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RELATIVE RELIABILITY AND REALIZABILITY RISK ASSESSMENT FOR SELECTING ROBUST CONCEPT DESIGNS

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ABSTRACT

Two evaluation criteria, namely Reliability and Realizability, are considered central to the selection of robust designs during the concept design (system design) phase. It is argued that both criteria offer an initial basis for an effective Competitive Technology Assessment of the design concepts and selection of the 'superior' or most robust concept. A controlled experiment, designed to allow observation of the application, by novice designers, of two formal evaluation methodologies developed to assist evaluation of Reliability and Realizability, is used to provide evidence of the validity of the methodologies. The purpose being to gain insight to the degree of assistance offered by the formal methodologies, the ease of application of the methodology by the novice designer and the potential consistency of the evaluation process.

Initial experimental trial results indicate that novice designers find the application of the Reliability methodology to be more intuitive, and are generally more consistent in their judgements, compared to the Realizability methodology. In addition the results raise interesting questions about selecting designs that are robust to variations in the physical/technical environment as well as the resource environment.

Keywords: robust design, concept design, evaluation, reliability, realizability, risk

1 INTRODUCTION

The ability to rapidly and reliably evaluate design ideas is an essential element in the goal to increase design productivity. Given the need for companies to produce more innovative products in an increasingly competitive market place it follows that designers have to consider an increased number of design options if the most appropriate and robust design is to be pursued through the product development process. Only through the generation of a relatively large number of concept design options along with a rapid and reliable means of evaluating the options will designers be able to increase design productivity whilst identifying and developing new innovative products. It is recognised that a significant difficulty with evaluating design options is that they are 'information poor'. That is, important decisions often have to be taken with very limited information [1]. This provides designers with a major challenge.

Matthiassen [2] has defined a product's robustness as: "determining its ability to either obtain and/or maintain its characteristics, functions, and product or activity related properties when subject to disturbances throughout its various life phases."

The notion of robust design has been gaining over recent years and has developed significantly, since first being suggested by Taguchi [3], to include the quality of complex engineering systems as well as individual components. Recent work in this area has focussed on robust multidisciplinary design and optimisation [4,5]. The aim is to optimise the performance, whilst reducing costs of complex engineering systems. This increasingly requires the integration of expertise from a range of engineering and design disciplines that are often geographically distributed.

What appears to be consistent within the literature is the idea that the selection of a robust concept design, or system design, precedes the parameter design and tolerance design phases of a robust design process. However the procedures for identifying and selecting the 'superior' or robust concept design are not so well described. One approach is known as 'Competitive Technology Assessment'. This requires designers to make judgement, based on previous experience, as to which concept comprises inherently robust internally and externally developed technology to deliver the desired product functions. One possible way of making this complex judgement is to consider how variations in both process and resources will influence the ability of the inherent technologies, resident in each competing concept, to deliver the desired product function. Two key criteria lend themselves to this approach. The first, Reliability considered a judgement of function robustness when subject to process variation. The list of processes include; design, manufacture, use and disposal. The second criterion is considered to be Realizability and is defined as being a judgement of function robustness when subject to resource variation. The resources include time, money, manpower, capacity etc at all stages in the product life cycle.

The methodologies used to consider each of he above criteria are now described.

2 RELATIVE RELIABILITY RISK EVALUATION METHODOLOGY

Various reliability analysis tools have been proposed and published literature is available on the range of these tools. However, in general, these tools demand extensively established quantitative data to predict system reliability and that conventional reliability calculations in the concept design phase are of limited use [6]. Methods such as failure rate calculations and fault tree analysis demand data available only in the detailed design phase or only in case of established products or when the testing has been performed. Since the data availability is less in the case of concept design (especially for original designs) phase these models do not solve the problem of reliability evaluations of concept designs.

It may be argued that the definition of concept design differs from company to company. Say for example, a company wishes to utilize the available components in the market for a new product. The product is definitely new but the conceptual design phase of such a product would entail selection of available components to make an "ideal" fit that the industry wishes to progress. Predicting and calculating reliability in such cases is possible using the techniques available. The definition of conceptual design we follow is that for original designs. Absolute reliability calculations in this case are not possible but a relative reliability indicator may be calculated in order to rate the generated design options and get ordinal rankings for them. A method is proposed to utilize functions for calculating a Relative Reliability Risk Index (RRRI or R^3I). The argument that functionality has less to do with reliability seems invalid here because performance is a measure of reliability and proper function satisfaction indicates the performance of the product considered during the concept design phase. Henceforth, we follow a relative approach in calculating R^3I using Analytic Hierarchy Process (AHP) [7].

To calculate the Relative Reliability Risk Index (R^3I), a four-step methodology (Fig.1) is used [8]. To begin with, the established function structure of the product is considered. Establishing Function structures in the Conceptual phase of design helps to pursue design in a systematic manner. In the initial stages of design, the technical systems are represented using function structures before their solution principles have been proposed**.** Initially a "Black box" approach towards the system is established representing the overall system goal with the inputs and outputs. The inputs and outputs are in the form of energy, matter and signals. Then sub-functions are added to this system and each of them is usually represented as a verb-noun pair. The detail of the structure depends on the level of abstraction one wants to achieve. There are two types of functions, main functions and auxiliary functions. Main functions are the ones that directly help achieve the overall goal and Auxiliary functions indirectly help in achieving the overall function.

After consideration of the function structure the Analytic Hierarchy Process (AHP) is applied, using the commercially available Decision Support Software by Expert Choice. The software is interactive with an efficient number crunching and provides a measure of Inconsistencies during the comparison. AHP is applied so as to relatively rate the main functions of the function structure using the "soft" information available to the designer. The functions compared are the main functions and they are compared with respect to the solution principles defined in each concept. After the comparisons have been made, priorities are obtained. The priorities here indicate the preference of a concept over another with respect to the main functions. Step three includes assigning weights to the functions. This is done using the Entropy method. The entropy method is a Multi Attribute Decision Making method (MADM) to calculate the weights of the attributes that have been considered during Decision-making process. It utilizes the information content of the Decision matrix to calculate the weights of the attributes. This method has been adopted as a part of calculating R^3I because it may be inappropriate for a designer to compare main functions relatively from the function structure. The information contents of the normalized values of the attributes can be measured using entropy values. The Entropy V_j of the set of normalized outcomes of attribute j is given by

$$V_j = -\beta \sum_{i=1}^{n} l_{ij}*(\ln l_{ij}) \qquad (1)$$

for all j, (j = 1 to k represents attribute and i = 1 to n represents alternative)
where β is constant which defined as $\beta = 1/ \ln (n)$ and l_{ij} is a normalized element of the Decision matrix. If there are no preferences available, the weights are calculated using the equation

$$w_j = e_j / (\sum_{i=1}^{k} e_i) \text{ and } e_j = 1 - V_j \qquad (2)$$

If the decision maker has the weights available beforehand w_e, it can be combined with the weights calculated above, resulting in new weights that are w_{new}.

$$W_{new} = w_{e*}w_j / \sum_{i=1}^{k} w_{e*}w_j \qquad (3)$$

This method has been adopted because it does not require designer to provide the weights. Instead weights are calculated by extracting the information content of the decision matrix. This also helps to rule out any chance of prejudice or manipulation to assign weights by the decision-maker. Even if the decision-maker has already assigned the weights, they can be combined with the weights obtained using this method.

Step four consists of calculating Relative Reliability Risk Index (R^3I).

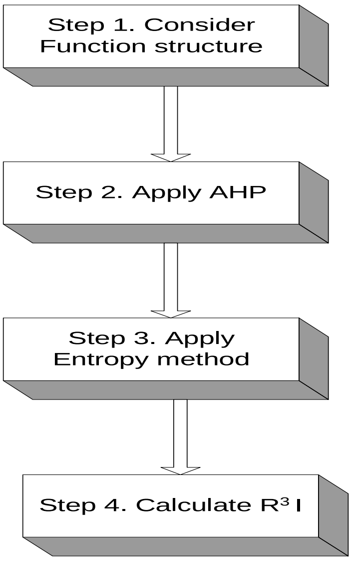

Figure 1. Relative risk evaluation methodology

3 RELATIVE REALIZABILITY RISK EVALUATION METHODOLOGY

Physical realizability refers to the ease with which the designs can be realized within the variable budgets of available resources, such as time and cost. It not only refers to mechanical products but also can be applied as a generic term and to various other products. There has not been much work put forth with regards to physical realizability as per the authors' knowledge. However the two major works that have been published are those of Asimov [9] and White [10]. Asimov first proposed the idea of physical realizability in the early 1960's but there is little evidence in the literature that it has been developed to any degree. Physical realizability has been defined as representing the fundamentals of ease of realizing a concept. In a decision matrix, various concepts have different benefits and difficulties/consequences associated with them. Using a decision-making method, one may come to a conclusion about the ‘Best’ concept but even after doing so, one may not be sure about the ease of physical realizability. This uncertainty may bind the Decision-making models to connect to one more aspect of evaluating concepts with respect to physical realizability.

The theory of physical realizability, as proposed by Asimov is based on 2 hypotheses:

Hypothesis 1: Any solution can be realised, if infinite amount of time and money is invested on the same. Having said this, it is clear that industry face an opposite situation to this in that they have the limited resources available.

Hypothesis 2: Belief that the particular design task can be accomplished successfully depends on the amount of favourable evidence.

With these hypotheses in mind, the theory of physical realizability by Asimov is discussed. Theory of physical realizability is a belief that a concept can be physically realized, which is based on the following points:

- Intensity of belief is an increasing function of positive evidence that the “sub – problems can be resolved”
- Intensity of belief is an increasing function of the size of budget allowed
- For reasonable accumulated evidence, a linear relationship will exist between favourable evidence and expenditure
- If the “increasing rate” of favourable evidence with expenditure is high, the intensity of belief that the outcome is physically realizable will also be high
- Decision maker would favour the concept with intense belief of physical realizability

Mathematically, Asimov defines this as:

$$L = f\left[E, X_B\left(\frac{dE}{dX}\right)_0\right] \tag{4}$$

Where, $\left(\frac{dE}{dX}\right)_0$ = Initial rate of increase in favourable evidence with expenditure (Tractability)

As L is measured on a probability scale, it can be represented by

$$L = P\ (A_i \mid X_B) \tag{5}$$

P (A_i) is the probability that the “proposition” of concept A_i is physically realizable is true. Then P (A_i | X_B) refers to the probability that concept A_i is physically realizable is true given the budget X_B. If some evidence is found, then Intensity of Belief (L) can be reformulated as:

$$L = P\ (A_i \mid E\ X_B) \tag{6}$$

This equation refers to the proposition that A_i is true given the Budget X_B and the evidence E. Using Bayes theorem, Asimov expresses this as:

$$P\ (A_i \mid EX_B) = P\ (A_i \mid X_B) * \frac{\mathrm{P}\,(\mathrm{E} \mid \mathrm{A_i X_B})}{\mathrm{P}\,(\mathrm{E} \mid \mathrm{X_B})} \tag{7}$$

Here, $\mathrm{P}\,(\mathrm{E} \mid \mathrm{A_i X_B})$ = Probability that Evidence E is true given the proposition that A_i is true and Budget X_B and, $\mathrm{P}\,(\mathrm{E} \mid \mathrm{X_B})$ = Probability that Evidence E is true given the Budget X_B.

4 APPLICATION OF RELATIVE RISK METHODOLOGIES

Novice designers at Glasgow University were asked to generate concept designs, for an electromechanical car jack. A large number of concepts were generated with eight concepts ultimately being selected for final evaluation. The eight concepts are shown, in their original schematic form, in Fig. 2. This level of detail is judged sufficient to convey the basic nature of the different technology being used, within each concept, to achieve the required functions. For comparison and to allow an appreciation of the technology involved, an embodiment design of concept 2 is shown in Figure 3.

The novice designers were then asked to rate and rank the concepts with respect to reliability and realizability using the previously described R^3I and Asimov approach respectively. Of course, the terminology was explained to the students before the evaluation experiment was conducted. Nine novices felt confident to apply the R^3I methodology but only three of the nine also felt able to apply the Asimov methodology. The results from these three novices (N2, N3 and N6) are therefore used to make the final selection decision.

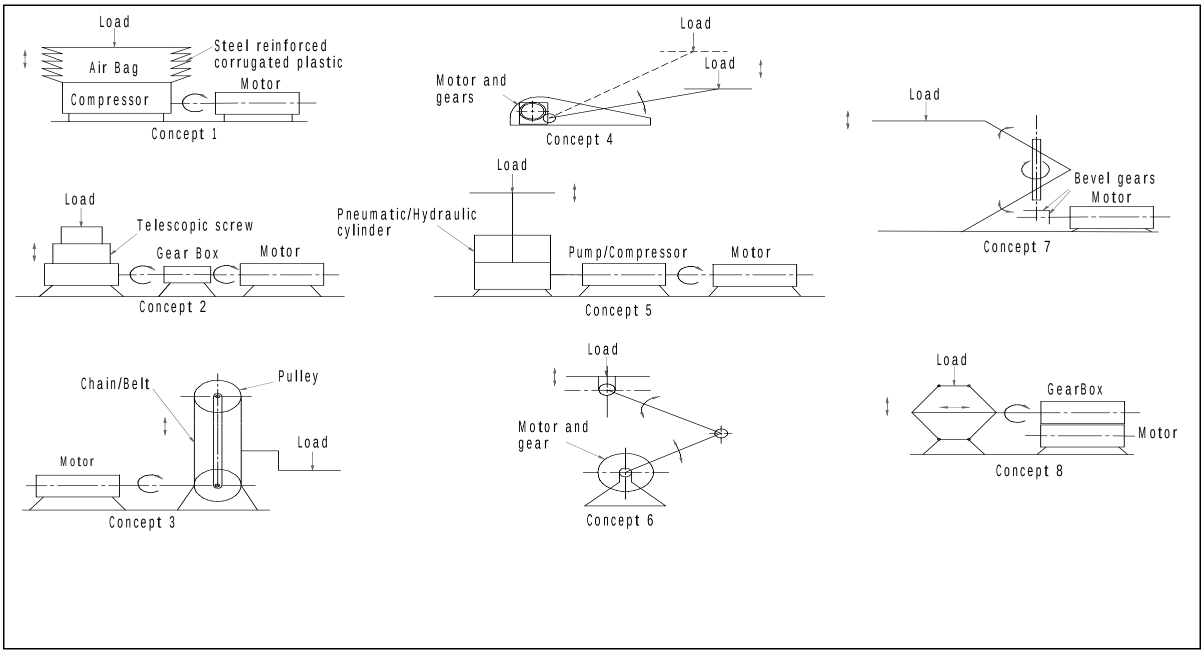

Figure 2. Automobile jack concepts generated by students

Figure 3. Automobile jack (embodiment design of concept 2)

4.1 Reliability Evaluation

For reliability evaluation using novice designer inputs for calculating R^3I, three main functions (Fig. 4) of the automobile jack were considered: Lifting, Supporting the automobile and Reaction to the ground. All of these three functions were relatively compared with each other using AHP and the reliability risk methodology was applied. The final result was the R^3I value and rank for each concept.

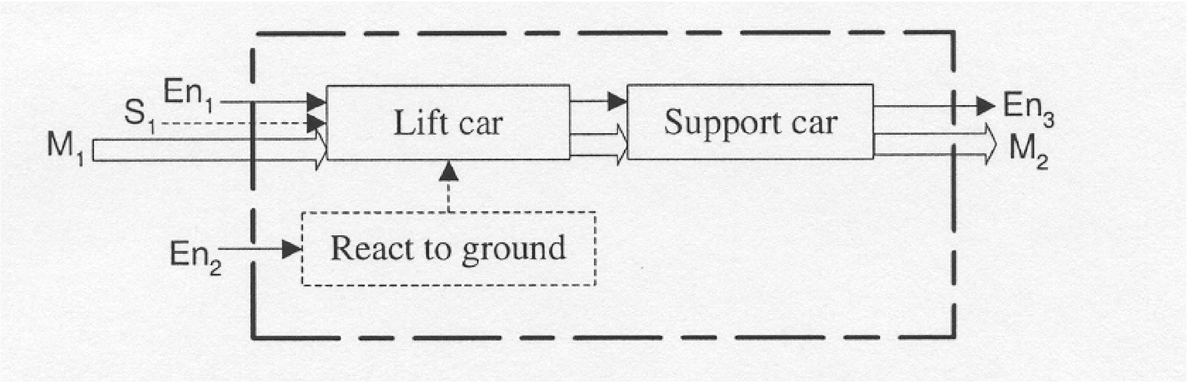

Figure 4. Function structure of a car jack

The comparison of reliability risk evaluation by three novice designers (N2, N3 and N6) is shown in Table 1. C1, C2 etc refer to Concept 1, Concept 2 and so on. Two types of ranks are shown in this table. Rank R_S is the direct, or intuitive, rank provided by the novice for concepts with respect to reliability. Rank R_R refers to the rank of concept obtained after the application of R^3I methodology.

Table 1. Ranking by Novice Designers on basis of reliability

	C1		C2		C3		C4		C5		C6		C7		C8	
	R_S	R_R	R_S	R_R	R_S	R_R	R_S	R_R	R_S	R_R	R_S	R_R	R_S	R_R	R_S	R_R
N2	8	**4**	1	**1**	7	**8**	4	**6**	2	**2**	5	**7**	6	**5**	3	**3**
N3	6	**6**	4	**2**	2	**5**	5	**8**	3	**3**	2	**4**	6	**7**	1	**1**
N6	7	**3**	6	**2**	8	**8**	1	**7**	5	**4**	2	**1**	3	**5**	4	**6**

4.2 Realizability Evaluation

The results obtained from the realizability comparison using Asimov's approach are summarized in Table 2. An 'Intensity of belief' value (L) is achieved for each concept, which is then used to rank the concepts. The higher the percentage values the higher the ranking.

Table 2. Asimov's 'Intensity of belief' (L) values

		C1	**C2**	**C3**	**C4**	**C5**	**C6**	**C7**	**C8**
N2	L (%)	2.71	4.71	90.7	61.8	77	74.2	69.6	80.7
	Rank	8	7	1	6	3	4	5	2
N3	L (%)	59	55	61.8	32	79.67	76.7	27.8	76.5
	Rank	5	6	4	7	1	2	8	3
N6	L (%)	67	38.6	24	61.8	41.7	72.1	83.1	72.54
	Rank	4	7	8	5	6	3	1	2

Table 3 provides a summary of how the novice's own intuitive judgement of concept rank compares with that obtained using Asimov's approach. The rank R_{RS} indicates the intuitive ranks provided by the student, and is obtained after averaging the ratings for Cost and Time getting a single indicator for Realizability. On the other hand, R_{RA} is obtained after the application of Asimov's approach.

Table 3. Ranks from Realizability

	C1		C2		C3		C4		C5		C6		C7		C8	
	R_{RS}	R_{RA}	R_{RS}	R_{RA}	R_{RS}	R_{RA}	R_{RS}	R_{RA}	R_{RS}	R_{RA}	R_{RS}	R_{RA}	R_{RS}	R_{RA}	R_{RS}	R_{RA}
N2	6	**8**	5	**7**	5	**1**	4	**6**	4	**3**	3	**4**	1	**5**	2	**2**
N3	6	**5**	3	**6**	2	**4**	4	**7**	4	**1**	2	**2**	5	**8**	1	**3**
N6	4	**4**	7	**7**	6	**8**	1	**5**	2	**6**	3	**3**	5	**1**	5	**2**

3.3 Robust design selection

Achieving the highest ranking in each category would, ideally identify the most robust design. However a review of the above summary tables shows clearly that this 'neat' result has not been achieved in practise. Novices have identified a different top-ranking concept both when using the evaluation methodology and when using their intuition. However what does emerge is an overall preference for a concept design when the range of the ranking is considered for each concept. In terms of reliability it can be seen in Table 1 that concept C2 exhibits least variation and high ranking across all three novices, particularly when the methodology is employed. Equally when realizability is considered concept C8 (Table 3) exhibits the least variation of the top-ranks across the three novices. Therefore, using this approach, concepts C2 and C8 emerge as offering the least risk to perceived variations in the process and resource environments likely to be experienced by the developing product concepts.

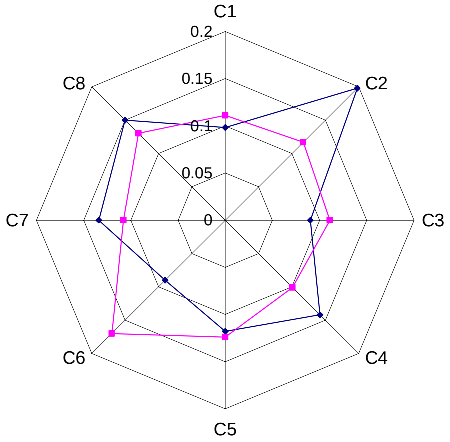

Figure 5. Experienced Designer Judgement

As a further check on the validity of the evaluation methodologies a small group of experienced designers was asked to give their judgement as to which of the competing concepts offered the least risk for both reliability and realizability. A simple 0-1 scale was used with the views of the experienced designers being averaged to obtain an overall appreciation of the experienced view. As can be seen from Figure 5 the preferred concept in terms of reliability is concept 2, with concept 6 best in terms of realizability. It is also interesting to note that concept 8 has significant support with respect to both criteria thus reflecting one of the outcomes of the novice designer evaluation using the methodologies.

4 CONCLUSION

The research described in this paper is based on the hypothesis that rapid and reliable evaluation of concept design ideas is an essential element in the goal to increase design productivity and more particularly to achieve risk tolerant and robust designs. Two key evaluation criteria, namely Reliability and Realizability as being capable of assisting with Competitive Technology Assessment and in doing so has followed a decomposition approach to evaluation. In addition, two methodologies thought to offer support to the consideration of these criteria at the earliest stages of the design process have been described and subjected to initial limited validation testing within a controlled experimental environment. Novice designers have undertaken evaluation of a range of concept designs with respect to reliability and realizability. Their intuitive judgement as to the 'best' concept has been compared with that determined via the use of two evaluation support methodologies and with the judgement of experienced designers. These initial experimental results indicate that the reliability support methodology appears to be more intuitive for the novice designers and that the methodology shows some signs of matching experienced judgement. The realizability method (Asimov's approach) appears more cumbersome to the novice designer as well as the experienced designer. Future research work will focus on testing and developing the Realizability methodology with a view to confirming the validity of the approach in aiming to realise the selection of robust design options and hence minimize risk. One approach will be to repeat the above experiment using a similar approach to the R^3I methodology rather than using Asimov's approach. In addition the methodologies reported here will be extended forward in the design process to link and support those already established within the embodiment and detailed phases of the engineering design process. The aim is to provide a series of support to tools that interlink throughout the design process to enable the achievement of robust design.

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