2013) found that encouraging designers to come up with lots of ideas can potentially increase the number of creative concepts. It is also likely that a preliminary 'screening' process is required to limit the number of concepts progressing to the evaluation stage to a manageable number in some circumstances.

One issue which has been observed as good practice when disseminating ideas to stakeholders is that the presentation quality and format type of all concept ideas should be consistent. Clear descriptions and annotations with a similar level of information for each idea better informs team members when assigning scores to evaluation criteria (the stage discussed next), measuring the potential of each idea against evaluation criteria. Again, CAD has been used to show the concept ideas when the numbers allow, and the designer(s) is proficient in CAD.

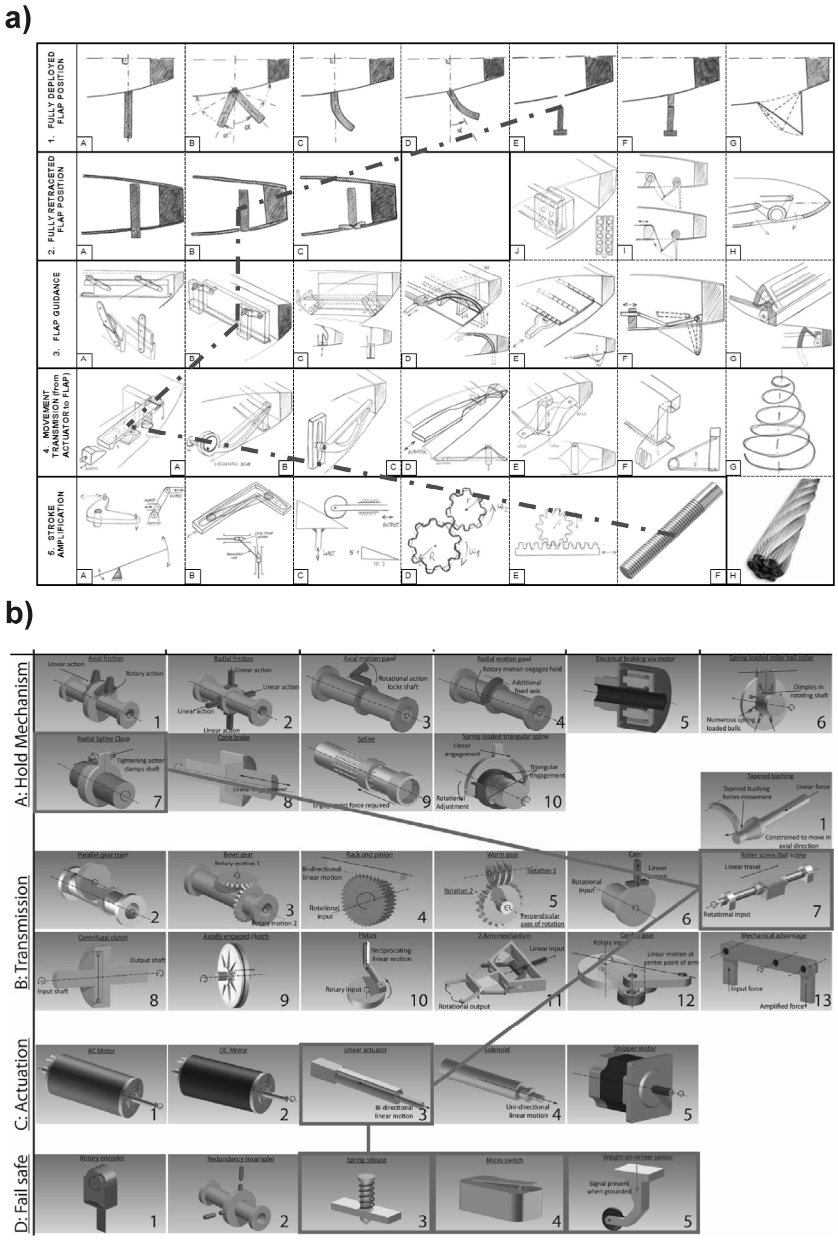


Figure 2 Morphological Diagrams used to Visualise Solution Principles and Generate Concept Designs a) Conventional Sketching, b) CAD Sketching

3.3 Evaluation Criteria and Weightings

Deciding on a set of criteria for evaluation of the concept designs is an important first decision in concept designing. Criteria should be carefully chosen based on their relevance to the specific problem, and refined from important issues in the PDS. The evaluation criteria don't usually satisfy exactly the quantifiable PDS issues, but some related design intent which embodies the top level requirements. The evaluation criteria for the six case studies are shown in Table 2 for example. Lamers (2009) recommends between 3 and 8 criteria in total. Frey *et al.* (2007) suggest 18 criteria as typical. Lamers (2009) also used a varied number of evaluation criteria to select concepts in the micro-electromechanical systems, and found that the selection was identical suggesting the number of criteria may not matter.

Table 2 Case Study Evaluation Criteria

Actuated Shaver Head	Energy Source for a Nuclear Waste Monitor	Pico-hydro System	Regenerative Braking System	Stop and Hold Device	Active Gurney Flap
• Spatial fit • Multi-positional • Linear profile • High mechanical advantage • Resistance to environment • High safety • Low complexity • High manufacturability • Ease of assembly • High reliability • High flexibility/ adaptability • Energy efficient	• Reliable holding mechanism • Orientation insensitivity • Low complexity • Low susceptibility to environmental degradation • High power density	• Power density • Full flow efficiency • Part head/flow efficiency • Civil works costs • High maintainability/ serviceability • Scope for modularity	• Meets torque-speed requirement • High reliability • Low overall mass/volume • Performance robustness • High heat dissipation • Experiential knowledge of motor topology, scalability and costs	• Low overall mass/volume • High reliability • Fault tolerant • Low cost • Scalable • Performance robustness • High transmission efficiency • High maintainability/ serviceability	• Flap deployment • Low overall mass • High reliability • Power transmission efficient • High maintainability/ serviceability • Fail retract safety mode • Low susceptibility to environmental degradation • Low manufacturing cost

An overriding objective should not be to minimise the number of evaluation criteria in an attempt reduce subjectivity. Subjectivity can in part be reduced by improving the criteria definitions. Kihlander (2011) says that criteria which are too well defined may not match onto design data well, and several iterations may be needed before the final set of criteria is agreed upon by stakeholders. Otto and Wood (2001) recommend forming a consensus on the definition of the criteria so that all stakeholders have a similar perception of their meaning. There are a number of criteria types which are popular still such as: cost, market potential, risk, safety, reliability and performance (Mistree *et al.*, 1994; Otto & Wood, 2001). Pugh (1981) suggests cost shouldn't be considered too early, though it is usually on the agenda of most companies and appears in the list of evaluation criteria for several case studies in Table 2. It is also useful to consider a criterion in conjunction with a direction e.g. low mass. It can also be advantageous to combine criteria to form a new one e.g. low mass and high power, would become high power density. Occasionally, criteria may be broken into several sub-criteria with detailed definitions. For example, a 'Scope for Modularity' criterion has two sub-criteria associated with portability and common interfaces, as shown in Table 3.

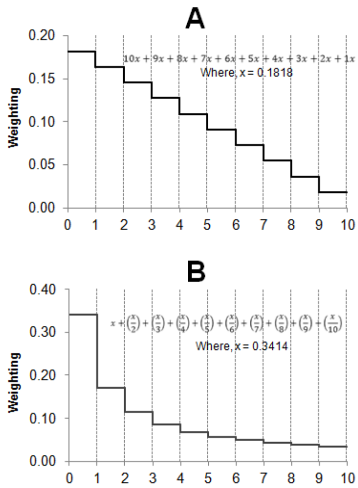
It may also be worth exploring, in a quantitative manner, at least one performance-based evaluation criteria at the first stage of concept evaluation. These criteria are simply developed from physics-based models relating to measures such as power, efficiency or related specific (mass or volume of the system) properties of a concept. There is also a potential for reduction in subjectivity through the use of the analysis models. Minimising mass and volume are key drivers in future electromechanical system development, whilst increasing performance, efficiency and reliability, and minimising maintenance requirements continue to be the main design intents.

Applying weightings to the evaluation criteria is a necessary enhancement as not all criteria have the same importance. The team may arrive at these by negotiation or simply by ranking each criterion in terms of most important to least important, and then applying a function to allocate weightings between 0 and 1, as shown in Figure 3 for several commonly used and demonstrated for the case of 10 ranked evaluation criteria. A Weighted Objectives Tree is also an effective and transparent way of partitioning weightings to a set of evaluation criteria (Hurst, 1999).

Table 3 Definitions used for a 'Scope for Modularity' Evaluation Criterion used in the Pico-hydro System Case Study

Definition – Modules that allow the system to be broken into carryable/shippable units and allow line replaceable for easy servicing and fault identification, with the ability to interchange identical modules.	
Scoring Criteria – Modular Portability	**Score**
Able to disassemble unit into manageable, man-carryable components; simple and quick assembly/disassembly	5
Some components large and unable to be carried by single man, most easy to carry; assembly/disassembly reasonably simple and quick	3
Unable to disassemble unit into manageable, man-carryable components; long and laborious assembly/disassembly	1
Scoring Criteria – Modular Unit	**Score**
Few, but standard, interfaces; few system elements; simple coupling mechanisms between elements; simple element architecture orientation	5
Few non-standard interfaces, some standard interfaces; manageable	3

architecture; some non-standard coupling between system elements	
Many non-standard interfaces; many separate system elements; complex coupling mechanisms between system elements; unusual element architecture orientation	1



Weightings			
A	B	C	D
0.1818	0.3414	0.19	0.271
0.1636	0.1707	0.17	0.217
0.1455	0.1138	0.15	0.169
0.1273	0.0854	0.13	0.127
0.1091	0.0683	0.11	0.091
0.0909	0.0569	0.09	0.061
00727	0.0488	0.07	0.037
0.0545	0.0427	0.05	0.019
0.0364	0.0379	0.03	0.007
0.0182	0.0341	0.01	0.001

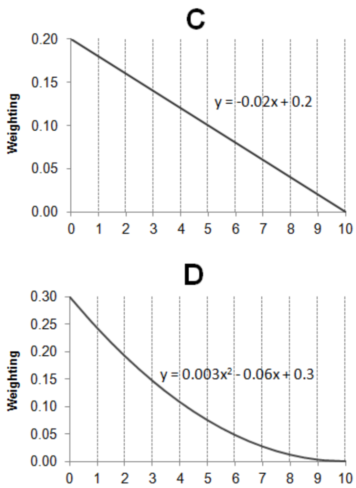


Figure 3 Weighting Schemes used for 10 Evaluation Criteria

3.4 Concept Selection

There are a variety of methods that can be used to aid concept selection including: advantages/ disadvantages, voting, trade studies, prototypes/mock-ups and decision matrices. For example, the Pugh Matrix (Pugh, 1990) is probably the most widely known approach for selecting concepts, being taught widely in academia, and being used at the system, product and component levels (Tomiyama *et al.*, 2009). One drawback is that it requires candidates to be compared to a baseline design, which may not necessarily exist, particularly with emerging electromechanical systems. This approach also assumes that the benchmark has some high level of satisfaction of a similar specification in the first place. Another approach to aid evaluation and selection is the Analytic Hierarchy Process (AHP), widely used to solve multi-criteria problems. It has been applied to a wide range of problem types, not just in engineering design. Caution is needed to ultimately direct final selection of one winning concept, with some practitioners finding it more useful in managing the decision making process (Triantaphyllou & Mann, 1995; Vinodh *et al.*, 2012).

A simple matrix approach is advocated using a standard scoring system to assign numbers against the potential satisfaction of the qualitative evaluation criteria. The numbers assigned are largely driven by experience and intuition rather than hard scientific evidence (Mistree *et al.*., 1994). Typically a scoring system ranges from 1-5 where 1 represents no satisfaction of the evaluation criteria, 3 represents a moderate satisfaction and 5 represents full satisfaction. A scoring system of 1-10 provides too much granularity it has been found. Scores are then summed across all evaluation criteria with weightings included, and normalised to a percentage figure to make it easier to compare concepts relatively, usually in a Pareto chart format.

Another enhancement to this decision making process, is the inclusion of confidence levels to be considered in conjunction with evaluation criteria scores, reflecting the experience and understanding of the team as a whole. Confidence ratings typically used are: Total confidence = 5, high level = 4, moderate level = 3, low level = 2, no confidence = 1. An example of their use is shown in Figure 4a). Initially, it is not clear which concept warrants selection as the first four (ranked left to right) are very similar in overall satisfaction. However, introducing a confidence level, as shown in Figure 4b), strengthens the case for the first concept to be progressed having attained a slightly higher level than competing concepts. Note that the highest confidence levels are still only around 80% here reflecting the uncertainties that exist and subjectivity at this stage of designing. Figure 4 also shows the break-down of the contribution of each evaluation criteria satisfaction and confidence rating in the bar which again in a relative mode of use can help decision making by quickly identifying the contribution of each criteria to the whole.

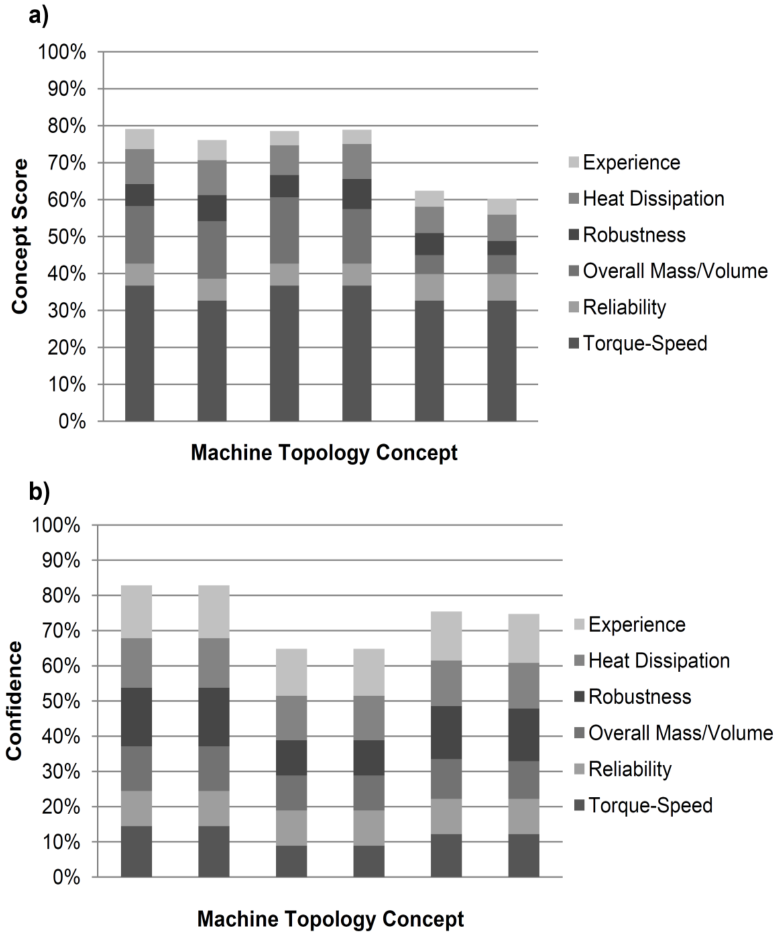


Figure 4 Use of Concept Scores with Confidence Levels for Regenerative Braking System Case Study, a) Overall Concept Score (% Satisfaction) b) Confidence Level (% Confidence in Score)

Making robust decisions is important in order to reduce subjectivity in concept designing. Therefore studies can be undertaken to show how insensitive the process is with small changes to number of evaluation criteria and weightings used in order to select the same concept. For example, Mistree *et al.*. (1994) suggests changing the weightings of each evaluation criteria by 5% and re-running the analysis. An example of a 'sensitivity analysis' is shown in Figure 5 where the five charts represent the different results of overall satisfaction, but for different weighting schemes across the evaluation criteria. The arrow represents the final 'winning' concept taken forward. In all but one case, the same concept is shown as providing the highest satisfaction of the criteria, therefore the decision making process is not fully robust, but indicates a preferred solution repeatedly.

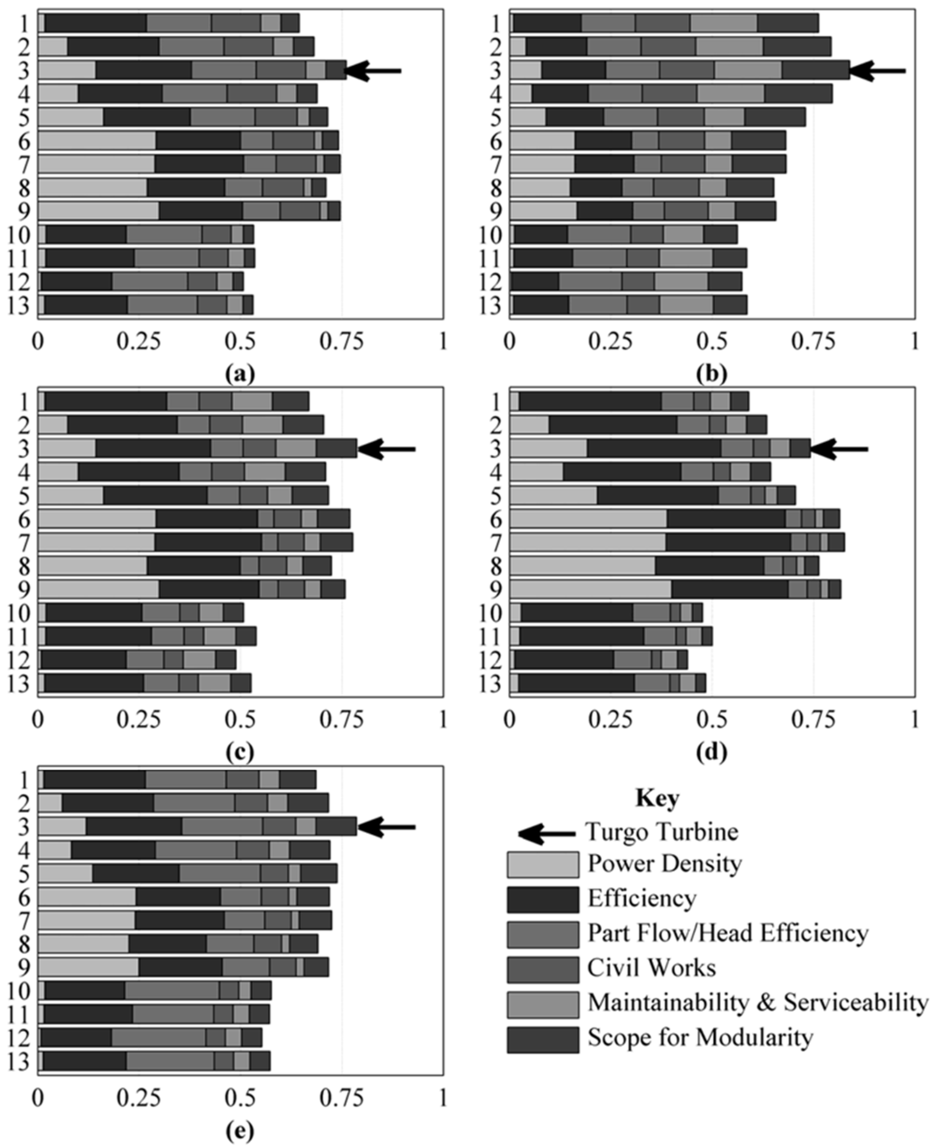


Figure 5 Charts for the Different Weighting Schemes used in the Pico-hydro System Case Study Sensitivity Analysis (the arrow represents the 'winning' system)

Convergence on a single winning concept design sometimes requires further assessment beyond the qualitative stage for example where two or more concepts are shown to be closely competing in terms of overall satisfaction and confidence level. The methodology in Figure 1 presents a fourth stage of concept evaluation and selection if required in these circumstances. Performance Metrics are used as quantifiable measures of the concept against target requirements in the specification. Some detailed definition of the concept is therefore needed, perhaps material type, geometry, load cases etc in order to conduct analyses and predict performance, populating the Performance Metrics. An example is shown in Table 4 where two out of six concepts generated were judged as closely competing from the initial stage of concept evaluation and selection process. Five Performance Metrics were subsequently used to decide the winning concept, where 4 out of 5 metrics are met by Concept B. The level of analysis needed to make the final decision was high (CAD, FEA and analytical tools were all used), but these were essential in order to have confidence going forward with the chosen concept (which was experimentally tested as part of the project successfully).

Table 4 Performance Metrics to Support Final Concept Selection for Active Gurney Flap Case Study (preferred values are in bold indicating Concept B was selected with 4 out of 5 Performance Metrics accepted)

Performance Metric	Units	Targets	Supporting Design Tools	Concept Scheme	
				A	B
Total Mass	g	Minimised	CAD	**1560**	1740
Flap Out-of-plane Stiffness	N/mm	≥ 20	FEA	43	**276**
Flap Chord-wise Stiffness	N/mm	≥ 500	FEA	146	**4563**
Energetic Efficiency	J/cycle	≤ 10	Analytical	4.7	**0.75**
First Natural Frequency	Hz	≥ 140	FEA	55	**400**

4. ANALYSIS OF CASE STUDY DATA

So far, the case studies have been used to highlight areas of effective practice, as well as discussing how the elements of the concept design methodology blend together. Certain case study data can also be used to observe trends more quantitatively. A number of important questions could be answered, if not directly, then inferred from the case studies. For example as shown in Figure 6, the idea that a ‘technically perfect’ concept is converged on using the concept design process was introduced earlier. If a technically perfect concept satisfies all the evaluation criteria fully using a preferred weighting scheme giving 100%, then on average the winning concepts for each case study only achieved 77% satisfaction. Compare this with an average of 47% satisfaction for the lowest ranked concept, giving a small range of 30% in which many of the concepts generated will finish within. Therefore, on average there is still 23% more from the winning concept needed to fully comply with requirements – a technically perfect concept does not exist, and perhaps we shouldn’t strive for one. Many designs need a great deal of work post-concept design to make up this difference, through an embodiment design phase typically.

The number of concept designs generated and number of evaluation criteria used in the selection process are tangible measures from the case study data. This data can be seen in Table 1 in relation to the different stages passed through to a winning concept design. Figure 6 shows these numbers on a chronological reference frame to gauge whether they varied over time. There appears to be some consistency on the latter projects where the number of criteria and concepts converge. On average the number of criteria and concepts was about the same at 8.

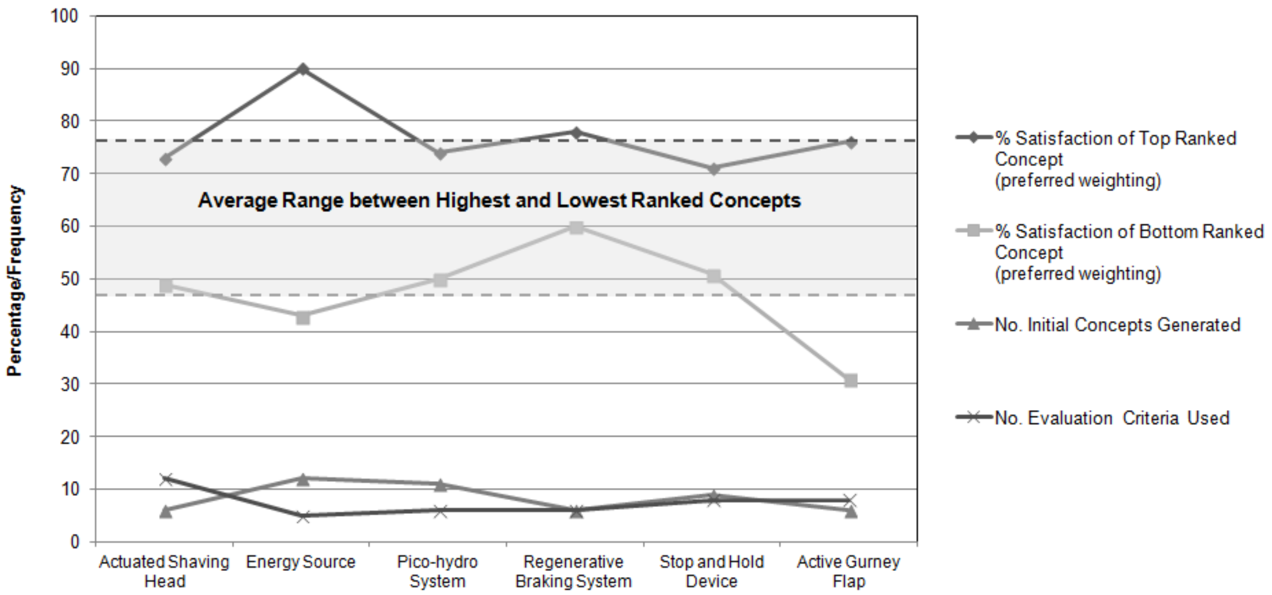


Figure 6 Case Study Data (projects in chronological order)

Looking deeper into the number of concept designs generated, Figure 7 shows there is a strong correlation (correlation coefficient, r = 0.93) between the number of concepts generated and the proportion of concepts eliminated at the first stage of selection. This might seem an obvious correlation however the optimum number of concepts generated can be inferred to be 11 in order that the maximum potential for reducing numbers to a single winning concept is achieved in one stage i.e. without having to go to a more quantitative analysis stage using performance metrics. (A second order polynomial model was chosen to fit the data as it provided the higher correlation coefficient compared to other models, but obviously with limited data, the true model is not known.) Too few concepts, as Fricke (1993, 1996) concluded, as a concept design strategy can lead to problems too, and as observed with the three case studies generating just 6 concepts for the first stage of evaluation and selection (Table 1), another stage of more detailed analysis using performance metrics has to be used to select the winning concept, potentially adding time, cost and complexity to the decision making process.

A relatively strong correlation (r = 0.79) exists between the reduction in concepts at the first stage and the number of evaluation criteria used, as shown in Figure 8. (An exponential model was chosen to fit the data as it provided the higher correlation coefficient compared to other models.) It indicates that an optimum number of evaluation criteria should be 5 based on the increased potential for concept number reduction, whereas the average number used across all case studies was in fact 8. It is more difficult to establish a recommended figure for evaluation criteria, but in conjunction with Figure 9, which shows that the most highly utilised evaluation criteria, 6 would certainly take account of the priorities in electromechanical system design problems i.e. reliability, robustness, geometric requirement, specific performance, high efficiency and mass minimisation.

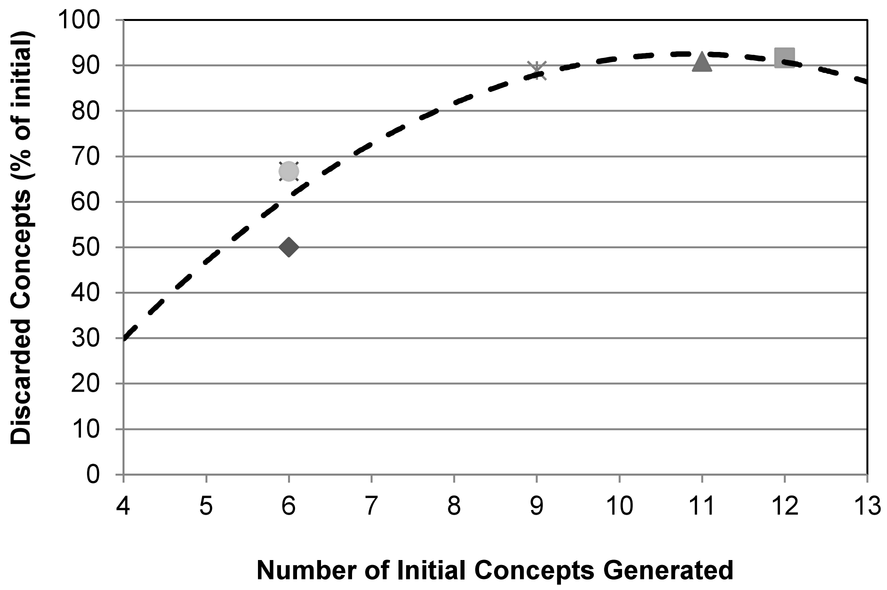


Figure 7 Correlation between Number of Concept Designs and Discarded Concept Designs at First Stage for all Case Studies

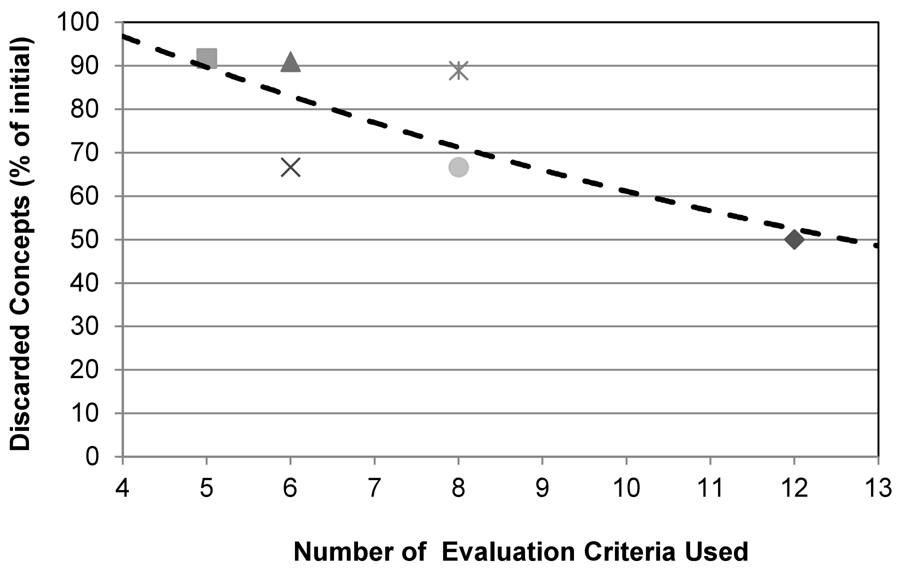


Figure 8 Correlation between Number of Evaluation Criteria Used and Discarded Concept Designs at First Stage for all Case Studies

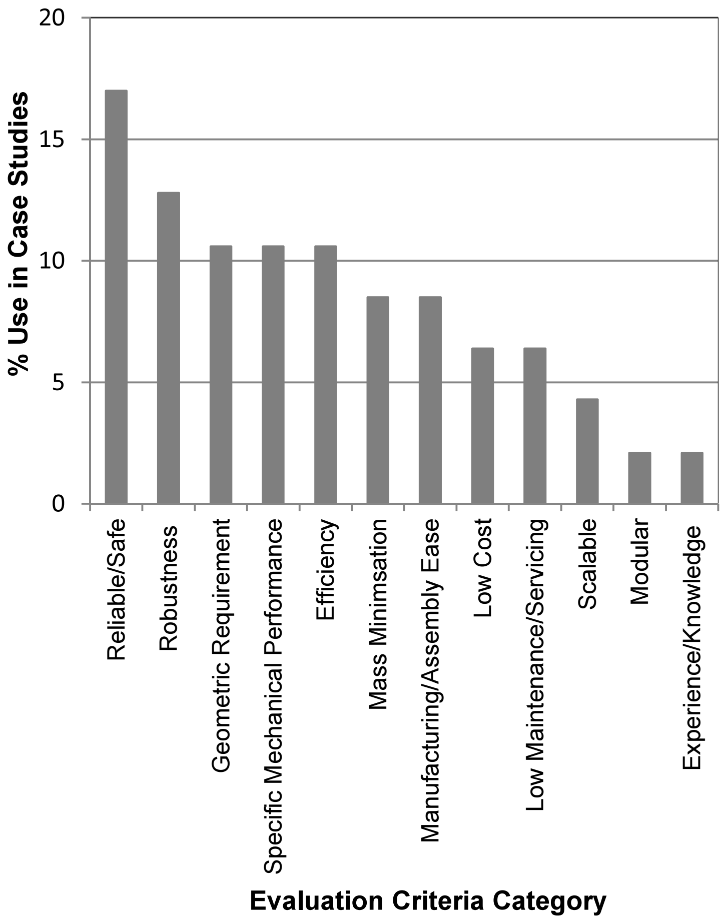


Figure 9 Pareto Chart Showing Frequency of Evaluation Criteria Use for all Case Studies

5. CONCLUSIONS

Increasingly, research projects are targeting higher technology readiness levels for novel electromechanical hardware in an attempt to demonstrate to industry the viability of new technologies. Concept design stage decisions in particular need to be transparent and robust so stakeholders have high degrees of confidence in the concept solution's success before committing to a generally longer design analysis and prototype testing stage. Concept designing needs to be driven by systematic approach to manage these activities.

The concept design methodology presented in this paper evolved through progressive application to a number of case studies in electromechanical machine design. Reflections on what worked, adaptations and adoptions of popular tools and approaches, all informed its development to suit the environment it is being applied in and products it is applied to. It has been readily implemented with minimal training of a range of different research staff (both electrical as well as mechanical) selecting concepts which have progressed successfully to prototype testing and ultimately validation against the specification.

However, the concept design methodology is not verified in any way - there are no guarantees that this, or any other approach for that matter, will yield the 'technically perfect' concept every time when used. There are certain tangible measures identified at the generation, evaluation and selection stages of projects which can be analysed and trends formulated to support the identification of effective practices. With a sample of only six case studies, it is difficult to argue that the trends will be seen across all problem domains. However, a purpose of this paper was to see if it was possible to measure the outcomes of a particular concept design methodology and observe trends in this first place. For example, the number of concepts generated should be sufficient enough to capture all possibilities and opportunities making a winning concept more likely and potentially avoiding more detailed analyses of competing concepts using performance metrics. It is also evident that the number of evaluation criteria should be minimised in line with issues important to the application domain e.g. in electromechanical machine design, reliability, robustness, performance etc are dominant.

In the cases where few concepts are generated, and there are many issues for evaluation against the specification, then it is more likely that a more detailed analyses are required in order to judge the winning concept. This is not an overly poor outcome of the decision making process – the concept design methodology presented accommodates this next level of selection if needed. It is also the belief that concept design and the early embodiment phases of design have become more blurred, and more detailed analyses and simulations can be readily conducted to judge performance, with the assistance from modern software and multi-disciplinary team working.

Proponents and practitioners of concept design methodologies are encouraged to appraise the effectiveness of these approaches using some tangible measures of the process and its outcomes in an honest and open manner. More generally, a framework for verification should be established accumulating evidence on what works, what does not, drawing trends across a range of products, sectors and user groups.

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