Reliability and Realizability Risk Evaluation
of
Concept Designs

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Abstract

This thesis addresses the improvement in quality of decision making in design through the use of decomposed design evaluation. Decision making is very important since a lot of resources are committed during the design process. Of the many decisions made in the design process, the decision on selection of concept during conceptual design phase is regarded the most important. A number of decision making tools have been proposed to perform this activity and all of them focus on evaluating designs from a holistic point of view. This thesis considers decomposition of this complex decision making activity for concept design evaluation. The research reported in this thesis is supported by the Design Research Methodology.

To perform decomposed decision making, it is necessary to identify criteria that are deemed important for this activity. Questionnaire surveys, literature review and interviews with industry helped to identify these criteria. Reliability and realizability are two criteria that are selected for research in this thesis. The questionnaire surveys are discussed in chapter 2.

A review of literature on decision making, reliability and realizability is reported in chapters 3 and 4. Various holistic methods for decision making are reviewed and their information capture phenomenon is discussed. The reliability review indicates that none of the existing methods are applicable during the conceptual design phase and for all types of designs. As far as realizability evaluation is concerned, physical realizability evaluation, as proposed by Asimov, is found to support the objective of this thesis and is hence adopted for further consideration.

Methodologies for evaluating reliability and physical realizability are discussed in chapter 5. A novel methodology for reliability evaluation, called Relative reliability risk assessment methodology is proposed for application in the conceptual design phase and for all types of designs. It is a four-step methodology aimed at calculating an index, called Relative reliability risk index (R^3I), to objectively compare concepts on the basis of reliability during design evaluation. The methodology uses Analytic Hierarchy Process and entropy method of extracting weights to calculate an objective value of Relative reliability risk index (R^3I). Asimov's theory of physical realizability is dealt with in detail. The theory is intended to calculate a level of confidence for a concept to predict whether the concept would be realized within the limits of cost and time budgets. The methodology employs Bayes probability theorem to evaluate physical realizability of concepts.

Relative reliability risk assessment methodology is applied to various examples consisting of university and industry projects in chapter 6. The application helps to reveal the strengths of the methodology and is termed 'Verification of the methodology'.

Validation issues of both the methodologies are dealt with in chapter 7 using the controlled experimental design. It is found that both the methodologies help to improve

the quality of decision making during design evaluation. Relative reliability risk evaluation methodology helps to improve the quality of decision making to a substantial extent but physical realizability evaluation methodology shows only a little improvement in quality of decision making. Since physical realizability evaluation methodology entails many limitations along with it, an improvement over it has been proposed and some more refinement is required before it can be applied to a fuller extent.

Finally, it is suggested that the decomposed design evaluation methodology helps to improve the quality of decision making and is therefore proposed to be used by both, novice and experienced designers. Further research ideas and recommendations on decomposed design evaluation are discussed in Conclusions.

Declaration

The author hereby declares that this dissertation is a record of the work carried out in the Department of Mechanical Engineering at the University of Glasgow during the period from October 2002 to January 2006. The dissertation is original in content except where otherwise indicated.

January 2006

Girish Mamtani

Contents

List of Abbreviations

Ac	Accuracy
AGREE	Advisory Group on Reliability of Electronic Equipments
AHP	Analytic Hierarchy Process
AI	Artificial Intelligence
B Eng	Bachelor of Engineering
BS	British Standard
CAD	Computer Aided Design
CFG	Concept Functionality Graph
CI	Consistency Index
CI_{random}	Consistency Index - Random
CR	Consistency Ratio
DCA	Design Compatibility Analysis
DFR	Design For Realizability
DFR	Design For Reliability
DLFI	Demand Level Fulfilment Index
DoD	US Department of Defence
DPI	Device Performance Index
DRM	Design Research Methodology
DS	Descriptive Study
DSP	Decision Support Problem
DSPT	Decision Support Problems Technique
EDC	Engineering Design Centre, University of Cambridge
ELECTRE	Elimination and Choice Translating Reality
FER	Failure Emergent Requirements
FFI	Function Fulfilment Index
FI	Feasibility Index
FMEA	Failure Modes and Effects Analysis
FTA	Fault Tree Analysis
FZA	Fault Hazard Analysis
HAZOP	Hazard and Operability Analysis
IITRI	Illinois Institute of Technology Research Institute
LR	Loading Roughness
M	Mean
MADM	Multi Attribute Decision Making
MAUM	Multi Attribute Utility Method
MCDM	Multi Criteria Decision Making
M Eng	Master of Engineering
MER	Misfit Emergent Requirements
MH	US Military Handbook
MI	Match Index
MINLP	Mixed Integer Non Linear Programming
MODM	Multi Objective Decision Making
MTA	Mineral Trioxide Aggregate
MTBF	Mean Time Between Failures

MTTR	Mean Time to Repair
NWFA	New Fuzzy Weighted Average
P	Price
PDS	Product Design Specification
PHA	Preliminary Hazard Analysis
PRT	Platinum Resistance Thermometer
PS	Prescriptive Study
QFD	Quality Function Deployment
R	Repeatability
RAC	Reliability Analysis Center
RFI	Redundancy Fulfilment Index
RPN	Risk Priority Number
SAE	Society of Automotive Engineers
SAW	Simple Additive Weighting
SD	Standard Deviation
SFI	Sharing Fulfilment Index
SM	Safety Margin
SOT	Standard scheduled Operating Time per year
SRL	Systems Realization Laboratory
T	Thermistor
TC	Thermocouple
TOPSIS	Technique for Order Preference by Similarity to Ideal Solution

List of Symbols

A^-	Negative ideal solution
A^*	Positive ideal solution
$A_{0,j}$	Base availability of j^{th} unit
A_j	Alternative j
A_j	Current availability of j^{th} unit
A_{sys}	System availability
C/T	Cutting Tool
$C/T_{deformed}$	Deformed Cutting Tool
$CI_{0,j}$	Investment cost for j^{th} unit calculated using conventional cost models
CI_j	Investment cost for j^{th} unit
C_{raw}	Raw material cost
C_j^*	Similarity to positive ideal solution
D	Detectability
d	Difference between a pair of ordinal ranks for calculating ρ
E	Amount of favourable evidence
En	Energy
F_i	Function
f_S	Characteristic function of crisp set
$f_i(\lambda_i)$	Failure probability distribution
Incon	Inconsistency (Consistency Ratio)
k_i	Scale factor for an attribute i
L	Intensity of belief
$\bar{L}$	Mean for a Load distribution
M	Matter
$MC_{cor,j}$	Corrective maintenance cost for j^{th} unit
M (s, K)	Match coefficient of component s with rest of the design K
m	Number of attributes
mlc_j	Cost of corrective maintenance per hour on j^{th} unit
m_S	Membership function of fuzzy set
$\max_i$	Pessimistic failure rate prediction value for a triangular distribution
$\min_i$	Optimistic failure rate prediction value for a triangular distribution
$\text{mod}_i e$	Most likely failure rate prediction value for a triangular distribution
$N_{ratings}$	Number of relative ratings in AHP
n	Number of alternatives
O	Occurrence
PR	Set of product and by-product streams in the process superstructure
Q_{E1}	Questionnaire 1 to experts
Q_{E2}	Questionnaire 2 to experts
Q_{N1}	Questionnaire 1 to novices
Q_{N2}	Questionnaire 2 to novices
R	System reliability

R^3I	Relative Reliability Risk Index
RM	Set of raw materials stream in process structure
R_i	Sub system reliability
R_j	Rank of an alternative j
r_{ij}	Local priorities of alternatives
R_{LPi}	Reliability corresponding to λ_{LPi}
R_{MPi}	Reliability corresponding to λ_{MPi}
R_{R1E}	Rank of concept for reliability, obtained directly from an expert
R^{da}_{R2E}	Rank of concept for score S^{da}_{R2E}
R_{R1N}	Rank of concept for reliability, obtained directly from a novice
R^{e}_{R1N}	Rank of concept for reliability obtained through R^3I methodology for a novice
R^{da}_{R2N}	Rank of concept for score S^{da}_{R2N}
R^{l}_{R2N}	Rank of concept obtained after the application of Asimov's approach for physical realizability
R_{SPi}	Reliability corresponding to λ_{SPi}
S	Crisp/Fuzzy Set
S	Severity
S	Signal
S_j	Score of an alternative j
S_j^-	Euclidean separation measure from negative ideal solution
S_j^*	Euclidean separation measure from positive ideal solution
$\bar{S}$	Mean for a Strength distribution
S^{da}_{R2E}	Average of Cost & Time scores obtained from an expert for physical realizability
S^{da}_{R2N}	Average of Cost & Time scores obtained from a novice for physical realizability
t_{i1}	Element of a column matrix T
U	Utility function of an alternative
U	Universe of discourse
u	Element of Universe U
u	Random number
u_i	Attribute utility function
utility (s)	Importance associated with a component s
V_i	Entropy of an attribute i
v_{ij}	Weighted normalised preference values
W/P	Work Piece
$W/P_{deformed}$	Deformed Work Piece
w_i	weight for an i^{th} attribute
X	Current expenditure
X	Independent variable (methodology) in experimental design
X_B	Allowed budget in terms of cost and time
X_i	Attribute i
x_i	Continuous process variable describing flow rate of i^{th} process stream

x_{ij}	Preference value
x_i^*	Best preference value for an i[th] attribute
x_i^-	Worst preference value for an i[th] attribute
y_{ij}	Normalised preference values
β	Answer by a company on using CAD tool with design evaluation
ϕ_j	Parameter for equipment j introduced to take into account differing investment costs of equipments
γ	Constant used in entropy method
ρ	Spearman's rank correlation
ξ_i	Cost of i[th] process stream
λ	Known failure rate
$\hat{\lambda}_i$	Unknown failure rate
λ_{LPi}	Largest possible (pessimistic) failure rate
λ_{max}	Principle eigenvalue of matrix
λ_{MPi}	Most promising failure rate
λ_{SPi}	Smallest possible (optimistic) failure rate
σ_L	Standard deviation for a Load distribution
σ_S	Standard deviation for a Strength distribution
$\cap$	Interference between functions
$\left(\frac{dE}{dX}\right)_0$	Tractability in Asimov's physical realizability model

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Chapter 1

Introduction

1.1 Problem Setting

Engineering design benefits mankind in several ways. Designed products provide various levels of comfort to human beings. Today, markets are inundated with a variety of products and so a customer has the leisure of choosing the one that benefits him the most. To remain competitive in today's marketplace, companies have to constantly come up with innovative products and increase design productivity. To do so, they have to focus on improving various aspects of design in their organisation. One of these aspects is the quality of decisions made during the early stages of design process. The ability to rapidly and reliably take decisions is an essential element in increasing the design productivity (Green 2000).

Decision making spans the whole design process (Muster and Mistree 1988). The decisions can be either important or trivial. The amount of time and effort spent on them generally depends on the consequences of taking the decisions. Still most of the important decisions are made during the initial phases of design. For now, it is sufficient to state that the initial design phase is one where various design ideas (i.e. concept designs) are generated and evaluated. A variety of "high-level" decisions are made during this phase. A "high level" decision here is characterized by various important implications associated with the outcome of the decision.

During the initial phases of design, generation of a large number of design options is necessary to ensure that the most appropriate concept is identified. The generation of large number of design options must be accompanied by a rapid and reliable means of evaluation, if designers wish to increase design productivity. It is recognised that there is a lack of information during evaluating design options. That is, important decisions often have to be made with very limited information (Antonsson 1997; Wu et al 1996).

Two kinds of evaluation approaches have been identified, holistic and decomposition (Green 2003). The holistic approach takes a complete integrated view of the design artefact and seeks to provide an evaluation of the acceptability of it. The decomposition approach, on the other hand, evaluates the design at criterion level and then recomposes them into an overall evaluation. It is human nature to try to reduce complexity when at all possible (Green 2003). Experienced designers, as opposed to novice designers, conform to this trait, and use their experience to solve problems while using decomposed strategy. Novice designers do not have the experience to deal with the ill structured design problems. If novice designers use explicit problem decomposition strategies, they could be as effective as experts (Ho 2001).

Consequently, there remains scope for work in decomposed design evaluation to help designers, especially novice designers, to make high-level decisions in the information poor, ill-structured initial phase of design.

1.2 Research Program

The time span of the research activities carried out in this PhD are shown in Figure 1.1. Please note the visits made as a part of this research. The author was fortunate to make research visits to the USA and Germany during his PhD. This was possible due to the MacRobertson travel scholarship by the committee of Glasgow and Strathclyde University. In USA, author's research (Mamtani 2004) was based on the decision making model proposed by Professor Farrokh Mistree at Systems Realization Laboratory (SRL) in Georgia Institute of Technology. A validation methodology called as Validation Square was learnt at the institute. Another visit mentioned in the research project is the visit to the Summer school on Engineering Design Research, Germany.

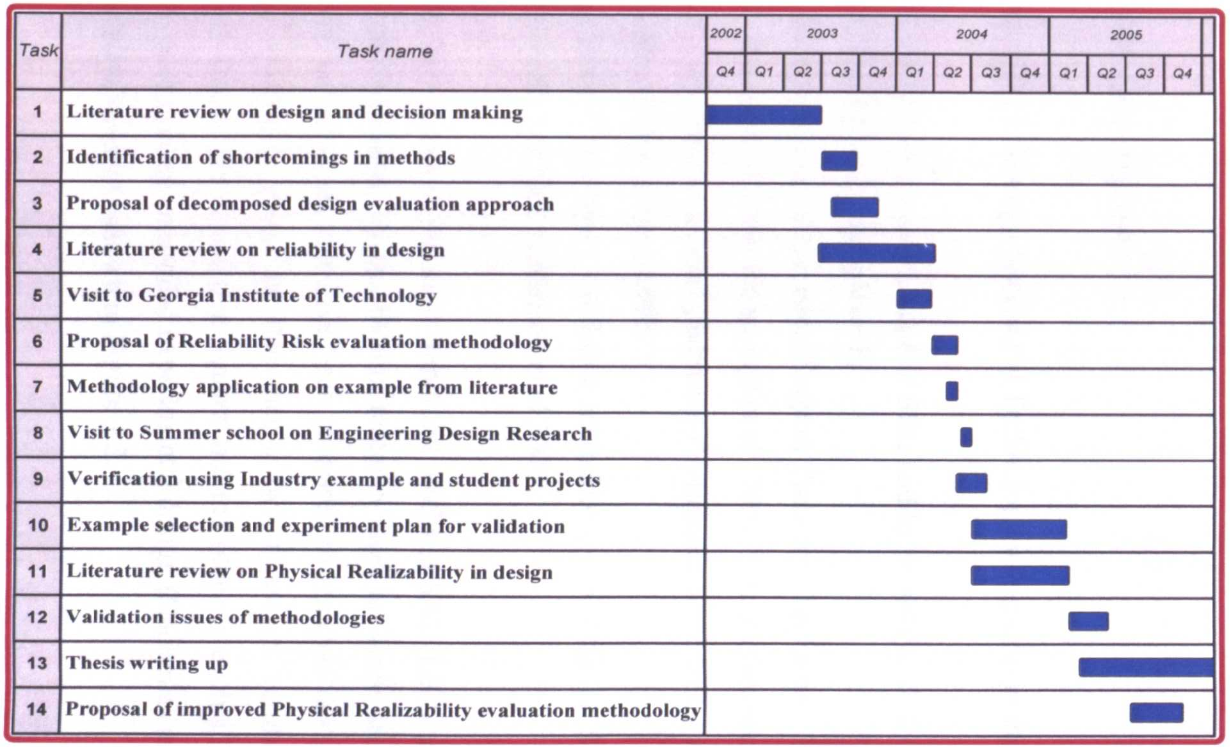


Figure 1.1 Tasks and their time spans during the PhD

This school was organised by the Design Society and was lectured by various Professors from European universities. The school was helpful in enlightening the author with the Design Research Methodology (DRM). Validation Square and DRM are followed in this thesis and they are dealt with in sections 1.3 and 1.4 respectively.

1.3 Validation Square

The visit to SRL at Georgia Institute of Technology was useful in the following aspects:

- Understanding the research done at SRL and to be able to differentiate between the US and European design research.
- To gain knowledge of Decision Support Problems Technique (Muster and Mistree 1988; Mistree et al 1994; Kuppuraju et al 1985). This is discussed in section 3.4.5.
- Gain knowledge on product platforms (Hernandez et al 2003; Meyer 1997; Meyer and Lehnerd 1997; Ulrich 1993).
- To understand and apply validation methodology (Validation Square) proposed by the researchers at SRL (Pederson et al 2000)

Out of the above, one of the most important works at SRL that is also followed in this thesis is the Validation Square. Design research faces an acute problem of validation. Many tools and methods that have been proposed to improve design processes do not have any validation roots. In this thesis, two types of validation strategies are considered. One is the Validation Square and the other is evaluation of methodology using the social science controlled experimental design (Nachmias and Nachmias 1998). The Validation Square is shown in Figure 1.2.

Pederson and co-authors (2000) have proposed Validation Square for validating design methods and have described it as a "process of building confidence in its usefulness with respect to a purpose." The Validation Square is broadly represented by 2 divisions, each considering 3 steps (steps 1 to 6). The two blocks Theoretical structural validity and Empirical structural validity refer to the effectiveness of the method proposed and include 3 steps. The remaining blocks of the Validation Square i.e. Empirical performance validity and Theoretical performance validity constitute steps 4, 5 and 6 and are suggested to confirm the efficiency of the method.

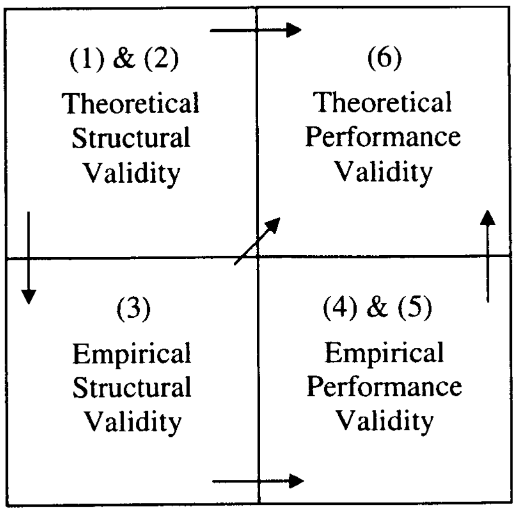


Figure 1.2 Validation Square for design method validation (after Pederson et al 2000)

Step 1 is 'Accepting the construct's validity'. This step is meant to validate the individual constructs (individual entities) used in the design method. This is done by the references and their number, type and recognition. Step 2 is 'Accepting method consistency'. This is done by assessing the way in which various constructs are put together in the method. It is suggested to use a flow chart to ensure the information flow in the method. Step 3 is 'Accepting the example problems', which is carried out by studying the aptness of the example problems that is selected for verifying the method.

Steps 1 and 2 refer to Theoretical structural validity and step 3 refers to Empirical structural validity. Step 4 is 'Accepting usefulness of method for some example problems'. This step is meant to check the usefulness of results after the application of the design method. Step 5 helps to know whether 'Accepting that usefulness is linked to applying the method' and this can done by comparing the solutions with and without the construct. Steps 4 and 5 together constitute Empirical performance validation. Step 6 is 'Accepting usefulness of method beyond example problems'. If the method is useful in more general cases, it fulfils step 6 of Theoretical performance validation. The application of Validation Square to this research is discussed in Table 1.2 (section 1.9).

1.4 Design Research Methodology (DRM)

The visit to the Summer School on Engineering Design Research was helpful in the study of DRM (Blessing and Chakrabarti 2002). Even after 30 years of research, design has not always been considered as a scientific discipline (Blessing 2002) and there has been a need for a research methodology that can provide a clear direction to the research and validate design methods. DRM has been proposed with a view to solving this problem.

Since DRM has been adopted in this thesis, some discussion of DRM is required. Its relation to this research work is discussed in section 1.6. The framework of DRM is as follows. The research is initiated by defining a success criterion. This success criterion is the final achievement after the application of the research method. This normally pertains to some high level achievement, for e.g. increase in profit, sales etc. Since realization of profit or sales cannot be attributed directly to the implementation of design method, a measurable criterion is introduced. This measurable criterion is linked to the success criteria. This criterion is the one that can be measured, be it in an indirect manner. This framework is shown in the Figure 1.3. The Descriptive Study I (DS I) is aimed to understand various influences on the measurable criterion. This pertains to the background literature review of the research area. If literature is not available then a study of the designers in laboratory or industry environment may be done.

In Prescriptive Study (PS), method is proposed to "generate the scenario of the desired situation" (Blessing 2002). Descriptive Study II (DS II) is the evaluation of the method that is proposed in the previous step. There are chances of iterations in this framework. Also, all of these steps may not be a part of a single project. Various types of research are possible using DRM. They are listed in Table 1.1. The research followed in this thesis is encircled in Table 1.1. Note that this thesis does an initial evaluation of the method proposed in this research.

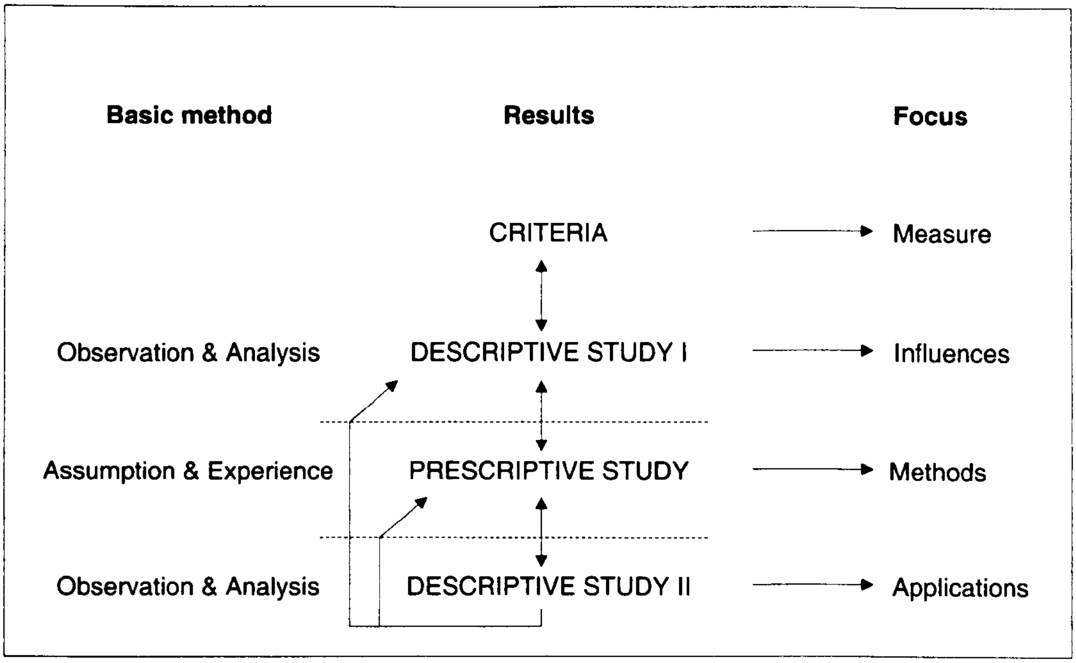


Figure 1.3 DRM framework (after Blessing 2002)

The detailed evaluation of the research may require the method to be applied to a "real" industry problem which may require a lot of resources, including time and industry contacts. Henceforth, an initial evaluation has been done in the University laboratory (discussed in chapters 6 & 7).

Criteria Formulation	Descriptive Study I	Prescriptive Study	Descriptive Study II
Review	Detailed		
Review	Detailed	Initial	
Review	**Review**	**Detailed**	**Initial**
Review	Review	Review	Detailed
		Initial/Detailed	
Review	Detailed	Detailed	Initial
Review	Review	Detailed	Detailed
Review	Detailed	Detailed	Detailed

Table 1.1 Different types of design research (after Blessing 2002)

1.5 Comparison between Validation Square and DRM validation

Validation in DRM is the DS II phase which is undertaken to evaluate the tools or methods proposed during the PS. Action research (Blessing et al 1998) is proposed to validate the design tools and methods. It has been proposed so as to "identify whether the method or tool has the expected effect on the influencing factors that are addressed directly" and to "identify whether this indeed contributes to success". Validation Square does not compare the results of method application with reference to a success/measurable criterion, as proposed in DRM. Validation Square's Empirical and Theoretical performance validity (section 1.3) is related to application of method on the example and its generic applicability to other relevant case studies. Success is not linked to any specific criterion. The DRM suggests evaluation of the method using rigorous application of the method and its effect on the measurable criteria. This thesis adopts the use of DRM for research and validation issues. But validation is also performed using the Validation Square.

1.6 Impact Model of Research

An Impact model shows the links between the success criteria and the measurable criterion. For this research, the Impact model is shown in Figure 1.4. A success criterion is defined here as increase in Sales/Profit. A measurable criterion has also been established and is linked to the success criterion. The measurable criterion here is Quality of decision making. The measurement of an improvement in Quality of decision making is defined in terms of a coefficient called ρ (Rho), given in section 7.3.4. The foot of the Impact model shows the Decomposed design evaluation proposed in this thesis and its positive effect on the Quality of decision making.

Analysing the Impact model, it can be seen that an increase in the Quality of decision making has three effects. Firstly, it would decrease the number of iterations or rework so that the lead-time is reduced. This would in turn increase the Sales/Profit.

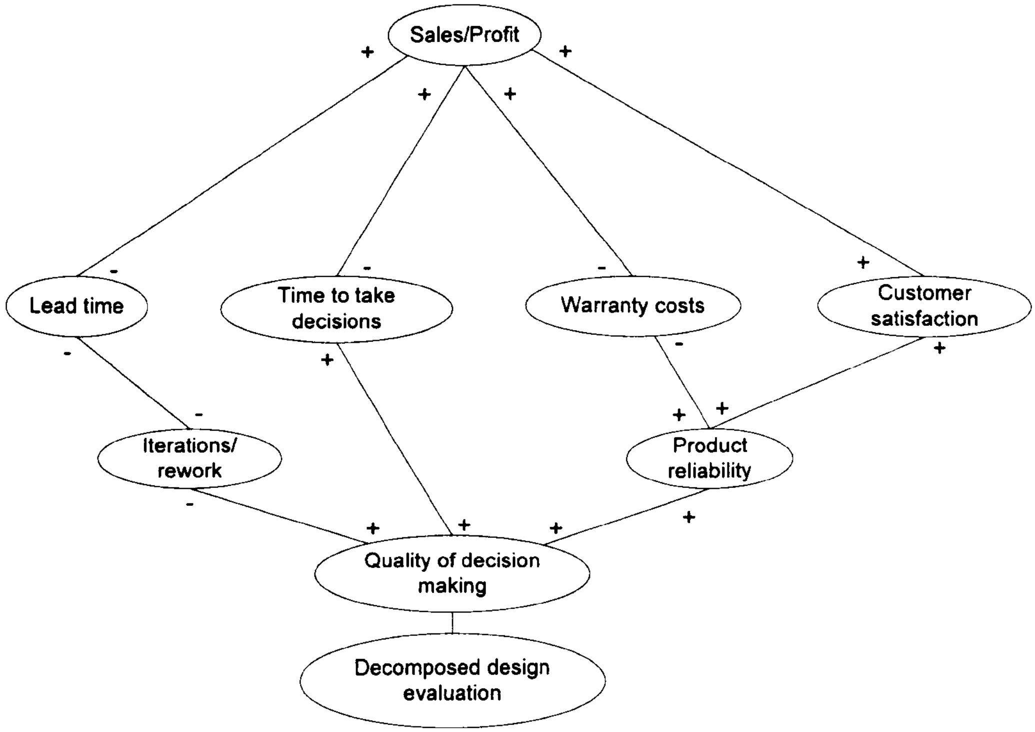


Figure 1.4 Impact model of research in this thesis

Secondly, increase in the Quality of decision making may also increase the time to take decisions. Normally, while speaking of conceptual design phase, the decision making time is relatively low. This was confirmed after meeting various mechanical engineering companies in Scotland. With the introduction of formal methods, this might increase the decision making time and may result in a little decrease in Profit (when converting time spent on decision making into cost). Although this would not have an effect of substantially increasing the time, this point will be discussed in section 5.4.1.

Thirdly, product reliability would increase with the introduction of this methodology into the system and it is in turn expected to have two effects. The warranty costs would decrease, thereby raising the Sales/Profit and/or Customer satisfaction would increase and this would bring about increase in the Sales/Profit. There may be some more combinations possible of these links but the current model serves the purpose of this research.

From the Impact model, it is seen that one of the links has a negative effect on Sales/Profit. But the gain from other links is expected to counter the negative effects of a little increase in time allocated for decision making when using these methods. Usually less time is allocated to decision making because only few concepts are generated during the conceptual design phase. But in case a large number of concepts is generated (ideally this should be the case so as find a "suitable" concept), time would increase. Consequently, quick evaluation of a large number of concepts would affect the Quality of decision making.

The DS I in this thesis is the study of various decision making, reliability and physical realizability methods. The PS involves proposal of a methodology for Reliability risk evaluation. Also, Asimov's (Asimov 1962) theory of evaluating Physical realizability has been adopted in the thesis.

The DS II comprises of verification and validation of the methodology proposed in the thesis. Verification includes application of the methodology to examples from literature and student projects. Validation includes application of the methodology on a student project using controlled experimental design.

1.7 Contribution to Knowledge and Research Objectives

The contribution to knowledge of this research is mainly in the arena of design evaluation when evaluating concept designs. The primary knowledge contributed by this research is the methodology proposed and the novel application of existing decision making tools for evaluating reliability and physical realizability in the conceptual design phase. The research helps to evaluate concepts in the initial phases of product development and helps to establish a link with various other methods applied during different phases of design.

The objectives of this research are:

- Understanding various decision making tools used (or those that can be potentially used) in design. With this understanding, core knowledge of the decision making tools is obtained and thereby used for application during the decomposed design evaluation.

- Understanding and classification of various reliability and realizability methods in design.
- Proposal of new methodologies to evaluate Relative reliability and Physical realizability for all types of designs in the initial phases of design.
- Validating the methodologies considered in this thesis.
- Create a link with various other reliability methods applicable to other phases of design.

1.8 Research Hypothesis

The hypothesis governing this research is:

The use of decomposition strategy in design evaluation during conceptual design phase would improve the Quality of decision making, especially for original designs, and for novice designers when compared with that of experienced designers. This decomposition approach would also be able to handle the complexity of decision making in the desirable case when a large number of concepts are generated.

1.9 Structure of the Thesis

The structure of this thesis is as follows. In chapter 2, the research background necessary for understanding this research is uncovered. Some design processes are studied and placement of this research in the design process is done. Finally, motivation behind this research is explored. The results of questionnaire surveys discussing companies' view about design evaluation are presented.

In chapter 3, decision making, in general and specific to engineering design is discussed. Classification of decision making by some authors is studied and various methods used for decision making are laid down. Chapter 4 aims at the study of various reliability methods used in engineering design. It also lists some unconventional reliability methods that incorporate the use of decision making tools. The study reveals the requirement of method in the conceptual design phase that can be applied to all types of designs. The requirement of a method is sought that considers both, decision making and reliability engineering. The idea of physical realizability is also investigated in chapter 4. Chapters 3 and 4 represent the DS I of DRM.

In chapter 5, the methodologies for Relative reliability risk assessment and physical realizability evaluation are proposed and explained. The tools required to understand the methodologies are discussed in detail i.e. Analytic Hierarchy Process, Entropy method, Bayes probabilistic evaluation. Illustration of methodologies' application is done using an example of conceptual design. Chapter 5 represents the PS of DRM.

In chapter 6, the Relative reliability risk assessment methodology is applied to various examples that consist of Ab board, Carr pack, Positive chair and Transmission systems. This is done so as to verify the methodology. In chapter 7, validation of Relative reliability risk assessment and physical realizability methodologies is done. An example of design of an electro-mechanical car jack, developed by students of Mechanical Design Engineering at the University of Glasgow is considered for the same. Relative reliability risk assessment methodology is combined with other reliability evaluation method to compare the results. Also, an improvement over physical realizability methodology is proposed and applied. Chapters 6 and 7 form the DS II of DRM.

The thesis is concluded in chapter 8 with a note on future research. The phases of DRM and Validation Square pertaining to this thesis are shown in Table 1.2. Validation Square is only applied to the Relative reliability risk assessment methodology since this methodology, unlike physical realizability methodology, has been proposed (and not simply adopted) during this research.

Chapter No.	DRM	Validation Square	Remarks
Chapter 1			Introduction
Chapter 2			Research Background
Chapter 3	Descriptive Study I		
Chapter 4	Descriptive Study I		
Chapter 5	Prescriptive Study	Steps 1 & 2	
Chapter 6	Descriptive Study II	Steps 3, 4 and 5	
Chapter 7	Descriptive Study II	Step 6	
Chapter 8			Conclusion

Table 1.2 Application of DRM and Validation Square to this research

The flow of research in this thesis is shown in Figure 1.5.

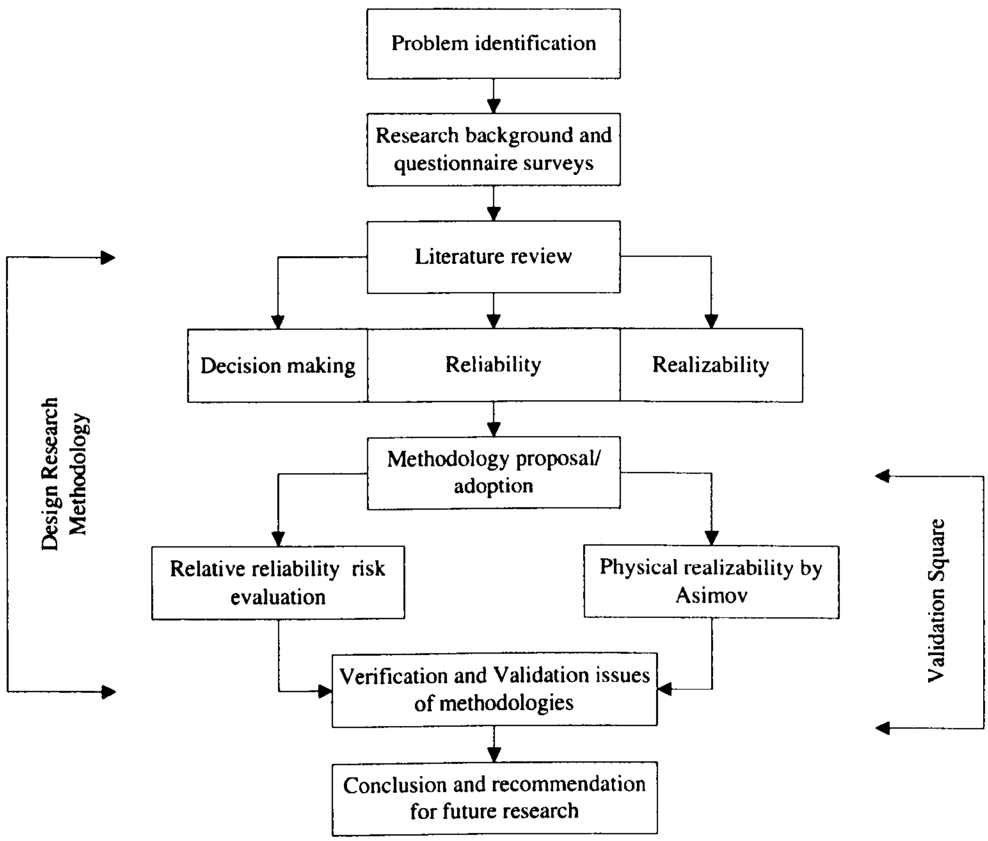


Figure 1.5 Research summary

Chapter 2

Research Background

This chapter offers the necessary background to understand the placement of this research in the design process. Design processes are studied in this chapter. As this research pivots around conceptual design phase, it is considered in some detail. An overview of the placement of this research is expressed. Initially this research aimed at computer support for the evaluation activity. Subsequently, a questionnaire survey and interviews with the industry personnel confirmed the requirement of a method for evaluation. The results of questionnaire surveys are discussed in this chapter. The chapter is concluded with a description of decomposed design evaluation approach.

2.1 Design Processes

To understand the application of methods proposed in this research, a discussion of some design processes is essential. There are various prescribed processes of design (e.g. by Pugh 1991; French 1998; Asimov 1962). A detailed list and their overview can be found in Blessing (1994). These prescriptive processes tend to define the way in which design should be done. These can also be called as models of design process (Smithers 1996). Models, in turn can be derived from theories of design processes (Hatchuel and Weil 2003; Gero and Kannengiesser 2004) or from the empirical knowledge. The design processes, discussed here, are the ones that are most recognised and are commonly studied by the designers. Detailed analysis on design processes not being the aim of this thesis, this study is only done to understand the design phases.

2.1.1 French's Model of Design Process

French (1998) has prescribed four important steps in his design process. The design process is shown in Figure 2.1. The important steps of the methodology are Analysis of problem, Conceptual design, Embodiment of schemes and Detailing.

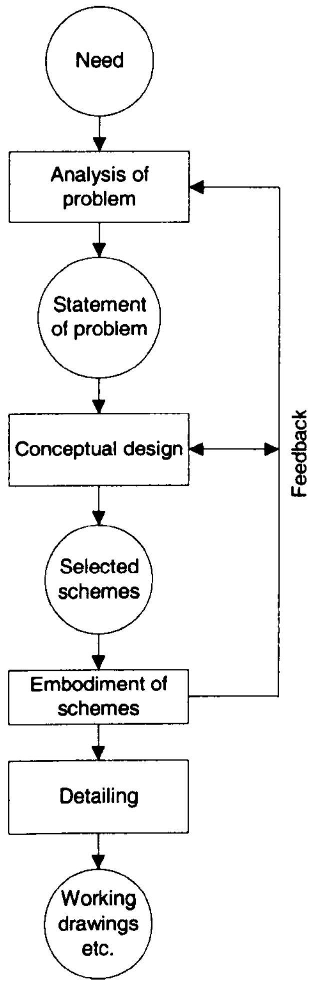


Figure 2.1 French's model of design process (after French 1998)

The circles represent the outcome and rectangles represent the stages of design process. Analysis of problems identifies the needs that are to be fulfilled. Conceptual design "takes the statement of the problem and generates broad solutions to it in the form of schemes." Conceptual design has been described as the most demanding phase for a designer. Embodiment of schemes involves working on the schemes of the Conceptual design phase and "a set of general arrangement drawings" is reached after this phase. A lot of feedback from this phase is given to the Conceptual design phase, which might result into iterations. The Detailed design phase decides some remaining essential points and adds on to the quality of design.

2.1.2 Pahl and Beitz's Model of Design Process

Pahl and Beitz (1996) have proposed a detailed prescriptive design process as shown in Figure 2.2. The phases listed are Planning and Clarifying the task, Concept design, Embodiment design and Detail design. The Upgrade and Improve (on the left hand side in the figure) spans all the above phases and refers to the iterations that can occur during the process. For each of the phases, working steps have been prescribed. These are the main working steps for each of the phases. With these steps, the phases are self-explanatory. The Planning phase results in a Requirements list after assessing the market, needs and the economy. These are also called as the Design specifications of the product. Conceptual design phase broadly, on the basis of the Requirements list, is meant for generations of concept variants and evaluating them against technical and economic criteria. In Embodiment phase, designers "determine the construction structure of a technical system in line with technical and economic criteria." It results in a definitive layout. In Detail design phase, all the details of components i.e. their forms, arrangements, dimensions and surface properties are laid down. It results in detailed drawings and product documentation. Pahl and Beitz offer a very detailed and clear design process.

2.1.3 Asimov's Morphology of Design

Morphology of design is coined by Asimov (1962) to indicate the study of chronological pattern of the design projects. The steps constituting design projects are shown in Figure 2.3.

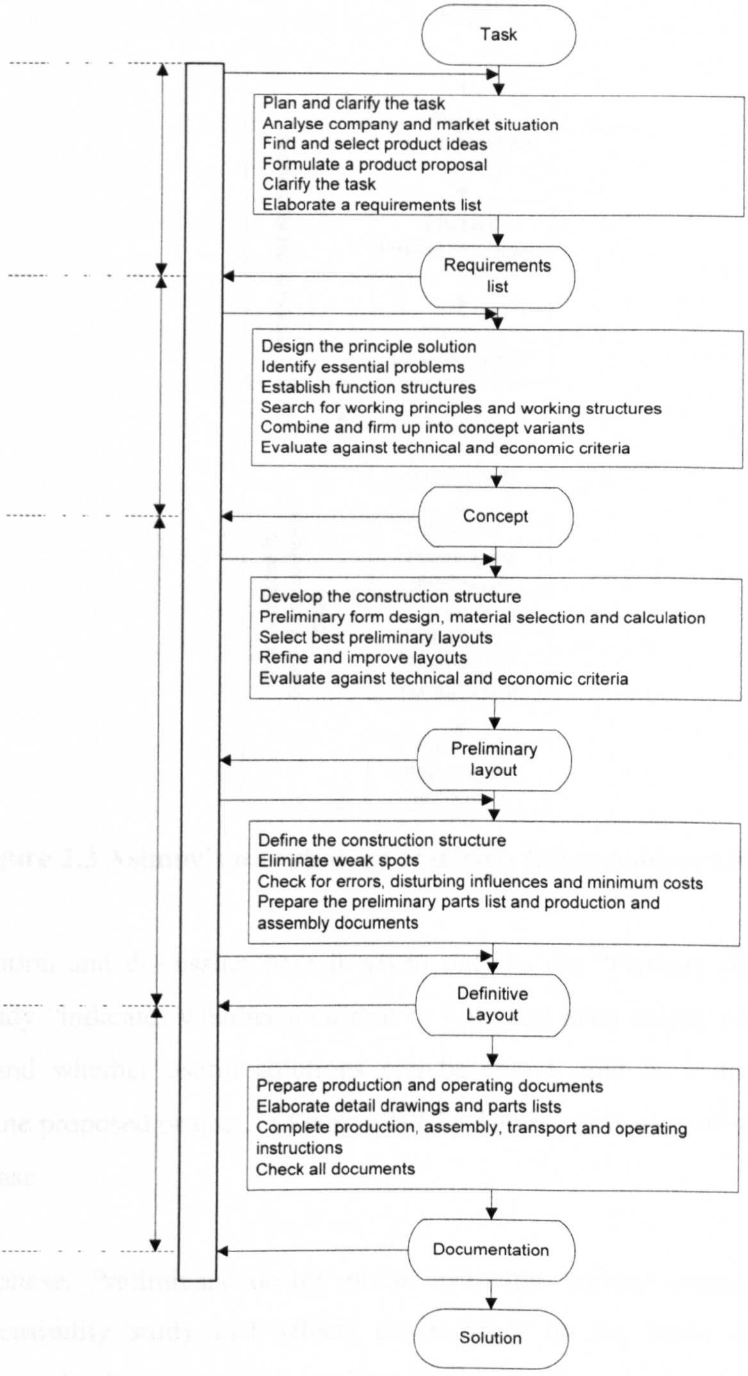


Figure 2.2 Pahl and Beitz's design process (after Pahl and Beitz 1996)

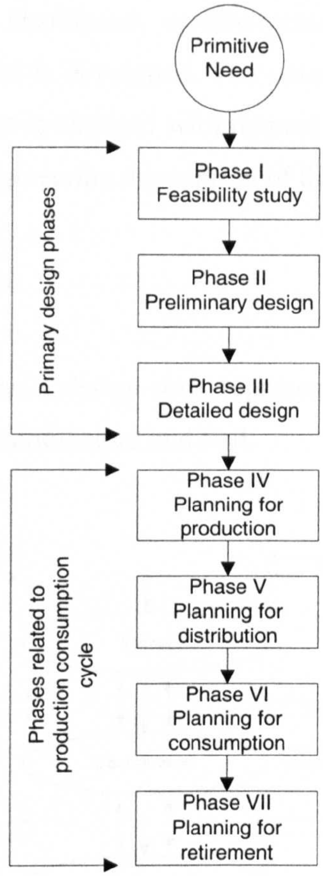


Figure 2.3 Asimov's morphology of design (after Asimov 1962)

The consideration and discussion here is given only to the "Primary design phases". Feasibility study "indicates whether a current or potential need exists, what the design problem is, and whether useful solutions can be found; that is, it investigates the feasibility of the proposed project." (Asimov 1962). The result is a set of solutions at the end of this phase.

The second phase, Preliminary design phase evaluates various concepts generated during the Feasibility study and selects the concept on the basis of "magnitude analyses". After selecting the concept, various studies are done, i.e. control of the range for the design parameters, tolerances in the characteristics of various major components of the system and projective-type studies to see how the concept will fare in time.

The Detailed design phase involves making a final decision about the concept, whether the final concept is accepted, abandoned, or new solutions are to be searched. A provisional overall master layout is developed. The detailed design of components is carried out and the master layout is changed with respect to the design of components. The result of this phase is the engineering description of the design.

2.1.4 Pugh's Total Design

This model (Figure 2.4) considers a design core, represented by Market, Specification, Concept design, Detail design, Manufacture and Sell.

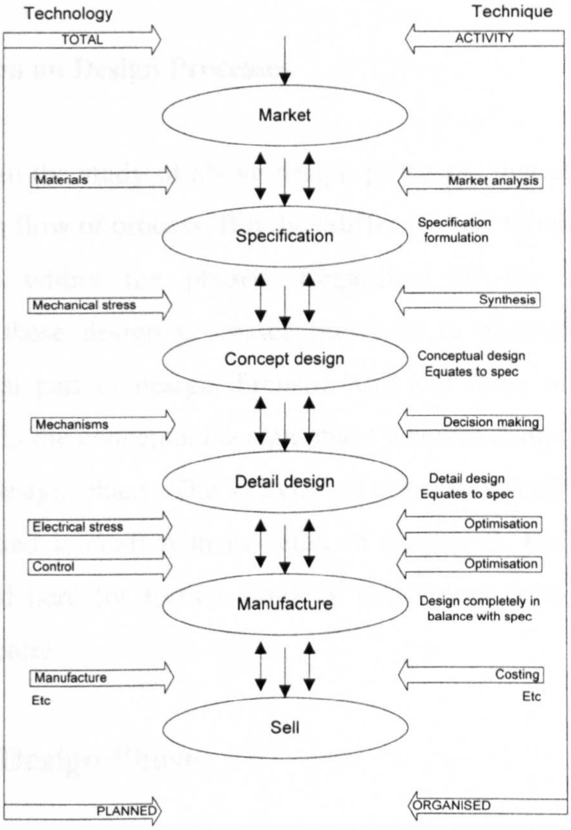


Figure 2.4 Pugh's Total design (after Pugh 1991)

This represents a cycle from the need of the product to selling it in the market. Pugh states that "Total design is the systematic activity necessary, from the identification of the market/user need, to the selling of the successful product to satisfy the need – an activity that encompasses product, process, people and organisation." (Pugh 1991). The

Product Design Specification or the PDS is formulated and this acts as an envelope for the subsequent stages of the core. Various iterations can be seen in Figure 2.4 that represents the flow of design. On the right hand side of the figure can be seen the techniques/tools required by the designers for designing effectively and efficiently. These are the discipline independent techniques. On the left hand side of the design core can be seen the techniques, knowledge and tools required by the designers for specific disciplines for e.g. Stress analysis, pneumatics, hydraulics etc. The structure of the design core, along with the techniques, both discipline independent and dependent (i.e. the partial elements), when placed in the framework of Planning and Organisation represents Total Design. In Figure 2.4, the envelope of PDS surrounding the stages has not been shown.

2.1.5 Discussion on Design Processes

It can be noticed from the study of above design processes that all of them have got a more or less common flow of process. But they differ in their terminology of phases and individual activities within the phases. Regardless of the differences in their terminology, all of these design processes prescribe to generate and then evaluate concepts in the initial part of design. French, Pahl and Beitz and Pugh prescribe to perform this activity in the conceptual design phase whereas Asimov prescribes to do so in the Preliminary design phase. The activity of concept selection is being focussed upon in this thesis and is dealt with in detail in chapter 3. Pahl and Beitz's design process is considered here for further study of conceptual design process due to its explicit detailed structure.

2.2 Conceptual Design Phase

This thesis is essentially related to the conceptual design phase and concept selection in particular, henceforth the steps of conceptual design phase are studied in this section. The design process model referred to in this thesis is that by Pahl and Beitz. This is because it is an established methodology in literature and provides a sound basis to base this research work on. Pahl and Beitz's conceptual design phase is shown in Figure 2.5.

The conceptual design phase starts with a Requirements list or a list of Specifications for the product in question. An Abstraction is proposed so that the problem solutions can be found without any fixation or adhering to conventional ideas. It refers to "ignoring what is particular or incidental and emphasising what is general and essential" (Pahl and Beitz 1996). Abstraction leads to a broad problem formulation, which is sufficiently abstract so as to generate solutions without referring to any particular solution. Establishing function structures helps to identify the overall function and then sub functions, thereby helping to identify solutions to satisfy each sub function. Since Function structures are important to the methodology proposed in this thesis, they are discussed in more detail in section 5.2.2.1. After establishing function structures, working principles are proposed. They refer to working principle for each sub function of the function structure. This represents breaking down a complex function into simple sub functions and then finding a working principle for each of them. "A working principle must reflect the physical effect needed for fulfilment of a given function and also its geometric and material characteristics". The geometric and material characteristics though cannot be determined in many cases. These working structures are then combined suitably so as to provide a working structure. An initial selection is done so as to reject the non-feasible working structures. Since the working structures are very abstract, some more work is done on them to firm them up into concepts. Concepts are working structures with more details. The amount of details in a concept depends on the amount of information available at the conceptual design stage and the type of design followed. After establishing concept variants, they are evaluated against various technical and economic criteria. Generally, the result of evaluation is a Principle solution. Chapter 3 lists various methods of evaluation.

2.3 Motivations for this Research/Importance of Design Evaluation

Following are the results of some exploratory studies undertaken to establish or confirm the importance of design evaluation. The "practical" aspects of industry view towards this activity are explored. 3 questionnaire surveys are discussed in this section.

They were conducted by Bjarnemo (1991), Taylor and Ben (1993) and Mamtani and Green (2004).

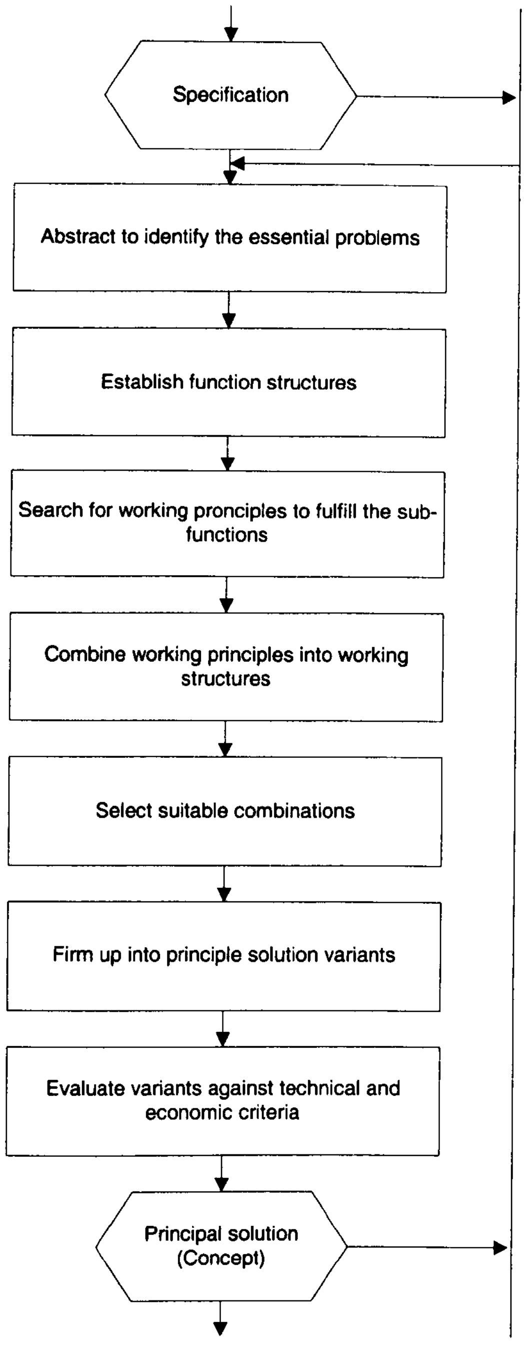


Figure 2.5 Conceptual design phase (after Pahl and Beitz 1996)

2.3.1 Bjarnemo's Questionnaire Survey

Bjarnemo (1991) surveyed 10 Swedish mechanical engineering companies. The results of his questionnaire showed that the evaluation techniques were not utilized and that most of the companies followed design catalogues, meetings, reviews and subjective ratings by their experienced staff.

When companies were asked about their views on "the need for an improvement of the evaluation – decision procedure", all of the companies replied in affirmative. The significance of evaluation was well understood by them. They stressed for a requirement of an improved evaluation procedure that should consider the following points:

1. Retrieval of information from the earlier evaluations,
2. An objective approach to evaluation and
3. Preference of quantitative techniques.

All of these points are addressed in this thesis (section 5.1) while proposing the methodologies. But at this point, this survey merely underpins the importance of design evaluation.

2.3.2 Taylor and Ben's Questionnaire Survey

Taylor and Ben's (1993) questionnaire survey received a more optimistic reply than Bjarnemo's. They received responses from 42 engineers of 24 companies. They found that "the current evaluation techniques were not used in the majority of companies". The questionnaire consisted of questions on the difficulty of evaluation faced during various phases of design and needs of evaluation methods. The questionnaire results are listed in Table 2.1. Though Taylor and Ben do not explain the meaning of early and later concept design phase, the inference can be made about the conceptual design phase, whether early or later. The table can be read as follows.

Phase	Difficulty of evaluation	Needs for methods
Early concept design	70%	79%
Later concept design	45%	74%
Detail design	35%	74%

Table 2.1 Taylor and Ben's survey results

In column 1 for early concept design phase, 70% of the respondents face difficulty in evaluation and 79% responded positively on the needs for methods during this activity. The respondents confirmed that new evaluation techniques were in demand during the conceptual design phase. These questionnaire results show that there is a scope of new evaluation method, even after the existence of current evaluation methods.

2.3.3 Mamtani and Green's Questionnaire Survey

The previous surveys confirm the importance of design evaluation and reveal that tools and methods are required for design evaluation activity during conceptual design phase. The author has extended the previous surveys by undertaking a survey on the companies' "openness" to accepting design evaluation tools (Mamtani and Green 2004). The companies were asked questions so as to know how much keen were they in accepting new design evaluation methods, if these methods were incorporated within the conventional Computer Aided Design (CAD) tools. The questionnaire also contained some questions to further research for the decomposed design evaluation activity. The questionnaire is attached in Appendix A.1.

As a pilot study, the questionnaire was initially sent to 3 companies and with the help of their feedback, the questionnaire was revised. Then it was sent to 20 companies in Scotland. Replies were received from 12 companies, including the first 3. The companies short-listed were design consultancies and manufacturing industries (large, medium and small) in Scotland. Table 2.2 lists the companies that answered the questionnaire and their types. The companies have been named as A, B, C and so on to maintain their anonymity. Various questions were asked in an "inverted funnel type" questionnaire (Robson 2002). When asked about the importance of conceptual design phase, all the companies rated it as the most important phase of design.

Type of company	Name of company
Manufacturing company	A, B, C, D, F, I, J, K, L
Design consultancy	E, G, H

Table 2.2 List of companies surveyed with their types

Two other important questions were asked. A question on the acceptability of a computer evaluation tool was asked so as to know the companies' attitude towards acceptance of design evaluation tools. This is on the basis of assumption that if systematic evaluation methods (as informed from the previous surveys) are not followed in the company, the use of computers and ubiquitous CAD tools might prove as an incentive towards the usage of these tools. An assumption is made of the availability of a design evaluation tool that can be embedded in the conventional CAD packages. The companies were asked if they would use this CAD tool. The options given to them were on a fuzzy scale (fuzzy logic is discussed in section 3.4.6) ranging from 1 through 10. 1 meant Definitely No and 10 meant Definitely Yes. Let these scale ratings (1-10) be called as β. Table 2.3 lists the answers β on fuzzy scale received from the companies. The Mean M and Standard Deviation SD for this sample are:

M = 5.66, and
SD = 2.46

Company	Type of company	β
A	Manufacturing	7
B	Manufacturing	2
C	Manufacturing	4
D	Manufacturing	10
E	Design consultancy	6
F	Manufacturing	10
G	Design consultancy	6
H	Design consultancy	5
I	Manufacturing	6
J	Manufacturing	5
K	Manufacturing	4
L	Manufacturing	3

Table 2.3 List of answers β received from the companies

Companies A and F were visited to know the reason for their assertive answers and informal interviews were conducted. It was clear that design evaluation tool was a necessity and that without which arbitrary techniques were used. These arbitrary techniques belonged more to the gut feeling and experience of the designers. The companies sometimes had to pay for such a technique when the concept did not ultimately meet the product expectations. They also started realising this and began to apply formalized evaluation techniques for their upcoming products. The answers to this question and the interviews reconfirm the importance of design evaluation.

Another important question asked was on the criteria that the companies consider as important during design evaluation. The companies were asked to rate some important criteria. The criteria they were asked to consider are Quality, Reliability, Maintainability, Manufacturability, Ease of assembly, Performance and Cost. The companies were also asked to prioritise the above criteria according to their importance to the company. Table 2.4 lists the first three criteria prioritised by the companies. Table 2.4, informal interviews with the company personnel and literature review (chapters 3 and 4) reveal that Reliability and Cost are two important criteria considered during the concept design evaluation. Further research is undertaken on these two criteria in this thesis. Reliability review is done in section 4.4. Cost criterion in conceptual design phase is believed to be indicated by Realizability and is discussed in section 4.5.

Company	**First 3 criteria prioritised**		
	Priority 1	**Priority 2**	**Priority 3**
A	Performance	Reliability	Quality
B	Reliability	Cost	Performance
C	Reliability	Quality	Ease of assembly
D	Performance	Reliability	Quality
F	Reliability	Performance	Quality
G	Cost	Quality	Manufacturability
H	Performance	Manufacturability	Cost
I	Cost	Quality	Reliability
J	Quality & Cost	Performance	Reliability
L	Cost	Reliability	Performance

Table 2.4 Criteria prioritisation by companies

2.4 Decomposed Design Evaluation

As quoted earlier in section 1.1, experienced designers use a decomposition strategy in solving problems and that if novice designers follow this strategy too, they can become very effective (Ho 2000). Design evaluation poses a problem of selection. Selecting concept design out of the generated concepts is a high level decision making problem and its importance has already been recognised. It is usually solved or performed holistically; in that designer provide inputs for each criterion considering a holistic view of the concept designs. This is shown in Figure 2.6. A generic matrix (called a decision matrix, explained in section 3.3) of design evaluation procedure is shown.

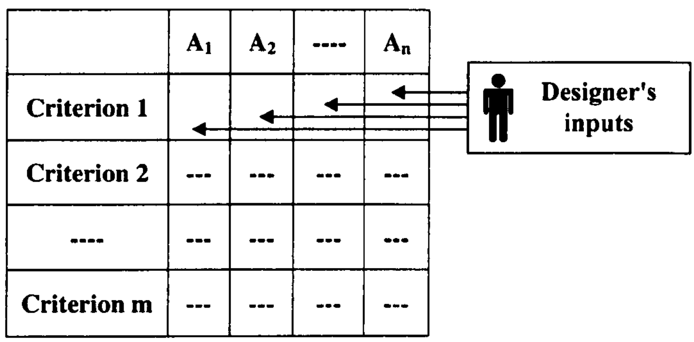


Figure 2.6 Holistic design evaluation

Since evaluation activity can have huge repercussions, it is proposed here to consider a decomposition strategy. Decomposed evaluation strategy may be described as a type of evaluation activity, whereby important criteria are individually reviewed and an objective value for the concepts for these criteria are evaluated. This is shown in Figure 2.7.

For each important criterion, a Black box is developed as shown. This Black box is the criterion evaluation toolbox that would help evaluate criterion by breaking down the problem into sub problems and has a means of information capture from the designer. The criteria in decomposition approach here is similar to the idea of "Excursions" proposed by Cooper and Thompson (2001). As informed from previous sub sections and literature, the important criterions identified are Reliability and Cost.

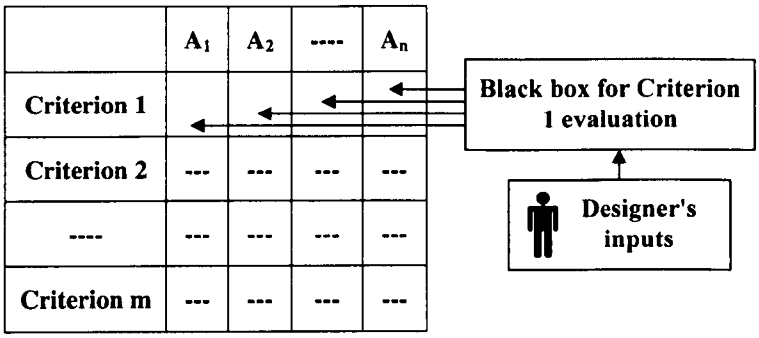


Figure 2.7 Decomposed design evaluation

Henceforth, this thesis considers the design evaluation decomposition strategy using evaluation of Reliability and Realizability (a word that is considered here to represent cost factors during the conceptual design phase). These criterion Black boxes should have an effective means of information capture. Hence, various holistic design evaluation methods are studied in next chapter and their information capture phenomenon is understood.

DRM
Descriptive Study I

Chapter 3

Decision making and Conceptual Design Evaluation

To understand the principles and guidelines of decision making, a study of decision making is undertaken in this chapter. The structure of this chapter is as follows. In section 3.1, a decision is formally defined. In section 3.2, decision making is discussed with respect to engineering design. Some models classifying the decision making methods are explored in section 3.3. To understand decomposed design evaluation strategy discussed in section 2.4, a study of various holistic decision making methods is done in section 3.4. These are the methods that have either been applied in engineering design decision making or have the potential of being applied during this activity. A study of these methods reveals the phenomenon of information capture during design evaluation. Study of these methods will also be helpful in understanding some reliability methods that use decision making methods for evaluating reliability (section 4.4.1.2). This chapter forms the DS I of DRM.

3.1 Defining Decision

In all walks of life, humans make a lot of decisions. There are some decisions that we take at the spur of the moment and some that require a lot of deliberation. The ones that require attention are those that have a lot of significance, mostly due to involvement of money or any other resources. A decision has been formally defined by Gregory (1988) as "the selection process leading to a particular action being taken".

Broadly put, there are two kinds of decisions. The decisions in which one does not deliberate much are called implicit decisions. As opposed to this, explicit decisions are those where one requires a lot of mental effort and deliberation before converting them into a particular action. This research is about the latter types of decision.

Although there may be different kinds of decisions made, they all share some common aspects (Figure 3.1). These aspects are:

1. The decision results in alternate actions to be pursued.
2. There is a preference associated with the actions, implicit or explicit.
3. These actions and preferences are processed in a way to come up with the most preferred action to be followed.

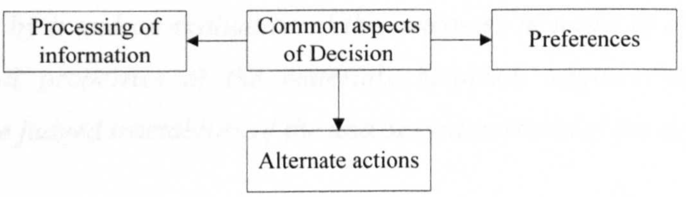


Figure 3.1 Common aspects of a decision

These 3 aspects of a decision form the foundation of a formal decision making theory.

3.2 Decision Making in Engineering Design

Decision making has been an important subject of study since a long time in management, economics, mathematics and sociology (Buchanan and O'Connell 2006). Only recently in the past few decades decision making has been formalized in a systematic manner for engineering design (Sen and Yang 1998). The theory of decision making has been accepted in engineering design because of various explicit decisions in conceptual design phase that have further implications on the product development process. Quoting the example of General Motors and Rolls Royce, Whitney (1988) has mentioned that 70-80% of the cost of manufacturing is committed during the design process. Although this statement has been disputed (Barton et al 2001) because of the numeric figures used, both, Whitney and Barton et al agree on the point that decisions made during design phase of the product development are very important and they have implications on the later stages of product development process. Ullman (Ullman 2001) confirms the same and quotes that in design "it is important to put heavy emphasis on decision making because a decision is a commitment to use resources."

The pioneering work on decision making in engineering design was undertaken by Marples (1961), in which he described the fundamentals of decision trees in engineering design solution search. After studying two design case studies, Marples concluded that:

"The analysis of these case studies suggests that designing consists of a sequence of critical decisions leading from the initial statement of the problem to the final specification of the "hardware". Each decision involves the consideration of various proposals; predictions of the outcomes of each with particular emphasis on the sub-problems raised by it and an evaluation of the outcomes in terms of criteria stemming from the natural properties of the materials involved; engineering values; prior decisions and the judged tractability of the unassessed portions of the design."

The above conclusion by Marples also highlights the common aspects of a decision shown in Figure 3.1.

The importance of decision making in design can be realised from the references by Mistree et al (1995) and Frey and Lewis (2005). They consider design essentially as a decision making process. Mistree et al's following statement underpins the importance of decisions in engineering design:

"While the decisions can be based on many things and may have wide ranging repercussions, it is the decisions themselves that mark the progression of a design from initiation to implementation to termination. They bridge the gap between imagination and service, between an idea and reality. They lock the whole together and they represent the central principles on which the design depends."

According to Mistree et al, the basic types of decisions during decision making are Selection and Compromise. They have proposed a Decision Support Problems

Technique (DSPT) for decision making. Their model of decision making is explored in detail in section 3.4.5.

It can be perceived from the above statements that it is the prediction of future from the present state or information in hand that a decision helps to make. It bridges the gap between the idea and reality and this reality is foreseen or predicted by the decision makers or designers during the decision making.

After realising the importance of decision making during design and the implications of this activity, a lot of decision making methods have been proposed or accepted in design (Hwang and Yoon 1981; Sen and Yang 1998; Triantaphyllou 2000). However the descriptive study (This descriptive study refers to the experiments performed in the laboratory/industry and should not be confused with the DS of DRM) by Dwarakanath and Wallace (1995) on decision making in engineering design still conclude that an understanding of this process is required to devise decision support tools. This statement also reaffirms the questionnaire surveys discussed in section 2.3.

3.2.1 Design Evaluation

The area of design evaluation is investigated here. Design process can involve a lot of explicit decision making, but decision making during design alternative selection (or concept selection) is termed as design evaluation. Various authors have formally defined design evaluation in their works (Green 1997; Otto and Wood 2000; Thurston 1991; Bjarnemo 1994). Though there are some differences in their terminology, the important idea conveyed is the evaluation and selection of the design alternative. Some definitions put forward by few researchers, to gain further understanding into design evaluation, are as follows:

Green (1997) has described design evaluation in a rigorous manner as:

"The process of trying to determine the results of prior decisions, via analysis, in terms of the design constraints and to provide knowledge and information to enable future decisions. It involves, particularly during the conceptual phase, both the identification

of the present state of the design with respect to the desired final state and also the ability to forecast, or predict, the likelihood of the design progressing from its present to the next identifiable state or to the final desired state, within defined time scales, given knowledge of resources and abilities."

This definition emphasises the importance of design evaluation as an ability to forecast or predict the future state of the design after considering the "present" state of design with the designer. Otto and Wood (2000) define design evaluation as those important decisions consisting of many "possibilities" (Alternatives) with many "Ramifications" (Criteria). This is close to the generic definition of decision by Gregory (1988) in section 3.1.

Thurston (1991) quotes design evaluation as an activity *"to determine the worth or value of a design alternative as a function of one or more attributes"*. The definition gets its basis from the utility theory (Siddall 1982), where the worth or value is the utility of the design alternative.

Bjarnemo (1994) refers to the evaluation activity as a type of procedure, where:

"Evaluation is the process where the objective is to determine the overall value for each and every one of the available solution proposals with respect to the evaluation criteria, with the objective of achieving a preference order or ranking of the proposal. and

Decision-making is the process during which the "best" solution is identified and selected, based on the results obtained during the evaluation activity."

All the above definitions may differ in their terminology but the authors have applied the decision making processes for design alternative selection in their research. The common elements extracted from these design evaluation definitions are listed in Table 3.1.

Author	Design evaluation	Design alternative	Criteria
Green 1997	Determining results of prior decisions	Present state of design	Design constraints
Otto and Wood 2000	Important decisions	Possibilities/ Alternatives	Ramifications/ Criteria
Thurston 1991	Determining worth	Design alternative	Attributes
Bjarnemo 1994	Evaluation procedure	Solution proposals	Evaluation criteria

Table 3.1 Common elements in design evaluation definitions

3.3 Classification of Decision Making Methods

In this section, a classification of decision making methods is done. Since there have been a lot of methods proposed in the area of decision making in general, the concentration here is only on the ones that have either been utilized in engineering design or are potential candidates for the same.

Before embarking towards gaining an insight into classification models, it is necessary to understand the terminology of decision making. In all the decision making methods, one comes across terms such as criteria, attributes, objectives, alternatives, decision matrix and so on. Following are the definitions associated with some important terms (Hwang and Yoon 1981; Sen and Yang 1998; Kirby 2001):

Alternatives: These are the actions available to be followed. In this thesis, alternatives refer to the concept designs. Alternatives are represented by A_j where j = 1 to n in Table 3.2.

Criteria: These are the characteristics of performance, based upon which the alternatives are compared and preference is obtained. Also called as design characteristics or dependent design variables (Siddall 1982). Criteria can be divided into objectives and attributes. Also refer to Table 3.1 for various terms used in place of criteria.

Attributes: These are the performance measures of alternatives. These may include cost, time, reliability etc. Also called as dimensions or predictor variables. The decision making is called as Multi Attribute Decision Making (MADM). MADM is followed in this thesis and attributes and criteria are used interchangeably. Attributes are shown in Table 3.2 as X_i, where i = 1 to m.

Objectives: These are criteria that have to be maximised or minimised. Attributes with direction are called as Objectives. They are normally used during synthesis of design solutions and entail use of optimisation techniques.

Decision matrix: A decision problem can be "housed" or processed using a matrix, known as Decision matrix. Rows represent the attributes and the columns represent the alternatives. Table 3.2 is a typical decision matrix for a MADM method.

Decision maker: The one who makes decisions. During design, it is normally a designer. In group decision making, there may be many people who contribute to this process of decision making.

Weights: Weights represent the importance associated with the attributes. They are represented by w_i, where i = 1 to m. Weight assigning techniques are discussed in appendix A.2.

Preferences: These are the inputs provided by the designer for alternatives with respect to attributes. This is a part of the information capture. Also called as preference values, preference information or judgements. Represented by x_{ij}, i = 1 to m and j = 1 to n.

Compensatory methods: Methods in which preferences values for attributes can be traded off. An alternative with high preference in one attribute may be traded off by a low preference in another attribute.

Non compensatory methods: Methods in which superiority in one attribute cannot be offset by inferiority in another attribute of an alternative.

Normalisation: Attributes may have different units of measure. To bring them to a similar platform for combining or information processing, the preference values are normalised. The normalized preference values are denoted here by y_{ij} where i = 1 to m and j = 1 to n (normalisation techniques are discussed in Appendix A.2).

Scores: After obtaining the decision matrix, preference values are combined and a final score is obtained (S_1 to S_n in Table 3.2) for each alternative in the matrix. There are various methods of obtaining the Score.

Ranks: Based on the scores evaluated for alternatives, ranks for alternatives can be obtained (R_1 to R_n in Table 3.2). These are based on the ordinal scales (scales are discussed in Appendix A.2).

All the above definitions apply in this thesis, unless otherwise specifically mentioned.

Attribute	**Weight**	**Alternatives**			
		A_1	A_2	...	A_n
X_1	w_1	x_{11}	x_{12}	...	x_{1n}
X_2	w_2	X_{21}	x_{22}	...	x_{2n}
...	...	...	...	...	...
X_m	w_m	x_{m1}	x_{m2}	...	x_{mn}
Score		S_1	S_2	...	S_n
Rank		R_1	R_2	...	R_n

Table 3.2 A typical MADM decision matrix

3.3.1 Sen and Yang's Multi Criteria Decision Making (MCDM) Model

Sen and Yang's (1998) work deals with the decision making during various phases of design. Criteria have been called as measures of performance and have been divided into attributes and objectives. Individual classification of Multi Attribute Decision making (MADM) and Multi Objective Decision making (MODM) methods is done. Objectives have been defined as attributes with direction (Figure 3.2). Attributes are required during the selection process and objectives during the synthesis. MODM is also called as design synthesis, as during this activity, a solution is synthesized or found.

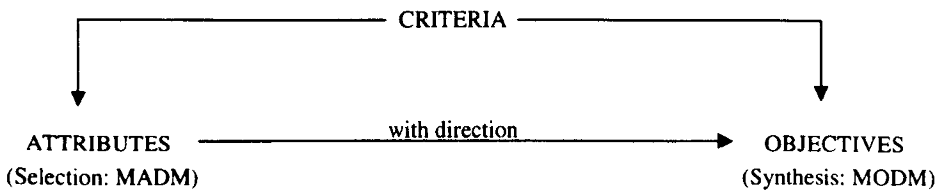


Figure 3.2 Sen and Yang's criteria definition

MODM methods incorporate the use of optimisation tools. During synthesising the solutions, a pareto front is obtained. Pareto front is the region where all the solutions are non dominated ones. A feasible solution is called as non dominated "if there exists no other feasible solution that will yield an improvement in one objective/attribute without causing a degradation in at least one other attribute" (Hwang and Yoon 1981). The concept of pareto optimality was coined in economics although it is now applied to many areas. Pareto optimality also applies to MADM methods in which a decision maker selects a non dominated alternative.

Seeking an optimum solution in reality is not usually possible and so the "best" solution found may not the best in terms of all the objectives but there is a compromise when selecting an alternative. Such a solution is called as a "satisficing" solution, a word coined by Simon (1990). MODM methods are not studied in this thesis since they are generally not used during design evaluation.

A part of MADM (Multi Attribute Decision Making) classification by Sen and Yang is shown in Figure 3.3. Some important decision making tools have been shown in this figure. The methods are classified here on the basis of type of the information available with the decision maker for example no information or standard level of information. The methods can also be differentiated on the basis of preference information from the designer i.e. whether it's the pairwise comparison value a decision maker provides or ranking information and so on. These methods are discussed in section 3.4.

(In Figure 3.3, TOPSIS stands for Technique for Order Preference by Similarity to Ideal Solution, ELECTRE for Elimination and Choice Translating Reality ("Elimination et choix traduisant la realite" in French) and AHP for Analytic Hierarchy Process).

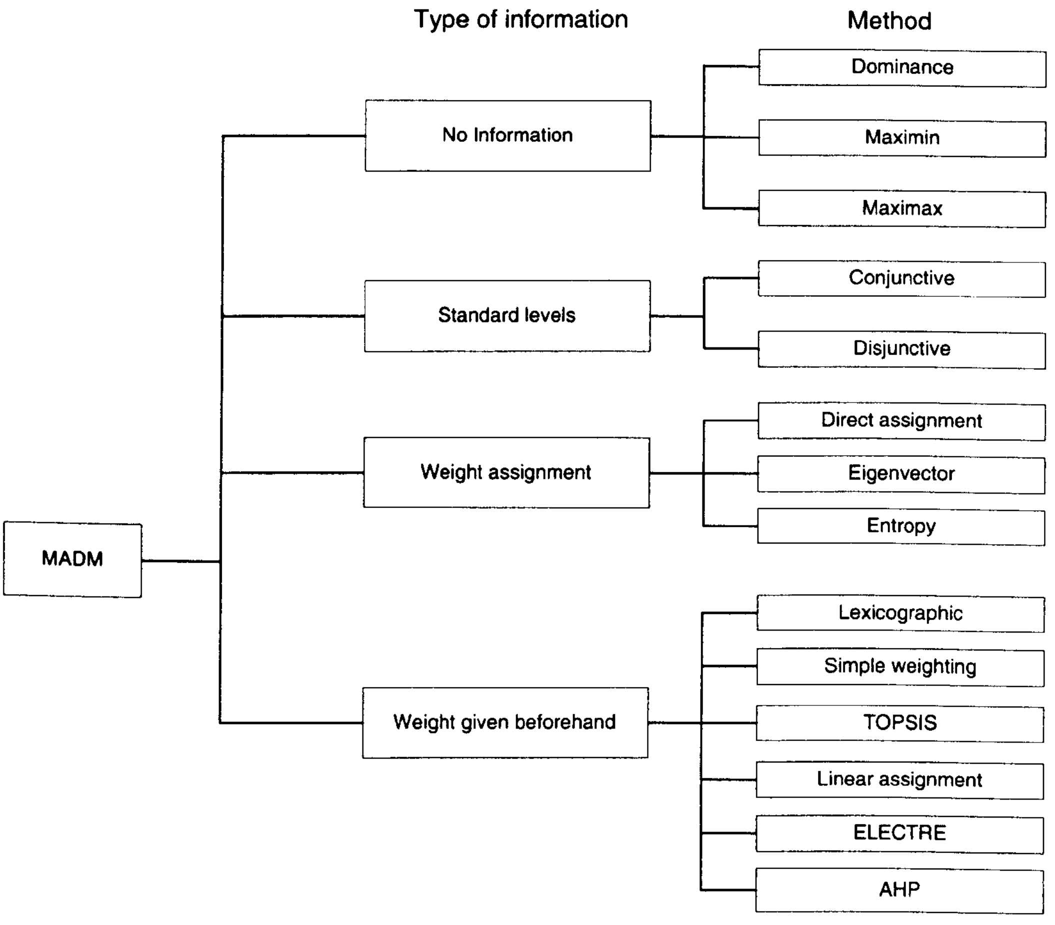


Figure 3.3 Part of MADM classification by Sen and Yang (after Sen and Yang 1998)

3.3.2 Hwang and Yoon's MADM Classification

The classification levels of MADM tools by Hwang and Yoon (1995) are shown in the Figure 3.4. The classification consists of three levels. The first level is the type of information from the decision maker. This relates to the information available on attributes or alternatives. The second level is the salient features of the information available i.e. ordinal, cardinal, pairwise etc. This then helps to classify methods or group of methods in the third level. There are many methods common to classifications by both, Hwang and Yoon and Sen and Yang.

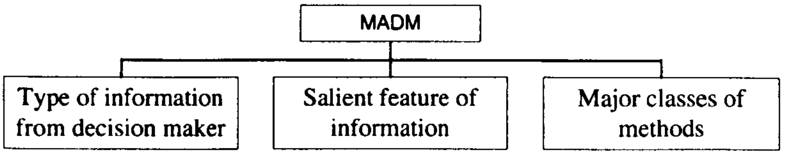


Figure 3.4 MADM classification by Hwang and Yoon

Triantaphyllou (2000) offers another insightful work on MCDM methods and has considered a similar classification model as Hwang and Yoon. The work offers a comparative study of various MCDM methods with several examples.

3.4 Decision Making Methods

Some important methods in decision making are studied here. All of the methods considered during the classification of decision making methods in section 3.3 are not studied in detail, hence a brief description on some of them is given in Table 3.3. More details on them can be found in Sen and Yang (1998) and Hwang and Yoon (1995).

3.4.1 Pugh's Controlled Convergence

Pugh's evaluation technique (Pugh 1991; Pugh 1981) has been one of the most widely used design evaluation tool in engineering design. Its wide usage can be attributed to its simplicity. Pugh's method also forms the basis of some other decision making methods (Mistree et al 1994; Liu et al 2003; Wang 2002).

Pugh proposed this idea because of the "conceptual vulnerability" factors. According to Pugh, there are two factors that contribute to conceptual vulnerability. They are:

1. Weak final concept selection due to lack of thoroughness in conceptual approach.
2. The chosen concept may be strong but there is a lack of understanding on the strength of this concept.

Pugh's evaluation technique consists of building up a matrix of concepts vs. criteria.

Method	Brief description of method
Dominance	An alternative is said to be dominated if there is another alternative that is better in one or more attributes and equal in other remaining ones. Otherwise an alternative is called as non-dominated.
Maximin	Based on the pessimistic strategy. Minimum preferences for all the alternatives are listed and the alternative with maximum one of these preferences is the "winner".
Maximax	As opposed to Maximin, the maximum preference values are noted for all the alternatives. The alternative with the maximum of these preference values is the one that is chosen.
Conjunctive	Alternative(s) must exceed a minimum requirement for each attribute to be selected.
Disjunctive	Alternative(s) much exceed a minimum requirement for one or more attributes to be selected.
Direct assignment	Direct assignment is a weight assigning method. Weights are directly assigned to various attributes under consideration (Appendix A.2).
Eigenvector	Weight assigning method similar to AHP. Refer to section 5.2.1.2 for details.
Lexicographic	Method strategy resembles the way in which words are ordered in a dictionary. Alternatives are ranked as per the most important attribute. In case there is a tie, second most important attribute is considered and so on.

Table 3.3 Overview of some decision making methods

While doing so, an important point to consider is to keep all the concepts on the same level of detail. In fact, this should be borne in mind while using any evaluation technique that the level of abstraction of concepts should be similar. Once the matrix is prepared, a datum is selected. Datum is usually a concept for which the design already exists or is the competitor's product. All the concepts in Pugh's matrix are compared with respect to this datum. A "+" in the matrix indicates that the concept is better than, cheaper than, easier than and so on than the datum concept with respect to a criterion. Similarly, a "–" indicates that the concept in consideration is worse than, dearer than and so on than the datum concept. Also, an S indicates equality sign to the datum concept. Pugh's matrix for 5 concepts and 6 criteria is shown in Table 3.4.

The concepts are A, B, C, D and E and the criteria are arbitrarily chosen for the sake of illustration.

After the scores of +. – and S have been assigned to concepts, analysis of the situation is done. Pugh has recommended several runs of this matrix to make sure that the concept that comes out as the strongest one is actually the strongest in terms of many criteria (many +'s). The negative scores in the matrix can be attacked by changing the concepts or recombining them into new ones and then again running the matrix.

Criteria	**Concepts**				
	A	**B**	**C**	**D**	**E**
Portable	+	-	DATUM	+	-
Reliable	+	-		-	-
Easy to use	-	-		+	+
Flexible	-	S		+	+
Good aesthetics	S	+		S	+
Good ergonomics	+	S		-	-
$\sum +$	3	1		3	3
$\sum -$	2	3		2	3
Total Score	1	-2		1	0

Table 3.4 Pugh's matrix

There are several runs that are required with this convergence and divergence strategy. This has been called as Pugh's controlled convergence.

Pugh's controlled convergence has been incorporated in a flow chart in Figure 3.5. Pugh's matrix represents a very simple approach for concept evaluation. Motivated by Pugh's controlled convergence approach, Liu et al (2003) have proposed multiple convergent and divergent approaches for an "ideal" generation and evaluation strategy.

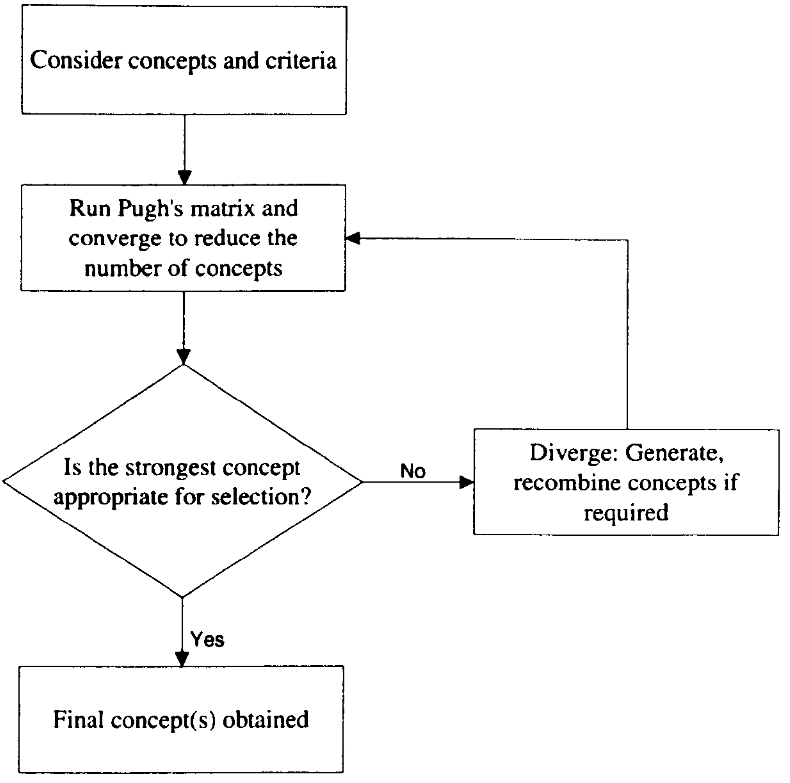


Figure 3.5 Flowchart for Pugh's controlled convergence

The strategy is proposed so as to strike a balance between convergence and divergence process. On one hand, this is helpful in generating concepts to such an extent that they can be evaluated. On the other hand, concepts generated should be sufficient in number so as avoid missing any important concept for evaluation purposes.

3.4.2 Simple Additive Weighting

Simple Additive Weighting (SAW) is a compensatory decision making method. The method consists of developing a decision matrix like Table 3.2. After obtaining the weights and preference values from the decision maker, the total score for an alternative A_j is calculated using the equation:

$$S_j = \sum_{i=1}^{m} w_i . v_{ij} \qquad (3.1)$$

This is essentially a scoring method and the preference information provided can vary from interval scales to cardinal values. Cardinal values are objective inputs from the decision maker.

3.4.3 Pahl and Beitz's Evaluation Procedure

Pahl and Beitz (1996) have proposed a systematic method for evaluating concepts. The total evaluation consists of "selection procedure" and "final evaluation". Selection procedure refers to an informal elimination of concepts and consideration of preferred concepts. This procedure is done on the basis of some basic criteria. They are:

- Compatibility of the concept with the task
- Concept fulfils demands of the requirements list
- Concept can be realised with respect to performance, layout etc
- Concept is expected to be within permissible costs

Other criteria may include safety measures and company's preference due to resource availability. Until this point, evaluation (selection procedure) can be done using an informal selection chart. The systematic evaluation comes into picture when the final evaluation of the concepts is considered after this selection procedure. Pahl and Beitz lay down the steps of the final evaluation explicitly. The steps of evaluation procedure are shown in Table 3.5.

In Step 1, set of decision relevant objectives are derived, usually from the requirements list. These objectives cover technical, economic and safety factors. Criteria can be derived from these objectives. Criteria are analysed and weights are assigned to them so as determine their relative importance in Step 2. In Step 3, assignment of parameters is done for criteria.

Step	Description
1	Identification of criteria
2	Analysis of criteria and determining their weights
3	Compiling parameters for criteria
4	Assigning parameter values in terms of scales
5	Determining Overall value of concept
6	Comparing concepts
7	Estimating uncertainties
8	Searching for weak spots

Table 3.5 Pahl and Beitz's concept evaluation steps

These parameters can define abstract criteria into measurable terms for e.g. consider criterion Portability in Table 3.5, the parameter assigned to portability can be mass or volume. In Step 4, values or "points" are assigned to the concept variants for each criterion. These parameter values refer to the preference values or judgements discussed earlier. This can be done using a subjective scale of either 0-4 or 0-10. Pahl and Beitz state that before performing these judgements, the designer must be aware of the value curves and parameter range. Value curves are a part of utility analysis. These are discussed in section 3.4.7. The overall value of concepts is derived in Step 5 using Equation (3.1) of SAW. Concepts are then compared on the basis of their overall values and rank ordered in Step 6. In Step 7, Pahl and Beitz suggest to estimate uncertainties due to subjective errors and procedure inherent shortcomings. Subjective errors include bias, incompatibility of criteria to all concept variants, strong criteria interdependence and so on. Procedure inherent shortcomings refer to the imprecision of the values or judgements assignment. The uncertainties that arise due to both of the above factors should be minimised. For Step 8, drawing value profiles is suggested to highlight the weak spots of concepts for each criterion.

3.4.4 Pro/Con Charts and Better/Worse Method

Pro/Con charts (Otto and wood 2000) are one of the easiest and simplest means of evaluating alternatives. In this type of method, there are three measures of demarcating the concepts, pro, con and neither. A chart is constructed, which contains alternatives in columns. The chart consists of "pro", "con" and "neither" as rows. For each concept, criteria are entered in these rows depending on whether a criterion is a pro, con or neither for this alternative. After obtaining the measures, alternatives are ranked subjectively. The alternatives are ranked depending on the combination of their pros and cons. This ranking is done considering the holistic performance of an alternative.

Better/worse is another simple strategy for evaluating alternatives. From the list of alternatives, an alternative is randomly picked. This alternative is then compared to other alternatives starting from the bottom of the list. Then, with respect to a criterion C, bubble sort is done and following question is asked during the sorting:

"Is alternative A_i as good as or better than alternative A_j with respect to criterion C?"

A bubble sort automatically rank orders the available alternatives with respect to criterion C.

3.4.5 Decision Support Problems Technique

Decision Support Problems Technique (DSPT) proposed by Muster and Mistree (1988) is decision based approach to solve the multilevel, multidisciplinary and multidimensional problems of engineering. It consists of three principle elements, a design philosophy, identification and formulation of DSPs and a software. It is based on the concept of satisficing by Simon (1990).

DSPT is placed in a hierarchical structure of a unified and continuous process of design, manufacture and maintenance as shown in Figure 3.6. The application of DSPT is shown in the figure. The rectangular boxes shown in the figure refer to collections of related decisions during the phases of design. Collections of decisions in turn are combinations of DSPs (Decision Support Problems). Similar boxes exist for manufacturing and maintenance (omitted in this figure).

Various DSPs can be formulated whereby decisions are structured and solved. Following are the important types of decisions that can be dealt using a DSP:

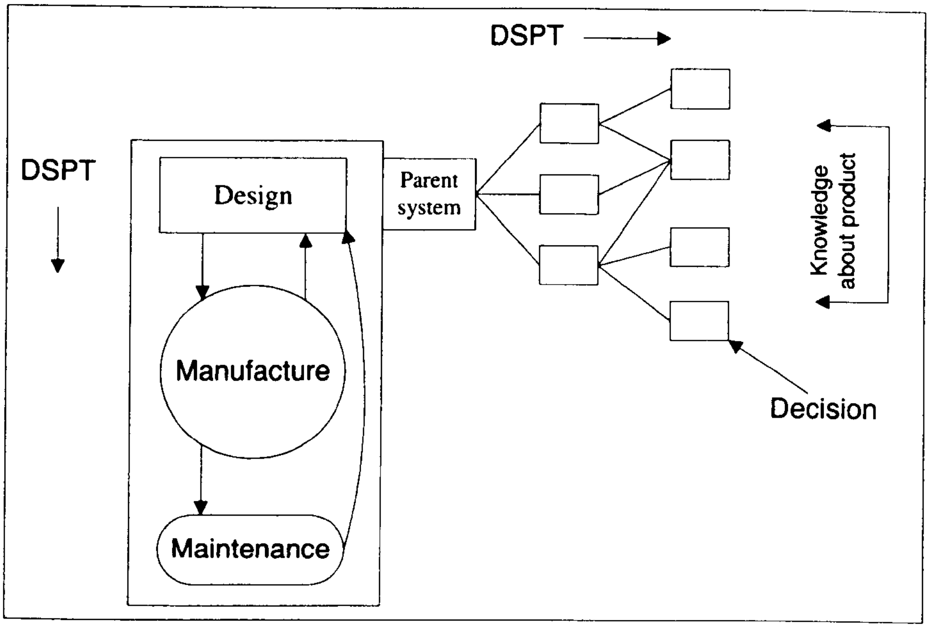


Figure 3.6 Muster and Mistree's DSPT in unified design, manufacture and maintenance

- Selection: Decisions that indicate a selection of a single alternative.
- Compromise: Decisions for improving an alternative.

Other types of decisions, hierarchical and conditional can be derived from the above two basic types of decisions.

The formulation and solution of DSP's are achieved in four phases (Table 3.6). The four phases of a DSP are Planning, Structuring, Solution and Post solution. Planning refers to the identification and stating the DSPs in word form. The designer identifies various requirements, limitations and success measures of the system with the available resources. With the completion of this phase, the process of design is defined in terms of tasks, the order in which the end goal is achieved and the grouping and ordering of the decisions to be made.

In Structuring, the word form of DSPs is converted into a mathematical form to solve the DSPs. Solution refers to determine a numerical solution. Finally, in the Post Solution analysis, design review is done to test the validity and sensitivity. These phases, further divided into six systematic steps help clarify the phases in more detail.

Phases	Steps
Phase 1 Planning	**Step 1**
	Given Story; **Write** Technical brief, Subsystem abstracts
	Step 2
	Write Problem statements
Phase 2 Structuring	**Step 3**
	Given Problem statement; **Structure** Decision Problem Support in words
	Step 4
	Given DSP in words; **Develop** Mathematical form of DSP and corresponding template
Phase 3 Solution	**Step 5**
	Given Mathematical form of template; **Determine** Numerical solution
Phase 4 Post Solution analysis	**Step 6**
	Given Numerical solution, **Gain** Insight and knowledge

Table 3.6 Phases and steps of a Decision Support Problem (DSP)

After gaining an insight into DSPT and DSPs, the formulation of DSPs during concept selection by Mistree et al (1994) is now discussed. Mistree et al (1994) use 2 types of DSPs for selecting a conceptual design. One of the DSPs is called as the Preliminary Selection DSP and the other as Selection DSP. Conceptual design, including these 2 DSPs, is prescribed by them in 5 steps:

1. Ideation: Refers to generation of concepts
2. Decision: The entails formulating and solving a Preliminary Selection DSP. This step leads to selection of "Most-likely-to-succeed-Concepts".
3. Engineering: Most-likely-to-succeed-concepts are converted to "candidate alternatives".
4. Decision: Leads to selecting one alternative by formulation of a Selection DSP.
5. Engineering: This involves evaluating the finally obtained alternative critically.

Mistree et al differentiate between alternative and concepts. Concepts are used during the Preliminary Selection DSP and alternatives during the Selection DSP. Alternatives represent engineered form of concepts. Preliminary Selection DSP is based on the Pugh's approach discussed in section 3.4.1. Selection DSP is similar to SAW (section 3.4.2) but is flexible enough to incorporate various subjective and objective inputs from the designer. A detailed explanation of DSPT and its applications is beyond the scope of this thesis. Hence, only the application of DSPT with respect to concept selection has been discussed here.

3.4.6 Paradigm of Fuzzy Logic in Design Evaluation

Fuzzy logic has become an important tool in design evaluation. Since a lot of work on design evaluation is being undertaken using this technique, fuzzy logic is first studied in this section. Some works on design evaluation that deal with fuzzy logic are then discussed.

What is Fuzzy Logic?

Zadeh (1965) introduced the idea of fuzzy logic or fuzzy sets to deal with fuzzy (or vague) information. Human beings tend to deal with a lot of fuzzy information in their daily lives for example, when one says that a car has a high mileage, one is not sure about the exact mileage of the car. This is called as a fuzzy expression. Fuzziness is numerically defined by the degree of membership. Each element of a fuzzy set belongs to it with a certain degree of membership. Referring back to the example above, one can say that there may be several cars with different mileage but the degree to which each car belongs to this set of cars (high mileage cars) is variable. Thus, a fuzzy statement is not either true or false but may be partly true or partly false to some extent. The concept of fuzzy logic becomes clearer with an understanding of crisp sets.

Crisp sets or classical sets are based on the idea of binary logic that uses one of the two values: true (1) or false (0). For example, when one says that all cars with a mileage of more than 10 miles/litre are considered to have a high mileage and below this 'not high' mileage. It means that a car can either have a high mileage (1) or 'not high' mileage (0). As opposed to this, element of fuzzy set has a degree of membership of its belongingness to the set of high mileage cars. Crisp sets are special cases of fuzzy sets when the degree of membership of element is either true or false.

A crisp set S of Universe U with elements u is defined by a characteristic function f_S (u)

$$f_S(u): U \rightarrow 0,1$$

which means,

$$f_S(u) = \begin{cases} 1, if & u \in S \\ 0, if & u \notin S \end{cases} \quad (3.2)$$

A fuzzy set S of universe U is defined by membership function m_S (u)

$$m_S(u): U \rightarrow [0,1]$$

where,

(a) $m_S(u) = 1$ if u is totally in S

(b) $m_S(u) = 0$ if u is not in S

(c) $0 < m_S(u) < 1$ if u is partly in S.

In case a and b above, fuzzy set becomes a crisp set. Hence, a car can belong to a fuzzy set of high mileage cars with a 0.8 degree of membership (or any other degree depending on the mileage). Fuzzy logic uses linguistic values (Negnevitsky 2001) to describe the fuzziness of any situation. In the example of a high mileage car, the linguistic value is high. Some other examples of linguistic values are tall, short, good, high, better etc. The concept of linguistic values is important because they are used for information capture during design evaluation. With this background of fuzzy logic, the references related to design evaluation are now discussed.

Application of Fuzzy Logic in Design Evaluation

Wang (1997) developed three models for selecting concepts using fuzzy logic. The models are based on the design information available on the relative importance of criteria. The three types of models used by Wang (1997) are pseudo-order preference model, semi-order preference model and complete-preorder preference model. The applications of models depend on the type of information available in the design phase. The pseudo-order preference model is used to differentiate between the dominance and non-dominance sets. Semi-order preference model is used while the information on relative importance of criteria is available and complete-preorder preference model is used to completely rank order the concepts available for evaluation. In all of the above three cases, to obtain the preference models, pairwise comparison is done between alternatives with respect to each criterion. This pairwise comparison of alternatives can be accomplished when preference values in the form of linguistic values have been obtained in the decision matrix. Wang (2002) has also extended Pugh's approach using fuzzy logic. Wang proposes to use linguistic values instead of +, - or S in Pugh's matrix. Vanegas and Labib (2001) have proposed a New Fuzzy Weighted Average (NWFA) technique to reduce the imprecision induced by Fuzzy weighted average method. Fuzzy weighted average is a mathematical expression, similar to Equation (3.1), but is a combination of "desirability levels" (preferences values in fuzzy form) and criteria weights. To combine them, fuzzy algebraic operations are performed. Due to this, the imprecision of the process increases. NWFA has been put forward to reduce this imprecision by modifying some algebraic operations. The fuzzy algebraic operations are not discussed here, as it would require an advanced knowledge of fuzzy logic.

Ishii and Barkan (1991) used artificial intelligence (AI) and fuzzy logic during the design evaluation activity. They proposed a methodology called as Design Compatibility Analysis (DCA) for evaluating designs. As the name suggests, it uses the rules in the AI system to compute the compatibility of the system with the requisite specifications. It also computes the compatibility of the components of the system at the same time.

To measure DCA, an index called as Match Index is calculated. Match index for a design comprising of components K is given by:

$$MI = \sum_{K} \text{utility}(s) * M(s, K) \qquad (3.3)$$

where, utility (s) is the importance associated with a component.
and M(s, K) is the compatibility of component s with the rest of design K. The specification. M(s, K) is called as match coefficient. Match coefficient is inferred from the rules of the knowledge base. Fuzzy linguistic values form an important part of DCA to evaluate MI.

Another fuzzy logic "preliminary design selection" technique was proposed by Joshi and co-authors (1991). They have developed, both compensatory and non-compensatory models of design evaluation using fuzzy algebraic operators. Some more works on design evaluation that incorporate the use of fuzzy logic are Khoo and Ho (1996), Yeo et al (2004) and Verma el al (1999).

3.4.7 Utility Methods in Design Evaluation

Utility can be defined as the worth or value of an item to a user. In design, the worth of alternatives is calculated to identify the alternative(s) that would provide maximum utility to a designer. To find utilities of alternatives, utility function is formulated and calculated for an alternative. This is called as an overall utility function U for an alternative and is a function of individual attribute utilities u_i. Pahl and Beitz's evaluation is also a type of utility determining method where utility for an alternative is calculated using Equation (3.1).

To obtain utility function for an attribute, value curves are plot using data points in 2 dimensional space. Value curves can be linear or non-linear, depending on the attribute. A value curve can be plot in the following manner. A linear utility function is considered here for simplicity. Consider an attribute, weight, in a decision matrix. Imagine that a decrease in weight increases its utility. The upper and lower acceptable bounds of performance measures (performance measures are different from performance values) of weight are identified, say 100 kg and 150 kg for lower and upper acceptable bounds respectively. These are then converted to a linear scale ranging from 0 to 10; say 0 indicates 150 kg and 10 indicates 100 kg. This means that utility of an alternative is 0 with respect to this attribute if its weight is 150 kg. And so, the utility (u_i) of alternatives will be ranging from 0 to 10. The performance values of alternatives for an attribute X_i can now be converted to their utility scores using this value curve. A non-linear value curve can also be plotted similarly using more number of points of attribute performance measures.

Overall utility score for an alternative can be evaluated by various methods. Thompson (1999) has proposed to evaluate overall utility score for an alternative using a Device Performance Index (DPI):

$$\text{DPI} = m / \sum_{i=1}^{m} (1/u_i) \tag{3.4}$$

In case the scale factors (scale factors determine the relative importance of attributes) of attributes k_i are available,

$$\text{DPI} = U^*K \tag{3.5}$$

where,

$$1/U = \sum_{i=1}^{m} k_i / u_i \tag{3.6}$$

$$\text{and } K = \sum_{i=1}^{m} k_i \tag{3.7}$$

Calculating overall utility using Equation (3.6) also offers an advantage as low performances in one attribute cannot be compensated by high performances in another attribute. This is due to the use of reciprocal addition.

Thurston (Thurston 1990; Thurston 1991) has used the Multi Attribute Utility Method (MAUM) to select alternatives for structural frames of automotives. The overall utility function for an alternative is calculated using a rigorous mathematical treatment. Individual attribute utility functions are non-linear and scale factors for them are calculated using lottery questions. Utility analysis requires cardinal data on preference values in the decision matrix. Fernandez et al (2001) have used utility theory by combining it with the Decision Support Problems (section 3.4.5). Utility analysis method by Thurston and Fernandez et al can be applied only when sufficient preference data is available.

3.4.8 Analytic Hierarchy Process

Analytic Hierarchy Process (AHP) is a generic MADM method proposed by Saaty (2000) which uses the pairwise component comparison. This method forms an important part of this research and is discussed in detail in section 5.2.1.2.

3.4.9 TOPSIS

TOPSIS, proposed by Hwang and Yoon (1981), is an acronym for Technique for Order Preference by Similarity to Ideal Solution. TOPSIS, as the name suggests, helps to search a candidate alternative, which holds "similarity" to the ideal solution. All the alternatives are considered as points in n dimensional space, where n represents attributes.

$$A_i = (x_{1i}, x_{2i}, \ldots\ldots\ldots\ldots x_{mi}) \tag{3.8}$$

An assumption is made that alternatives exists having the ideal preference values and that there would exist two ideal alternatives. One is the positive ideal alternative and other is the negative ideal alternative solution. The "best" alternative then is the one that is nearest to the positive ideal solution and farthest from the negative ideal solution. The positive ideal solution is denoted as:

$$A^* = (x_1^*, x_2^*, x_3^* \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots x_m^*) \tag{3.9}$$

where x_1^*, x_2^*, x_3^* and so on represent the best preference value for i[th] attribute from the available alternatives. Similarly, the negative ideal solution is represented by:

$$A^- = (x_1^-, x_2^-, x_3^- \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots x_m^-) \tag{3.10}$$

where x_1^-, x_2^-, x_3^- and so on represent the worst value for i^{th} attribute from the available alternatives. After finding the positive and negative ideal solutions, euclidean distances are calculated for each alternative from the positive and negative ideal solutions. Since, the alternatives may not simultaneously have the least distance from the positive ideal solution and the farthest distance from the negative ideal solution, both the euclidean distances are suitably combined to represent a similarity to the positive ideal solution.

TOPSIS consists of the following five steps:

1. Calculate normalized ratings:

The normalisation of preference values x_{ij} is done using the formula

$$y_{ij} = \frac{x_{ij}}{\sqrt{\sum_{j=1}^{n} x_{ij}^2}} \tag{3.11}$$

2. Calculate weighted normalized ratings:

$$v_{ij} = w_i \, y_{ij} \tag{3.12}$$

w_i represents the weight of i^{th} attribute

3. Identify positive ideal and negative ideal solutions:

Ideal positive and negative solutions are identified using Equations (3.9) and (3.10).

4. Calculating separation measures:
Separation measures of alternatives from the ideal alternatives are calculated using euclidean distance. Separation from the positive ideal solution is calculated using:

$$S_j^* = \sqrt{\sum_{i=1}^{m} (y_{ij} - y_i^*)^2} \tag{3.13}$$

and separation distance from the negative ideal solution is given by:

$$S_j^- = \sqrt{\sum_{i=1}^{m} (y_{ij} - y_i^-)^2} \tag{3.14}$$

5. Calculate similarity to positive ideal solution:

$$C_j^* = \frac{S_j^-}{(S_j^* + S_j^-)} \tag{3.15}$$

6. Provide ordinal rankings using the C_i^* values calculated.

Although TOPSIS has not been utilized in engineering design decision making, it has the potential of being used during this activity. But it required cardinal values for information processing.

3.4.10 ELECTRE

ELECTRE (Hwang and Yoon 1990) is based on the idea of outranking relationships between the alternatives. Outranking relationships between the alternatives suggest that one alternative is preferred to another by the decision maker, even if both the alternatives are non dominated.

Using the outranking relationships between the alternatives, a "kernel" is obtained. This kernel represents a core which contains the final preferred alternatives. To be an element of a kernel, an alternative should have the following properties:

- Each alternative inside the kernel should not be outranked by any other alternative inside the kernel.

- Each alternative outside the kernel should be outranked by at least one alternative inside the kernel.

A kernel is shown in Figure 3.7 for 5 alternatives decision problem. The outranking relationships for the alternatives are obtained by a rigorous mathematical approach. Figure 3.7 is called as a digraph consisting of a kernel with 2 alternatives, A_1 and A_3. Therefore, A_1 and A_3 are the final preferred alternatives that outrank other alternatives.

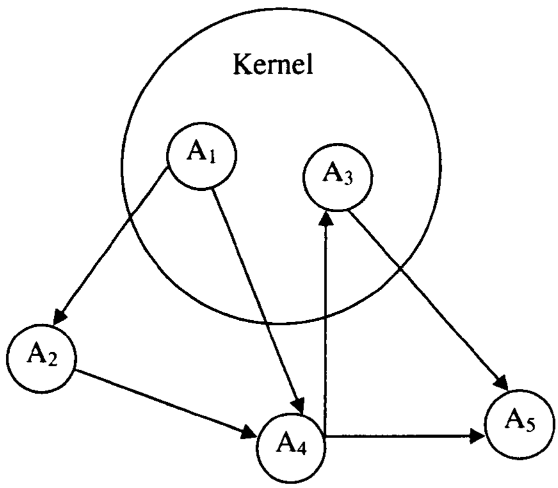


Figure 3.7 Digraph for a 5 alternative decision problem

3.4.11 Additional Methods

Czuilik and Driscoll (1997) differentiate "solutions" (concepts) using function metrics providing feedback on decisions at the functional design level. The methodology consists of calculating various indices and combining them into single index of Function Fulfilment Index (FFI), which is:

$$FFI = SFI - DLFI - RFI \quad (3.16)$$

where,

FFI = Function fulfilment index

SFI = Sharing fulfilment index

DLFI = Demand level fulfilment index

RFI = Redundancy fulfilment index

Czuilik and Driscoll suggest that the positive FFI indicate that the concept contains small number of elements that are neither redundant nor heavily used, negative values of FFI indicate presence of non-essential or highly demanded elements. A zero FFI value might indicate one to one element and function ratio. Concepts can be rank ordered on the basis of FFI values. A qualitative programming method is utilized by Chen and Lee (1993) to evaluate the ordinal ranks for concept selection. A set of equations is arrived at and solved using 0-1 integer programming. The preference values are captured using pair wise comparisons using >, < and = symbols. King and Sivaloganathan (1999) apply the existing concept selection methods for the selection of flexible designs. They propose to utilise a core design for developing different products. A core design is found by combining various design configurations and the selection of configurations is aided by Quality Function Deployment (QFD) and utility theory.

3.5 Discussion

Decision and decision making is defined and understood in this chapter. Some classification methods have been explored and various decision making methods are studied. The selection of a decision making method for any application depends on various factors for example information availability, simplicity of applying the method and so on. None of the available methods is a "cure all". There are various advantages and disadvantages associated with each method. For example, Pugh's approach is a simple means of concept evaluation but it lacks the objective selection of concepts. All the attributes are treated as equally important in this method. On the other hand, it offers a simple approach for evaluating concepts. Pahl and Beitz's evaluation method uses scales for capturing preference information and also takes into consideration the importance of attributes. But it is a very systematic methodology with many steps. Similarly, all other methods discussed have pros and cons and it only depends on the user (or decision maker) as to what purpose is he looking for, to get served through the use of decision making method. In this thesis, study of decision making tool is done with respect to its ease of information extraction from the decision maker. This ease of information capture will be used in developing a methodology that can be used by novice designers and can be applied to all types of designs. Henceforth, some important decision making methods from section 3.4 are listed in Table 3.7 with respect to their method of information capture. All the methods have been rated on a scale of 1-5 which reflects its ease of information capture. Cardinal information refers to the parameter values for a cell in a decision matrix. It can be noticed that Pugh's method, Pro/Con charts, AHP and the method by Chen and Lee (1993) offer the easiest way of capturing the information.

Method	Preference information required	Objective output	Rating
Pugh 1981	+, - and S		1
Pahl and Beitz 1996	Scale 0-4 or 0-10	✓	3
Pro/Con charts	Pros, Cons, Neither		1
Better/Worse method	Ordinal information		2
Mistree et al 1994	+,- and S, cardinal information and/or interval scales	✓	3
Wang 1997	Linguistic values	✓¶	2
Wang 2002	Linguistic values	✓	2
Vanegas and Labib 2001	Linguistic values	✓	2
Ishii and Barkan 1991	Cardinal information, AI rules	✓	5
Joshi et al 1991	Cardinal information	✓	3
DPI	Cardinal information, scale conversion inputs	✓	4
Thurston 1990	Cardinal information and lottery probabilities	✓	4
Fernandez et al 2001	Cardinal information and lottery probabilities	✓	4
TOPSIS	Cardinal information	✓	4
ELECTRE	Cardinal information	✓	4
AHP	Pairwise comparison	✓	1
Czuilik and Driscoll 1997	Information on components of design	✓	3
Chen and Lee 1993	<,> and =	✓*	1

Table 3.7 Design evaluation methods and their ease of information capture

1= Very easy, 2 = Easy, 3 = Moderately easy, 4 = Difficult, 5 = Very difficult

¶ = Objective output only for 1 model (section 3.4.6)

* = Provides only ordinal ranks as objective output

DRM
Descriptive Study I

Chapter 4

Reliability and Realizability Methods

Decomposed design evaluation was discussed in section 2.4. It was found that reliability and realizability are 2 important criteria considered during evaluation by the companies. In this chapter, the fundamental concepts of reliability and realizability are sought.

Classification of reliability methods by some authors is studied. It is found that the existing classifications do not consider the methods ideally they should. Henceforth, a broad classification of reliability methods is undertaken here that also includes reliability methods that evaluate reliability using decision making tools. The objective here is to understand how can one assess reliability in design (especially conceptual design) and for all types of designs (original, adaptive, variant and catalog), if at all possible. A discussion on reliability methods is then undertaken.

As regards realizability is concerned, only few authors have undertaken research on realizability evaluation in engineering design. In this chapter, the literature on realizability studies is reviewed and realizability is linked to cost during the conceptual design phase. This chapter is a part of DRM, DS I.

4.1 The Origin and Development of Reliability

The idea of reliability (Denson 1998) dates back to second world war when the US military realised that their equipments were failing heavily. Due to this, in early 1950s they formed a committee called as AGREE (Advisory Group on Reliability of Electronic Equipments), since electronic equipments were the main cause of concern.

The formation of AGREE committee was amongst the 5 point conclusions chalked out by the ad hoc groups for improving the reliability. The AGREE advisory group was meant to "identify actions that could be taken to provide more reliable electronic equipment". Due to this, it was realised that there should be a means to quantitatively estimate reliability before the actually equipment is built. A lot of pioneering work was done during this decade. In 1960s, MH-217 (MH denotes US Military Handbook) was published by the US navy. This was a document that "included design guidance on the reliability application of electronic components".. The institutions in the US that were active in reliability engineering area were US Department of Defence (DoD), Reliability Analysis Center (RAC), Rome Laboratory and Illinois Institute of Technology Research Institute (IITRI). Reliability prediction was undertaken by systems engineers and scientists modelling the physical causes of failure.

In the 1970s, MH-217 was revised to incorporate advancement in technology. Other innovative models for reliability prediction were proposed but the users did not accept them. The reason for this was their complexity and demand for extensive knowledge of data and hence they appeared unrealistic and costly and were discarded. MH-217 had been updated many times in 1980s. Many agencies started to develop reliability methods specific to their industry needs. The Society of Automotive Engineers (SAE), for example, came up with different standards for reliability predictions of automobiles. Still, the area of reliability improvement concentrated mainly on electronic circuits. With the technology advancement, other quality standards came into picture especially due to the complexity of the electronic circuits. In 1990s, a broad definition of reliability was introduced and more steps and contracts were awarded for introducing new methods of predicting reliability. Reliability also included considering system level factors like design, manufacturing etc. and not only component reliabilities. Today, there are various methods proposed for reliability evaluation and have been classified according to their types and applicability. In section 4.3, some classifications are studied and a new classification is proposed.

4.2 Reliability Definition

The standard definition of reliability accepted in this thesis is:

"The ability of an item to perform a required function under stated conditions for a stated period of time" (BS 4778 1990).

As is evident from the definition, reliability depends on function satisfaction and that performance of a function over time is an indicator of reliability (Thompson and Nilsson 2001). Additionally, failure in this thesis is also referred to as failure of performing the function to the expected level and not only "breakdown" due to manufacturing defects, fatigue etc. This will be discussed in some detail during the explanation of methodology proposed in this thesis (section 5.2).

4.3 Classification of Reliability Methods

Some authors have classified the available reliability methods in a way that supports the objectives of this research. They are studied here and with an inclusion of literature on reliability evaluation using decision making tools, a classification is then made of the available reliability methods.

Figure 4.1 shows different types of reliability methods as classified by Stephenson (1995). This classification has been done with regard to the design process. Various methods have been positioned according to their applicability to different design phases. From the figure, it can be noticed that most of the reliability methods are applicable to the later phases of design.

Smith (2002) has considered two broad categories of the available reliability methods. They are the "Designer oriented" and the "Data oriented" methods. This is in fact, an extension to the classification by Stephenson by including the data oriented methods. The designer oriented reliability methods are all similar to the ones discussed by Stephenson in Figure 4.1.

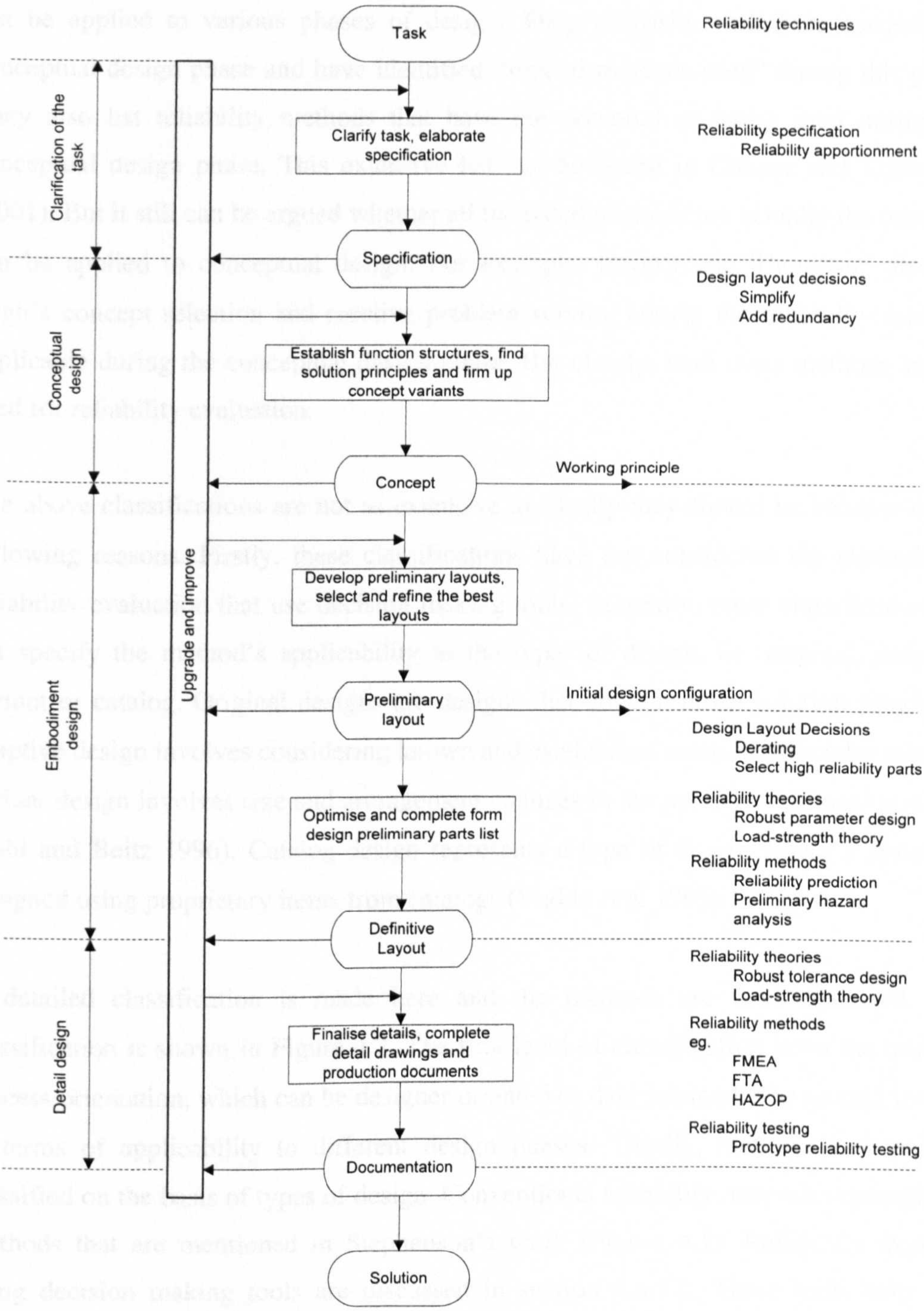


Figure 4.1 Reliability methods in design process (after Stephenson 1995)

Data oriented methods include methods that determine the statistical reliability of an item. Cooper and Thompson (2001) have provided an exhaustive list of methods that can be applied to various phases of design. They primarily contribute towards the conceptual design phase and have identified "several methods used" during this phase. They also list reliability methods that have the potential of being used during the conceptual design phase. This extensive list can be found in Cooper and Thompson (2001). But it still can be argued whether all the listed methods are actually the ones that can be applied to conceptual design. For example, Cooper and Thompson also list Pugh's concept selection and creative problem solving among the reliability methods applicable during the conceptual design phase. But clearly, both these methods are not used for reliability evaluation.

The above classifications are not as extensive as ideally they should be because of the following reasons. Firstly, these classifications have not considered the methods for reliability evaluation that use decision making tools. Secondly, these classifications do not specify the method's applicability to the types of design, i.e. original, adaptive, variant or catalog. Original designs are designs that contain novel solution principles, adaptive design involves considering known and established solution principles whereas variant design involves size and arrangement changes in the previous designed products (Pahl and Beitz 1996). Catalog design represents a type of design where a system is designed using proprietary items from catalogs (Vadde et al 1995).

A detailed classification is made here and the methods are then discussed. The classification is shown in Figure 4.2. The first level of classification is on the basis of process orientation, which can be designer oriented or data oriented. The second level is in terms of applicability to different design phases. Thirdly, methods can then be classified on the basis of types of design. Conventional reliability methods represent the methods that are mentioned in Stephenson's work (Figure 4.1). Reliability methods using decision making tools are discussed in section 4.4.1.2. These tools help take decisions and are proposed to be used in conceptual design. This thesis contributes towards this arena of reliability methods in which decision making is primarily involved for evaluating reliability. Design for Reliability (DFR) methods represent the work done at Cambridge University, which addresses "Designing in" Reliability in the initial

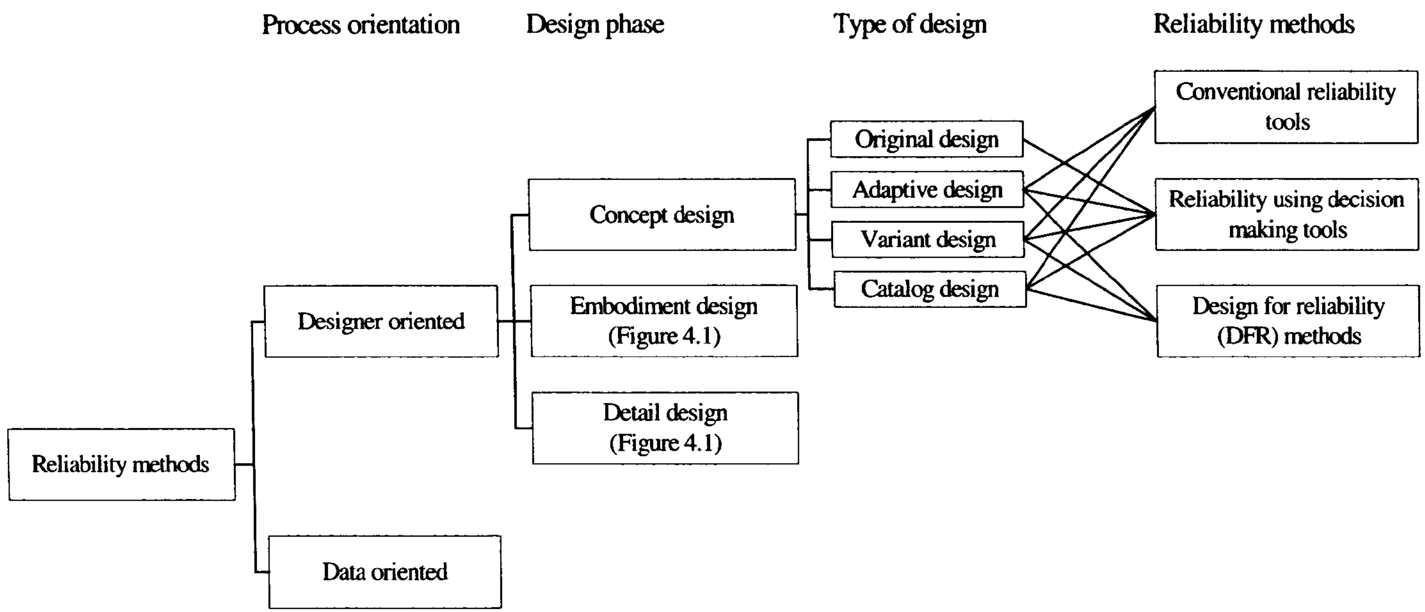


Figure 4.2 Classification of reliability methods

phases of design. Note from the figure that for original designs, not all the types of reliability methods that are mentioned for conceptual design are applicable. Reliability methods that can be used during the embodiment and detail design phase are shown in Figure 4.1. Data oriented methods are not discussed in this thesis and further knowledge on them can be gained from Smith (2002).

4.4 Reliability Assessment in Design (Designer Oriented Methods)

Design has an important influence over product's reliability (Golomski 1995). This being true, still most of the companies evaluate reliability after the product rolls out of the assembly plants (i.e. they apply data oriented methods). In this section, important reliability methods are studied that are/can be used in the design process. They are studied in chronology of design process as conceptual design, embodiment design and detail design. All the reliability methods in embodiment and detail design that can be found in other literature are not discussed. This is because in this research, reliability is considered in conceptual design and hence, most of the methods in conceptual design, especially the ones using decision making tools, have been covered.

4.4.1 Concept Design

4.4.1.1 Conventional Reliability Methods

Reliability Apportionment

Reliability apportionment or allocation has been defined as a "process of assigning reliability requirements to individual components to attain the specified system reliability" (Kapur and Lamberson 1977). In short, a system reliability aim is defined and sub-system reliabilities are calculated so as to achieve the target system reliability. While it can be easy enough in case of simple systems, it can prove to be very complex in case of complex sub-systems. It may include optimisation techniques so as to achieve an optimal allocation of reliability. Some advantages of the apportionment are that the designer is forced to consider the system, sub-system and components scenario and that it helps understand the reliability problems in design. Application of such a methodology reveals the importance of reliability.

Mathematically, apportionment can be described as:

$F (R_1, R_2, R_3 \ldots\ldots\ldots\ldots\ldots\ldots\ldots R_n) \geq R$

Here, F denoted the function of combination of reliabilities for various sub-systems,
R is the system reliability, and
R_1, R_2 and so on are the individual sub-system reliabilities

This technique, though can be applied in the initial phases of design, involves a clear sub system analysis of the system under study. Sometimes, it also involves component level analysis for allocation of reliability requirements. Hence, it cannot be applied to all types of designs. Moreover, it is simply a tool to help allocate reliabilities and does not help in decision making during concept selection.

4.4.1.2 Reliability Methods using Decision Making Tools

Reliability methods in this area are the ones that are combined with the decision making tools like fuzzy logic (section 3.4.6), Bayes probability theorem and optimisation techniques to evaluate reliability in the conceptual design phase.

Goel and coauthors (2003) have proposed a reliability method to optimise the availability of chemical plants. They suggest a two-fold benefit of using their method. Firstly, an optimum flow process structure of the plant is achieved and secondly, reliabilities of equipments are selected so that the chemical plant availability is maximised. Initially, there exists a superstructure or the feasible design space from which various process flowsheets can be derived. These different flowsheets represent the alternative paths or various alternative designs available. A reliability block diagram representing such flow sheets is derived and an optimisation routine is run. The optimisation technique used is Mixed Integer Non Linear Programming (MINLP) and the objective function is represented by:

Expected annual profit = Revenues – annualised investment cost – maintenance cost – raw material cost – other operational costs

where,

$$\text{Revenue} = \text{SOT}*A_{sys}* \sum_{i\in PR} x_i \xi_i \qquad (4.1)$$

$$\text{Investment cost } CI_j = CI_{0,j} * e^{\phi_j\left(\frac{A_j}{A_{0,j}}-1\right)} \quad \text{(for each equipment)} \qquad (4.2)$$

$$\text{Maintenance cost } MC_{cor,j} = \text{SOT} * mlc_j * \left(\frac{1-A_j}{A_j}\right) \text{ (for each equipment)} \qquad (4.3)$$

$$\text{Raw material Cost } C_{raw} = \text{SOT} * A_{sys} * \sum_{i\in RM} x_i \xi_i \qquad (4.4)$$

Availability of the system,

$$A_{sys} = \prod A_j \text{ for a series system} \qquad (4.5)$$

where,

SOT is Standard scheduled operating time per year,

A_{sys} is the current availability of the system,

x_i is the continuous variable that describes the flowrate of i^{th} process stream,

ξ_i is the cost of i^{th} process stream,

$CI_{0,j}$ is the investment cost calculated using conventional cost models,

ϕ_j is a parameter for equipment j introduced to take into account the differing investment costs of equipments,

A_j is the current availability,

$A_{0,j}$ is the base availability,

mlc_j is the cost of corrective maintenance per hour on j^{th} unit,

PR is the set of product and by-product streams in the process superstructure,

RM is set of raw materials stream in process structure.

It is evident from Equations (4.3) – (4.5) that all the costs are functions of availabilities of process components in the flow structure. The base availabilities are calculated using the following equation:

$$A_{0,j} = \frac{MTBF_j}{MTBF_j + MTTR_j} \tag{4.6}$$

MTBF is the Mean time between failures and MTTR is Mean time to repair. Though this model reflects a rigorous methodology to calculate optimum reliabilities, it is very specific to chemical processes. It represents an application for only catalog types of design and cannot be applied to other designs. Since evaluating base availability in equation (4.6) requires MTBF and MTTR values, these values are not available during original designs. Even the costing data for evaluating various equations may not available during the conceptual design phase.

Broadbent (1993) proposed a systematic approach for evaluating reliability of concept designs. The approach prescribes 4 stages. The stages of evaluation are as follows:

"

1. Identifying possible failure modes

2. Studying the environment to see if the conditions likely to induce failure exist

3. Studying each design to see if its vulnerability to a given condition can be reduced.
   - as delivered
   - over the life of the design

4. Ranking the designs for reliability

"

Broadbent studied the application of this methodology on student projects. From the above stages, it can be noted that the method involves considering various failure modes of the concept designs. This step is considered advantageous by Broadbent because "it will force the designer to consider all the components". But in doing so, the designer is taking a leap and leaving the conceptual phase of design. Also, original designs do not consider components in the conceptual design stage, which makes it difficult to use this method in all situations. Additionally, considering various failure modes during this phase does not seem to be a pragmatic approach.

Verma and Knezevic (1996) use the fuzzy logic paradigm (section 3.4.6) to evaluate reliability Feasibility Index (FI). This feasibility assessment involves analysing the compliance between the required reliability profile and the predicted reliability profile of a concept. Fuzzy logic helps create the requirements and anticipation profiles on a number scale. The reliability requirement profile is delineated using fuzzy QFD method (Verma et al 1999). All the profiles are analysed and a weighting wedge mechanism method is used to provide the measure of FI. FI is calculated using:

$$FI_{Reliability} = \frac{Projected\ \ volume\ \ of\ \ overlap}{Total\ \ projected\ \ volume\ \ of\ \ profile} \tag{4.7}$$

On the basis of this compliance and a feasibility threshold, concepts are discarded or selected for the next stage of the product development process. Delineating requirements profile and anticipation profiles for the concepts form a complex part of this method.

Ormon and co-authors (Ormon et al 2001; Ormon et al 2002) have also proposed a methodology for predicting reliability in conceptual design phase. They have proposed 3 methods:

1. Component level analysis
2. Subsystem level analysis
3. Analytic models

The first two methods make use of Monte carlo simulation. All the methods consider the system block diagram that includes active and standby redundancies. The computation also involves both, the known failure rates and the unknown failure rates. The unknown failure rate, used in simulation modelling is calculated using triangular probability distributions. To evaluate unknown failure rate, designer is asked to predict

$\min_i$ (optimistic), $\text{mod}_i e$ (most likely) and $\max_i$ (pessimistic) values of the triangular distribution. The unknown failure rate then can be predicted by:

$$\hat{\lambda}_i = \begin{cases} \min_i + \sqrt{\Delta_1 * \Delta_3 * u} & \text{if} \quad u \leq \frac{\Delta_1}{\Delta_3} \\ \max_i - \sqrt{\Delta_2 * \Delta_3 * (i-u)} & \text{otherwise} \end{cases} \tag{4.8}$$

and $\Delta_1 \equiv \text{mod}_i e - \min_i$ (4.9)

$$\Delta_2 \equiv \max_i - \text{mod}_i e \tag{4.10}$$

$$\Delta_3 \equiv \max_i - \min_i \tag{4.11}$$

u in above equations is a random number.

In Component simulation analysis, Ormon et al recommend a 5-step process. The steps are:

Step 1) Generate the failure rate for the components
Step 2) Generate a time-to-failure for each component in the system
Step 3) Determine simulated time to failure for the subsystem
Step 4) Determine time-to-failure for the system
Step 5) Determine mission success. Based on the number of successes in various simulations, mission reliability is calculated. The average system cost is also estimated.

In the Subsystem level analysis, either the subsystem failure rates are available or they are calculated using the triangular probability distributions. For the Subsystem level simulation analysis, a 3-step procedure has been recommended:

Step 1) Determine subsystem failure rates
Step 2) Determine subsystem reliability
Step 3) Determine system reliability

To take into account the variability of triangular probability distribution due to replications, Analytic model has also been proposed. It is applied at the subsystem level. When the failure rates of the subsystems are unknown, the probability distribution is:

$$f_i(\lambda_i) = \begin{cases} \dfrac{2(\lambda_i - \min_i)}{\Delta_3 * \Delta_1} & \min_i \le \lambda_i \le \mathrm{mode}_i \\ \dfrac{2(\max_i - \lambda_i)}{\Delta_3 * \Delta_2} & \mathrm{mode}_i \le \lambda_i \le \max_i \\ 0 & otherwise \end{cases} \qquad (4.12)$$

When the failure rates are unknown, reliability is calculated using probabilistic laws. These prediction techniques, simulation or analytic, demand the value of maximum, minimum and most likely values for generating unknown failure rates. The designer has to predict these 3 values for individual component/subsystem in each concept. In case of large number of concepts to be evaluated, designers may not find it easy to provide these 3 figures, especially in case of original designs. In fact, these values can be predicted only when the designer is experienced enough. Additionally, the subsystem analysis cannot always be done for original designs.

Nachtmann and Chimka (2003) incorporate fuzzy logic in their method and extend Ormon et al's approach. Instead of triangular probability distribution in Ormon et al's model, they use fuzzy triangular number, which is represented by a triplet. The fuzzy failure rate number is represented as ($\lambda_{SPi}, \lambda_{MPi}, \lambda_{LPi}$), and

λ_{SPi} = Smallest possible (optimistic) failure rate

λ_{MPi} = Most promising failure rate

λ_{LPi} = Largest possible (pessimistic) failure rate

The steps proposed for applying the methodology are:

Step 1) Determine the failure rates for all the components in the system. Here the membership function for a component failure rate is calculated.

Step 2) Determine the subsystem reliability. For each subsystem, when failure rates are unknown, 3 types of reliabilities are calculated. They are R_{SPi}, R_{MPi}, R_{LPi} corresponding to λ_{SPi}, λ_{MPi}, λ_{LPi} respectively.

Step 3) Determine system reliability. Again for unknown failure rate condition, 3 reliabilities are calculated. Defuzzification is then employed to obtain the system reliability.

Step 4) The average cost of the system operation is calculated.

The method, though helps counter uncertainty and imprecision by the use of fuzzy logic, has got similar drawbacks as Ormon et al's method.

Yadav et al (2003) have also proposed a framework for predicting reliability during the product development process. They propose a methodology incorporating Bayesian approach to predict reliability at every stage of the product development process. Fuzzy logic is used to quantify engineering judgements and incorporate them into Bayesian approach. This methodology involves, as one of the inputs, consideration of warranty data of the product, which requires either the previous existence of the product or quantitative data input. Secondly, the framework involves testing samples at every stage of the development process (although a few in initial stages of product development). In original design, the warranty data is not available. Also design samples are not available in the conceptual design phase. This limits this model for application to conceptual phase for all type of designs.

4.4.1.3 Design for Reliability (DFR) Methods

Some work on "Designing in" reliability in the initial phases of design has been done at the Engineering Design Centre (EDC), University of Cambridge. This research represents qualitative assessment of designs to improve designs with respect to reliability.

Aguirre's Work on Properties of Systems

Based on an extensive literature review and design guidelines, Aguirre (Stephenson 1995) has defined the principles of Simplicity, Clarity and Unity related to technical systems. These 3 principles have been identified as internal properties of the system and an appropriate mix of these internal properties of the system determines the external properties of the system, the external properties being Economy, Reliability and Performance (Figure 4.3).

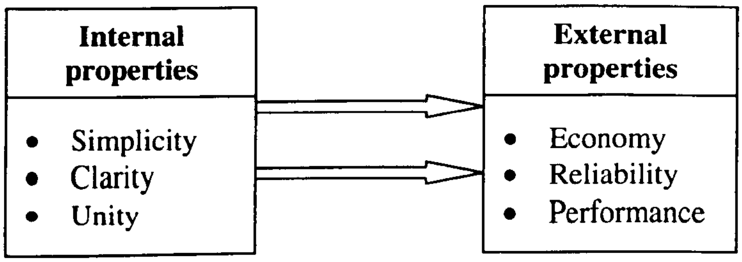


Figure 4.3 Aguirre's relationship between internal & external properties' of technical systems

The 3 principles have been defined by Aguirre as follows:

1. Simplicity: "The number of elements in a technical system should be the minimum necessary for its correct operation". This principle can be utilized in the conceptual design phase where information and data availability is less and one can attribute simplicity as a factor for selecting reliable designs.

2. Clarity: "The degree of independence between the physical and the functional relationships defining the configuration of a technical system should be the minimum necessary for its correct operation". Since this involves the physical embodiment of the concept to evaluate, this principle is likely to be applicable to the embodiment design phase.

3. Unity: "The relative contribution that each element in the configuration of a technical system makes to the correct operation of a technical system should be

equal". This principle involves consideration of strength of the components of the system and is related to the detail design phase.

Stephenson's Design for Reliability (DFR)

Building up on Aguirre's principles, Stephenson (1995) came up with the theory on Design for Reliability (DFR). He extended the 3 principles of Aguirre and proposed a methodology for qualitatively "evaluating" reliability in the initial phases of design. Stephenson redefined the 3 principles of Simplicity, Clarity and Unity as:

1. Simplicity: "The number of components and active interfaces should be the minimum necessary to perform the functions required". This extended definition also includes the interfaces because interfaces are considered as the regions of failure.

2. Clarity: "A clear active interface is one in which each function is able to operate independently of all other effects. Independent operation is achieved at an active interface if the variation of the force in reserve for performing each function is at a minimum".

3. Unity: "A component should have sufficient strength for the static and dynamic loads it has to carry". This principle is related to the loads sustained by various components and the strength of the components. This is applicable to the detail design phase.

Clarity is more important from the reliability point of view. There are 3 clarity values assigned depending on the configuration. They are 1, 2 and 3, where 1 refers to the clearest type of interface and indicates a reliable configuration and 3 refers to the least clear interface and indicates least reliable configuration. The clarity ratings provided to the configurations is very subjective and may vary from designer to designer and company to company. Like Aguirre's principle, since this also involves components, this is more likely to be implemented in the embodiment design phase. The clarity

values have been defined in terms of input force and resistance force to the interface in a linkage mechanism. The meaning associated with clarity values are as follows:
Clarity value 1: This clarity value is a straightforward case where maximum input force is constant and resistance force to the interface is also constant.

Clarity value 2: This value is assigned when the maximum input force is varying and resistance force also varies. But still, the resistance does not increase to the extent that it surpasses the Maximum input force.

Clarity value 3: Here, the maximum input force the resistance forces are both varying and at some point, the resistance force surpasses the maximum input force resulting in a failure.

A step-by-step method is proposed by Stephenson to assess clarity of interfaces. A part of this assessment, for evaluating a function's clarity, is shown in Figure 4.4. Stephenson has applied his approach to various configurations of sub assemblies for backhoe loader using their case histories. The methodology is applicable mainly to the embodiment design phase or to the adaptive or variant designs in conceptual design phase. Both Stephenson's work and this research concur to the definition of failure discussed in section 4.2.

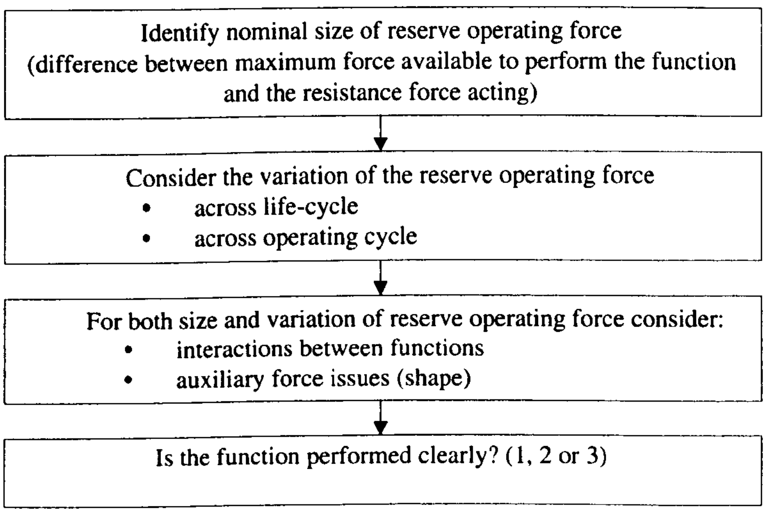


Figure 4.4 Stephenson's clarity assessment for a function

Covino's Work on Design for Reliability

Extending Stephenson's idea, Covino and co-authors (2000) have proposed another methodology for assessing reliability in the initial phases of design. Since Stephenson's method requires "expertise and knowledge of the system" to assign clarity values, Covino and coauthors proposed a method for evaluating clarity values to the mechanical systems. The method follows the steps shown in the flow chart (Figure 4.5).

As an overview of the methodology, the system is broken down into overall function, main functions and components (that support the main functions). Then "Black box" components are identified ("Black box components" has been coined by Covino and authors to refer to the types of components with certain undesirable characteristics. It should not be confused with Black box in the decomposed design approach). Black box components satisfy two characteristics:

- These components are involved in two or more main functions.
- They have forces that are not contained on the same line.

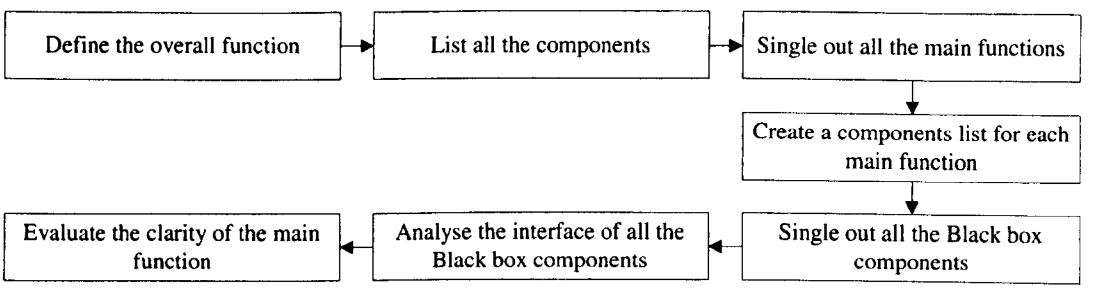


Figure 4.5 Covino et al's methodology for assessing clarity of design

On the basis of type and number of Black box components, clarity values are assigned to the interfaces. Again this method is applicable to the embodiment design phase, as does Stephenson's work. It is merely an extension of it and helps assign clarity values with relative ease. Also, qualitative assessment of designs does not help in decision making and so the method cannot be used for an objective comparison of the designs.

"Designing in" reliability methods appears to work better when a concept has already been selected at the end of the conceptual design phase and then variants of this selected concepts are present for further selection. For example, Mattson and Messac (2003) have described a decision making situation whereby, a concept has different variants that are termed as "alternatives".

Smith's Work on Reliability

Another DFR method has been proposed by Smith (Smith 2002; Smith and Clarkson 2001). The method helps highlight the design areas that need an improved to enhance reliability. The theory of phenomenology has been used to "consciously" understand the conceptual design process. The method consists of 2 parts, descriptive and prescriptive. Descriptive part helps build "Groups". Groups are structured representation of requirements, relationships, entities and properties. After building the Groups, prescriptive part is applied to identify Misfit and Failure Emergent Requirements (MERs & FERs). MERs are the requirements that reveal the misfits. Misfits in a design are the potential failure areas that emerge whilst satisfying the initial requirements. FERs prevent the structural failure of a design. Smith's method does not aim at comparing concepts on the basis of reliability but only provides with a tool to highlight areas where work is required to improve reliability in a design.

4.4.2 Embodiment Design: Derating

Derating is a practice normally applied in the field of electronics. It has been described as "a technique through which either electrical stresses acting on a part are reduced or the strength of the part is increased, to increase the stress rating of the part by replacing it with a component with higher values in correspondence with allocated or rated strength-stress factors." (Radu 2003). This means that either the parts having higher strength can be used or load acting on the part is reduced.

4.4.3 Detail Design

4.4.3.1 Robust Design

Dr. Genechi Taguchi came up with an idea of robust design for quality improvement. Reliability is considered to be in the domain of quality. A product is robust when "it is insensitive to the effects of sources of variability, even though the sources themselves have not been eliminated." (Fowlkes and Creveling 1995).

The aim of robust design is to design product or processes which are insensitive to the variation. This variation is called as noise. Different types of noise factors have been identified. They are external, unit to unit and deterioration (or internal) noise factors. The idea is to induce robustness in the product and process so that they are insensitive to these noise factors. Robust design can be applied to different phases of product development. Primarily, it is applied to off-line quality phase, which consists of the concept, parameter and tolerance design. With regards to robust design, concept design phase is aimed to identify robust technology and concept, parameter design aims to identify the control parameters of the design and tolerance design aims to provide tolerance values to the parameters identified. Various robust design methods have been proposed for application in each of these phases, especially during parameter design. Taguchi has proposed to design experiments using orthogonal arrays. The method is suitable for parameter and tolerance design. Although it has also been proposed for concept design, it does not offer any systematic approach to "identify the best system design" (Stephenson 1995). Details on robust design methods in various phases can be found in (Fowlkes and Creveling 1995; Matthiassen 1997; Roy 1990).

4.4.3.2 Theory of Failure (Load Strength Interference)

This theory is based on the load bearing capacity of a component. To put it in simple words, if the strength of the component is more than the load borne by the component, it would not fail. But the complexity arises due to the distribution of the load and strength functions. Both, strength and load of component have their distributions (generally taken as normal distributions) and the interaction between them decides the probability of failure. Different types of interaction between distributions can be noticed based on the scatter. They are called as smooth loading ($\sigma_L << \sigma_S$), rough loading ($\sigma_L >> \sigma_S$) and loading of intermediate roughness ($\sigma_L \approx \sigma_S$) (Carter 1972). σ_L and σ_S are the standard deviations of the load and strength distributions respectively

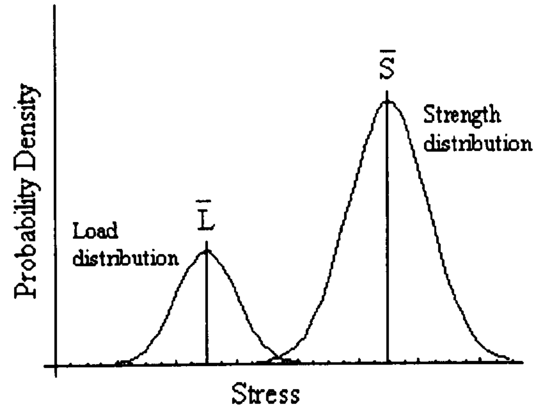


Figure 4.6 Load-Strength interference diagram

The two factors defined for this scatter of distributions are:

$$\text{SM (Safety Margin)} = \frac{\bar{S} - \bar{L}}{\sqrt{\sigma_S^2 + \sigma_L^2}} \tag{4.13}$$

and $\bar{S}$ and $\bar{L}$ are the means of the strength and load distribution respectively.

$$\text{LR (Loading roughness)} = \frac{\sigma_L}{\sqrt{\sigma_S^2 + \sigma_L^2}} \tag{4.14}$$

Both of these factors help understand the interference pattern of load and strength distributions and to determine the probability of failure (O'Connor 1995). This theory demands extensive data for calculating the expressions, i.e. the Load distributions and is therefore applicable to the later phases of design.

4.4.3.3 Fault Tree Analysis (FTA)

This is a top down approach to locate faults in a system. It is a qualitative approach but also helps carry out the quantitative estimation of the failure probability of the "Top event" (NUREG0492 1981). Various symbols, including logic gates are used in this method for representing information. The top event is the undesired event that represents the highest in the hierarchy of the FTA. With this event, the events that lead to this undesired event are found and the system is broken down into various low level events. The details of this method can be found in the reference on Handbook of Fault Tree Analysis (NUREG0492 1981).

4.4.3.4 Failure Modes and Effects Analysis (FMEA)

FMEA is a technique to identify modes, effects and causes of failures in components, products, processes and systems. It is a systematic approach to identify potential failures that have further implications. It represents a "powerful and documented method" of processing the subjective thinking and experience of engineers (Kara-Zaitri et al 1991). By the identification of failure modes, their causes and effects, one can work upon improving the design or fixing the problems to avoid the effects that failures can lead to.

The steps of FMEA are:

1. Identify the failure mode
2. Identify and list the effects of this failure mode
3. Find and list the causes of the failure mode
4. Calculate Risk Priority Number (RPN)
5. Describe corrective actions to counter the potential failures

A Risk Priority Number (RPN), an indicator of risk, is a product of three entities. They are:

Occurrence (O): This varies on a scale of 1 to 10. The ratings are given on the basis of occurrence of the failure mode identified.
Severity (S): The severity of a failure is represented by this factor. It also varies on a scale of 1 to 10.
Detectability (D): This may be defined as "the probability that the fault will go undetected before the failure takes place." (Booker et al 2001). The ratings vary from 1 to 10.

$$\text{RPN} = \text{O} \times \text{S} \times \text{D} \tag{4.15}$$

FMEA can be applied to the later part of design stage when the components and sub-assemblies are defined. FMEA differs from FTA in that FTA is a strictly top-down approach (O'Connor 1995).

Some other reliability methods that can be used in detail design phase are Preliminary Hazard Analysis (PHA), Fault Hazard Analysis (FZA) and Parts Counts approach (NUREG0492 1981).

4.4.4 Discussion on Reliability Methods

After studying various reliability methods, it is found that there is a requirement for a reliability method that would evaluate reliability of concept designs for all types of design. Current methods do not fulfil this requirement (though they claim to do so). Various methods studied in section 4.4.1 and their shortcomings are listed in Table 4.1. The shortcomings are discussed as follows:

1 - Specific applicability: The method can be applied only to specific application areas, for example in Table 4.1, Goel and coauthors (2003) have proposed their model for the area of chemical plants.

2 - Considers sub system/component level analysis: The method breaks down the system design into its subsystems and/or components for calculating the reliability. In Table 4.1, all of the methods except Verma and Knezevic's (1995) method are characterized by this drawback.

3 - Requires extensive data: The data requirement for evaluating reliability is "hard" (e.g. Failure rates, MTTR or MTTF values) as opposed to "soft" (subjective inputs). The methods that demand such extensive data are those by Goel et al (2003), Verma and Knezevic (1995), Ormon et al (2002), Nacthmann and Chimka (2003) and Yadav et al (2003).

4 - Complex in application: The method requires knowledge of other tools for its application. For example, Yadav et al's (2003) method requires complex fuzzy logic mathematics coupled with a Bayesian approach.

5 - Verification of methodology: The methods are judged not to have been verified to the extent that they can be accepted for application.

6 – Does not provide an objective output: The method does not finally provide ranks and scores of the concepts under consideration. These types of methods are proposed by Stephenson 1995, Covino et al 2000, Smith 2002 and Broadbent 1993.

Method by	**1**	**2**	**3**	**4**	**5**	**6**	**Notes**
Goel et al 2003	✓	✓	✓	✓			Uses optimisation technique
Broadbent 1993		✓			✓	✓	Considers failure modes of components
Verma and Knezevic 1995			✓	✓			Use of fuzzy logic
Ormon et al 2002		✓	✓				Triangular distribution
Nacthmann and Chimka 2003		✓	✓				Fuzzy triangular distribution
Yadav et al 2003		✓	✓	✓			Bayes theorem and fuzzy logic
Stephenson 1995		✓				✓	DFR method
Covino et al 2000		✓			✓	✓	DFR method
Smith 2002		✓			✓	✓	DFR method

Table 4.1 Summary of reliability methods in concept design

1 = Specific applicability

2 = Considers subsystem/component level analysis

3 = Requires extensive data

4 = Complex in application

5 = Verification of methodology

6 = Does not provide objective output

4.5 Physical Realizability

Various reliability methods have been discussed in section 4.4. As regards cost criterion is concerned, evaluating physical realizability is indirectly believed to be an indicator of cost in terms of probability of ease of realizing a concept. Some authors have researched on the cost estimating models in design. Hicks et al (2002) list various cost estimation models in their work. Their review indicates that the cost estimation methods exist only for manufacturing and machining phases. They have also proposed a cost estimation model to be used in the early design phase. The model works well when applied to designs consisting of standard components. For bespoke component cost estimation, they make use of various costs including machining costs and materials costs. Again this data is not available during the conceptual design phase and so this limits the applicability of the method in conceptual design. Park and Seo (2004) stress on the need for cost analysis models that are "easy-to-use and approximate methods to support cost-effective decision making in early product development.". Roy et al (2001) have researched on cost estimation specific to aerospace industry components. They have built a model for estimating total costs for building 3 D part models. Qualitative assessment is also included in their model but the model considers designers' experience while calculating costs.

It is believed that estimation of cost can only be done using prediction techniques in conceptual design phase. There can be some exception though, like for catalog designs. Henceforth, concepts are evaluated here in terms of physical realizability. Physical realizability refers to the ease with which the designs can be realised within the budget of cost and time. The easier it is to realize a concept, the cheaper a final product would be.

There has been very little research done on physical realizability. Research on physical realizability has been contributed by Asimov (1962) and White (1996). In fact, Pahl and Beitz (1996) assert to include realizability evaluation as one of the primary criteria to base "selection procedure" upon (see section 3.4.3). The realizability evaluation methods in design process are shown in Figure 4.7.

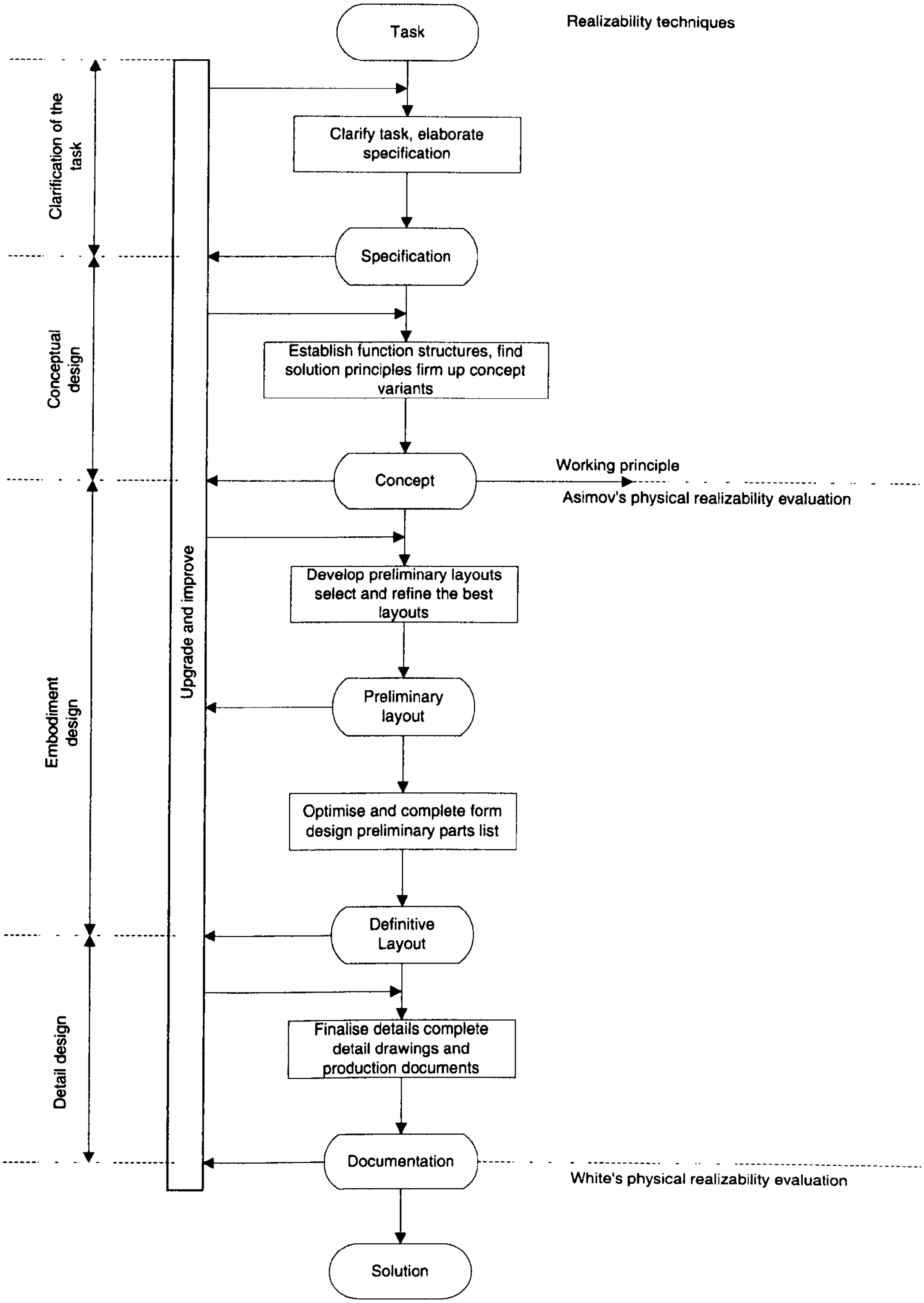


Figure 4.7 Realizability methods in design process (after Pahl and Beitz 1996)

Physical realizability by both, Asimov and White is now discussed. Eventually, since Asimov's physical realizability evaluation is applicable to the conceptual design phase, it is adopted for further investigation in this thesis.

4.5.1 Asimov's Model of Physical Realizability Evaluation

The idea of physical realizability has been proposed by Asimov in his book "Introduction to Design" (Asimov 1962). Though this idea had been proposed a long time ago, it has not been investigated yet (as per authors' knowledge).

Physical realizability has been coined by Asimov to represent ease of realizing an alternative (again an alternative represents a concept in this thesis) within the budget of cost and time. When considering a decision matrix, each alternative exhibits benefits and difficulties/consequences of realising it. Asimov mentions that after using a decision making method, one may come to a conclusion about the "Best" Alternative by listing all the benefits of an alternative. But even after doing so, one cannot be sure whether the alternative selected could be easily physically realized. This uncertainty may bind the decision making models to connect to one more criterion of evaluating alternatives, i.e. physical realizability.

The theory of physical realizability is based on the hypothesis that virtually any solution can be realised, if infinite amount of time and money is invested on the same. But clearly, companies face an opposite situation in the sense that they have limited resources available for all processes, including product development. Henceforth, Asimov has proposed to evaluate physical realizability of alternatives in the conceptual design phase. Details on Asimov's physical realizability and its quantitative aspects are reviewed in section 5.3.

4.5.2 Physical Realizability Evaluation by White

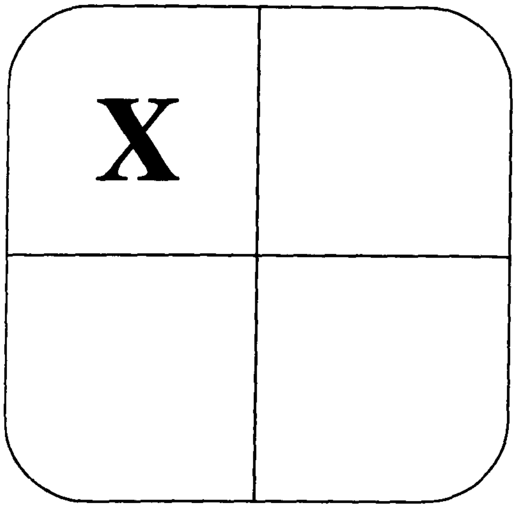
White (1996) has proposed a Design for Realizability framework during the design process. Though it has been proposed to be used during the preliminary design phases, the demand for data restricts it to be applied only to the later phases of design.

White has defined Design for Realizability (DFR) as "the task of inspecting the abstract design description with regard to the implementation resources (processes, operations, equipment, labor, and materials) required to construct the specified artifact." and that it is "a domain-independent framework for the integration of the design and realization phases of product development" (White 1996). Realization has been used in generic sense to refer to different types of artefacts ("hardgood" as furniture and "softgood" as software). For the purpose of hardgood products, realizability has been referred to as manufacturability.

White also adds that "the purpose of DFR is to provide the designer with a manufacturing expert's viewpoint of the design i.e., a realizability evaluation. The realizability task confronts the practicalities and possibilities of implementing a given design.". This statement indicates that DFR framework for hardgood (designing products) can be applied only when the detailed specifications of the designs are known for e.g. the type of manufacturing processes, material to be used and so on. This restricts the model to be used only during the detail design phase.

4.6 Closing Remarks

In this chapter, reliability and realizability methods have been reviewed. After reviewing various reliability methods, it is found that none of the existing methods can be applied to all types of designs in conceptual design phase. Hence, a method is proposed in chapter 5 that can satisfy this requirement. For realizability, the review indicates that Asimov's model of evaluating realizability (or physical realizability) serves the purpose and is adopted for further research. Asimov's model is also explored in chapter 5.



Validation Square

DRM
Prescriptive Study

Chapter 5

Investigating the Black Box of Reliability and Realizability

In this chapter, the Black boxes of reliability and realizability are investigated. The idea of Black box for decomposed design was discussed in section 2.4. The Black box with its inputs and outputs is shown in Figure 5.1. The input to this Black box is the designer's input of information and the output is the preference values of the decision matrix.

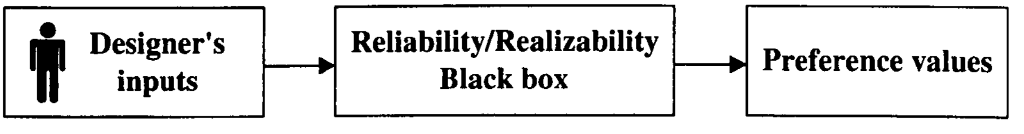


Figure 5.1 Reliability/Realizability Black box

This chapter explains the methodologies for evaluating reliability and realizability using the decision making models discussed in chapter 3 and reliability and realizability literature in chapter 4. Reliability evaluation methodology is proposed and realizability evaluation methodology is adopted from Asimov's work (Asimov 1962). This Chapter is the PS of DRM and covers the theoretical structural validity of Validation Square.

5.1 Black Box Constraints

To investigate the Black box, the constraints in which it should work are identified. All these constraints reflect the requirements that ideally reliability and realizability methodologies should fulfil. The requirements are listed as follows:

1. It should fulfil the required purpose i.e. it should be able to evaluate concepts with respect to reliability and realizability.

2. It should be able to process the qualitative information, so that both novice and experienced designers can use it. Qualitative or soft data (Sen and Yang 1998) refers to the subjective judgements and are relatively evaluated. Brintrup et al (2004) define qualitative data as "narrative information, observations, opinions, and beliefs of a given topic" and is subjective in nature. This means that the framework of information capture in the methodology should be flexible so as to allow qualitative information input.

3. It should be capable of being incorporated into a computer environment. The methodologies proposed here would to be of more assistance if they offer a possibility of being incorporated in a computer environment for example, Mistree and Muster's (1985) computer based approach for design.

4. It should provide an objective evaluation using the subjective inputs from the designers. The methodologies should process the designers' inputs and should provide an objective output which can be used for further judgements.

5. It should have the capability to process the complexity, when the number of alternatives is large. As the number of alternatives increase, the complexity also increases. The methodologies should be capable of handling this complexity.

6. It should be applicable to all types of designs i.e. original, adaptive, variant and catalog.

7. It should be based on the principles of engineering design. The reliability and realizability evaluation should of course be undertaken considering the engineering design rules.

Along with these, the methodology should also be easy to apply. Needless to say, designers will use the methodology only if it is easy to apply. Many of the above constraints combine to reflect the ease of applying the methodology. Keeping the above constraints in mind, the methodologies for reliability and realizability evaluation are now discussed.

5.2 Reliability Black Box

The Black box for reliability is now derived. In section 4.4.4, it was concluded that none of the currently available reliability methods can be applied to the conceptual design phase for all types of designs, for reasons discussed in the same section.

Considering the Black box of reliability in Figure 5.1, an equivalent generic method for reliability evaluation is shown in Figure 5.2. In this figure, the designer's input refers to the qualitative information input to the Black box. This information is captured and processed by the Black box and an output is provided in the objective form. As a result, the deliberation now shifts to these three parts of the methodology. i.e. information input, information capture and processing and objective output.

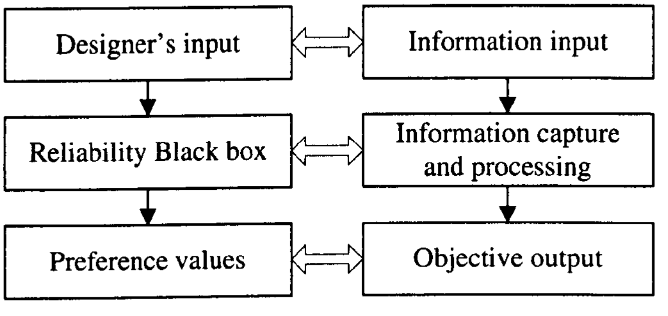


Figure 5.2 Generic reliability evaluation methodology

Since conventional reliability calculations are not possible in conceptual design phase, it is only through the prediction of the future state (through the use of decision making methods) that an objective output can be arrived at. Individual parts of the generic methodology in Figure 5.2 are discussed now.

- **Information input**

Once again, considering the standard definition of reliability of section 4.2, Reliability is:

"The ability of an item to perform a required function under stated conditions for a stated period of time" (BS 4778 1990).

It can be inferred from this definition that it is the performance of a required function (Please note that this is not the overall performance of an item, but only the performance of a function) over time that defines reliability. Based on the above, the information input obtained from the designer can be in the form of performance of function of the item that the concept represents. Again, due to lack of information, this can only be done through the prediction of future state of this concept that the designer foresees.

- **Information capture and processing**

The above information based on the performance of function of the concept can be captured and in turn processed to provide a useful output. The capture of information can be done in various ways, as studied in section 3.5. But since the information to be captured is in the qualitative form (which is a narrative input or subjective data in relative form, point 1 in section 5.1), the decision capture can be done using preference values in relative forms. The information capture in decision making methods was discussed in section 3.5. It was found that Pugh's concept selection, Pro/Con charts, AHP and Chen and Lee's (1993) method provide the easiest data capture. Preference values in relative forms are captured by Pugh's concept selection, AHP and Chen and Lee's method. Pugh's concept selection (section 3.4.1) and Pro/Con charts (section 3.4.4) do not provide an objective output. Additionally, Pugh's method requires a datum concept and is suitable only for holistic design evaluation. Hence these methods cannot be considered here for data capture. Chen and Lee's method (section 3.4.11) requires only simple relative inputs but it does not provide an objective output for judgement in terms of scores. Also, it is prone to the effects of condorcet n-tuple (discussed in section

5.4.1). Hence, AHP is adopted in this research due to its generic applicability and other advantages (discussed in section 5.2.1.2).

- **Objective output**

The objective output can be derived after the information has been processed using the AHP. To combine the data, SAW (section 3.4.2) or other scoring equations (section 3.4.7) can be used.

With the above constraints and generic methodology in mind, a methodology called Relative reliability risk methodology is now proposed. It is called relative because it takes relative inputs from designers. The word risk is used since the method does not provide "absolute" reliability measurements like conventional reliability methods do. The methodology helps to provide an objective output for the risk associated in terms of reliability with the concepts.

5.2.1 Relative Reliability Risk Assessment Methodology

Relative reliability risk methodology is derived from the generic reliability methodology of Figure 5.2. Its steps are listed in Table 5.1.

<table>
<tr><th>Generic reliability evaluation</th><th>Relative reliability risk methodology</th></tr>
<tr><td rowspan="2">Information input</td><td>Step 1. Consider function structure</td></tr>
<tr><td rowspan="2">Step 2. Obtain preference information on function(s) performance using AHP (Apply AHP)</td></tr>
<tr><td rowspan="2">Information capture and processing</td></tr>
<tr><td>Step 3 Apply entropy method to process information (Apply entropy method)</td></tr>
<tr><td>Objective output</td><td>Step 4. Objective output using SAW</td></tr>
</table>

Table 5.1 Relative reliability risk methodology

In a nutshell, the Relative reliability risk methodology is as follows. The input information consists of considering the function structure of the product. This is done to find the important functions performed by the product. Since the performance of function(s) is what reliability is about, the consideration of function structure would help list the important function(s) that the product would perform. The preference information is then captured from the designer in relative form as to how well would the function(s) be performed by a concept. This information is processed using the AHP math. Since, both information capture and processing can be done using AHP, it is a common step between the stages of information input and information capture and processing. Entropy method is then applied for further processing the data. Entropy method is a weight assigning method and the reasons for its adoption in this research are discussed in section 5.1.1.3. The objective output is obtained using SAW which was discussed in section 3.4.2. The final objective output is called as Relative Reliability Risk Index (R^3I). To understand the above steps, knowledge of function structures, AHP and entropy method is required. Henceforth, initially these are studied individually and then there relationship to this methodology is explained.

5.2.1.1 Functional Modelling

Establishing function structures is a part of systematic conceptual phase of design. In this thesis, Pahl and Beitz's (1996) function modelling is followed. It is the most commonly referred and convenient means of modelling functions. In conceptual design phase, the technical systems are represented using function structures before their solution principles are 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. Auxiliary functions indirectly help in achieving the overall function but can be equally important like main functions. To better understand function structures, an example of a common 3-axes horizontal lathe machine is used. The function structure of a lathe is shown in Figure 5.3 (Black box) and Figure 5.4 at different levels of abstraction.

Initially the overall function is laid down in which main task of the lathe is considered i.e. Machining W/P (Work piece) (shown in Figure 5.3). The conversion of matter, energy and signals takes place. The key for the icons and symbols used for functional modelling is given in Table 5.2.

When considered at a detailed level of abstraction, one arrives at a structure shown in Figure 5.4. The auxiliary functions are shown in dashed box and main functions are shown in bold boxes. Since here the functional modelling is done for a known product, a complex product like lathe could be modelled with ease but during the conceptual deign phase of new designs, it can be very subjective and challenging. Kirschman et al (1998) have proposed taxonomy for mechanical functions during such an activity to help designers during functional modelling. Automated computer support has also been investigated during this activity. Still function structures, though powerful in use, are not widely used in industry (Sridharan and Campbell 2005).

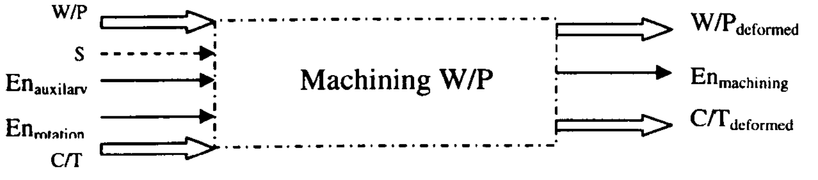


Figure 5.3 Black box for a function structure of Lathe

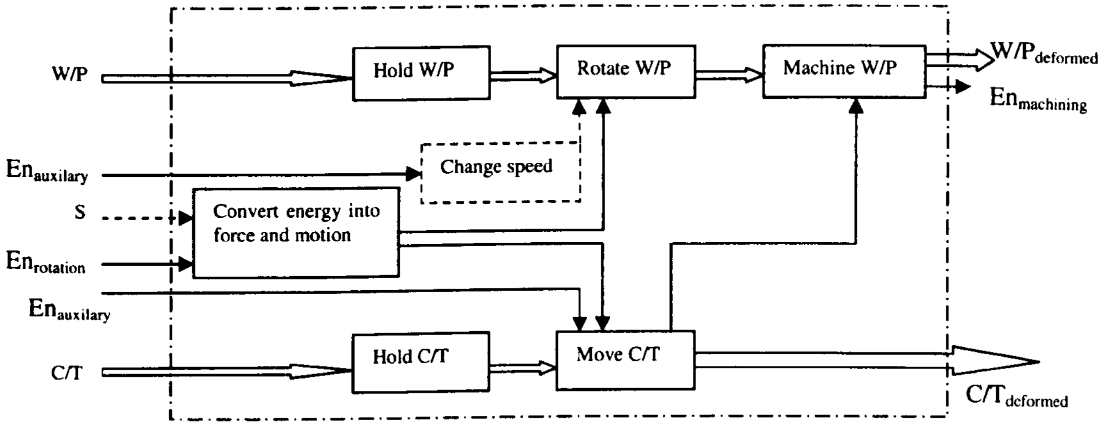


Figure 5.4 Function structure of a Lathe

Description	Icon	Symbol
Energy	——►	$En_{auxiliary}$, $En_{rotation}$, $En_{machining}$
Signal	- - - - - -►	S
Matter	⇨	W/P (Work piece), $W/P_{deformed}$, C/T (Cutting Tool), $C/T_{deformed}$

Table 5.2 Icons and symbols used for functional modelling

Hereafter, in all function structures, the symbol En_k is used for energy, M_k for matter and S_k for signal, where k is any positive integer.

5.2.1.2 Analytic Hierarchy Process

Analytic Hierarchy Process, developed by Saaty (1990), is a MADM tool that uses relative ratings using the pair wise comparison of components. The strength of this tool lies in utilising insight based qualitative information from the decision makers in the form of relative values. Some important advantages offered by AHP are:

1. Systematic approach

AHP structures the problem in a systematic fashion, making it easier to understand a complex problem. The problems are broken down into sub problems and a hierarchy is developed to apply AHP.

2. Hierarchy

Breaking the problem into a hierarchy helps identify criteria and sub criteria. Since the system is decomposed into various "sub-systems" as so on, it is easy to deal with simple entities thereby working on a complex system.

3. Information in relative form

AHP can handle relative assessment of components and provide an objective output. The strength of processing qualitative information makes it a very strong and widely accepted decision making tool.

4. Scale

The scale used in AHP is the ratio scale (scales discussed in Appendix A.2). This helps to relatively assess the elements at various levels. For using the ratio scale, the preferences can either be numeric or verbal. Verbal measurements are easier to obtain from the designers. The conversion of verbal to numeric scale is given in Table 5.4.

5. Consistency measurement

This represents one of the most important advantages of AHP. Consistency measurement in AHP helps maintain transitivity so that the decision maker cannot simply "get away" after applying the relative ratings. The designer's consistency is checked. This provides an indication as to how much serious/sincere a designer is in providing the relative preferences.

6. Generic applicability

AHP is a generic decision making tool and it has been applied to a wide variety of application areas, including management (Tam and Tummala 2001), medicine (Stutsker 1998; Sloane et al 2002) and engineering design (Yeo et al 2004; Zavbi and Duhovnik 1996).

To understand the application of AHP, a walkthrough example is undertaken along with the explanation of the method in this text. The example problem is a selection problem of a Temperature sensor.

Example problem: Selection of a Temperature sensor

Consider that a University's thermodynamics laboratory wants to purchase a temperature sensor for temperature measurement experiments. The alternatives available in the market are Thermistor, Platinum resistance thermometer and Thermocouple (Figure 5.5).

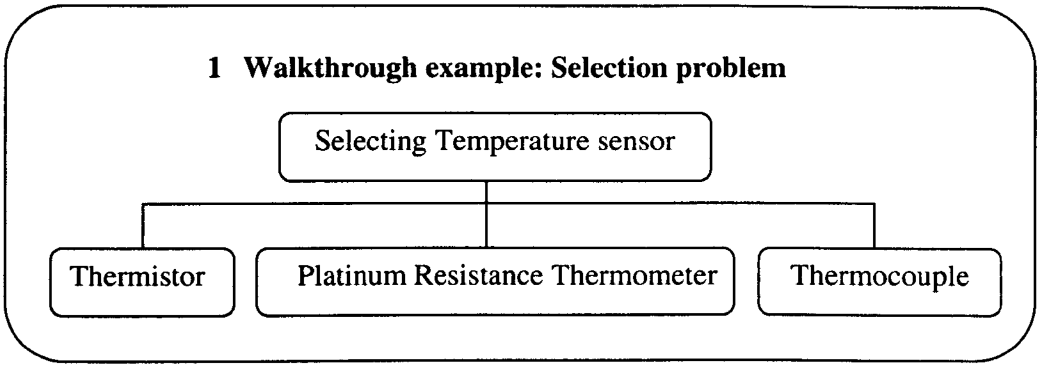


Figure 5.5 Selection of Temperature Sensor

Developing Hierarchy

A hierarchy is developed in which the main objective forms the highest level. The next lower level is occupied by the criteria and the next by sub-criteria and so on. The bottom most level of hierarchy is occupied by the alternatives available. In the case of Temperature sensor selection, the criteria on which the selection depends are Accuracy, Repeatability and Price of the sensor. Please note that this is a hypothetical situation where we limit the available alternatives and criteria to three only for the ease of explanation. In real world scenario, there could be more criteria and alternatives for this specific problem. The Hierarchy developed for Temperature sensor selection is shown in figure 5.6.

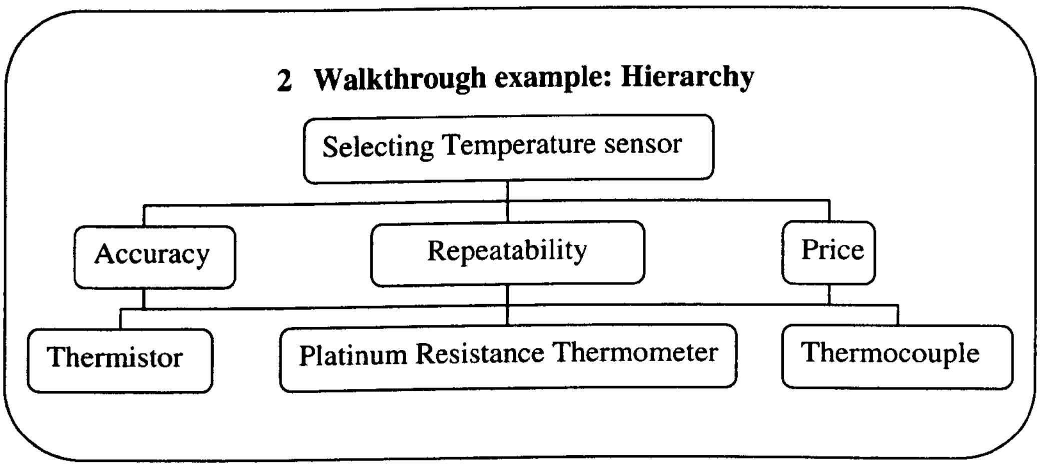


Figure 5.6 AHP Hierarchy of Temperature Sensor selection problem

Making comparisons

Once the hierarchy has been established, comparison matrices are formulated and comparisons of lower level property with respect to the property at upper level are done. Only the essential elements of AHP math are considered here and discussed. A lot of literature is available on AHP that deals with the mathematics of this method; the most accessible is by Saaty (2000).

Comparison matrix is one of the important parts of AHP. It is used to compare each alternative/criteria with the other using the pair wise comparisons (with respect to the property at the next higher level). An instance of such a comparison can be seen in Table 5.3, for example.

X	A_1	A_2	A_3	A_4
A_1	1	2	4	8
A_2	1/2	1	1/2	1/4
A_3	1/4	2	1	1/2
A_4	1/8	4	2	1

Table 5.3 AHP comparison matrix

In this table, X is any criteria and A_1, A_2, A_3 and A_4 represent the alternatives. An AHP comparison matrix is a reciprocal matrix where,

$$x_{ij} = 1/x_{ji} \tag{5.1}$$

In Table 5.3, relative comparison starts with column on the left. Each element in this column is compared with the top row i.e. one starts with the column element A_1 and compares it with the top row elements A_1, A_2, A_3 and A_4 and so on. In the example matrix shown, A_1 when compared to A_2 provides twice (2) more merits than A_2, four times (4) more merits than A_3, eight times (8) more merits than A_4. For the purpose of comparison, a numeric scale is used. This numeric scale has been proposed by Saaty (2000) for pair wise component comparison. The numeric scale intensities and their verbal equivalents are shown in Table 5.4.

Numeric scale intensity	Verbal equivalent
1	Equal importance
3	Moderate importance of one over another
5	Strong or essential importance
7	Very strong or demonstrated importance
9	Extreme importance
2,4,6,8	Intermediate values

Table 5.4 Saaty's ratio scale

Reciprocals of the numeric values in Table 5.4 during comparison are used when the element in the left hand column is less important (or provides less merits) than the element in top row. 0 can also be used when there exists no relation between the entities. The "importance" used in Table 5.4 is equivalent to "merits" used in Relative reliability risk methodology.

Referring back to the Walk through example, a top - down approach in hierarchy (Figure 5.6) for comparison is applied. All the criteria would be compared first, i.e. Accuracy, Repeatability and Price with respect to the objective i.e. Selecting Temperature sensor. Next, the alternatives are compared with respect to these criteria.

Comparison of criteria with respect to the objective is shown in Table 5.5. Next, all the three alternatives are compared with respect to each property at the level above it. There are three comparison matrices for these comparisons and are shown as Table 5.6, 5.7, and 5.8. In these tables, Ac = Accuracy, R = Repeatability, P = Price, PRT = Platinum Resistance Thermometer, T = Thermistor and TC = Thermocouple.

3 Walkthrough example: Criteria comparison

Sensor	Ac	R	P
Ac	1	3	1/2
R	1/3	1	1/3
P	3	3	1

Table 5.5 Comparison matrix for Objective

1 Walkthrough example: Sensor comparison for Accuracy

Accuracy	PRT	T	TC
PRT	1	5	5
T	1/5	1	2
TC	1/5	1/2	1

Table 5.6 Comparison matrix for Accuracy

5 Walkthrough example: Sensor comparison for Repeatability

Repeatability	PRT	T	TC
PRT	1	5	6
T	1/5	1	2
TC	1/6	1/2	1

Table 5.7 Comparison matrix for Repeatability

6 Walkthrough example: Sensor comparison for Price

Price	PRT	T	TC
PRT	1	1/3	1/2
T	3	1	2
TC	2	1/2	1

Table 5.8 Comparison matrix for Price

Evaluating priorities

Once the relative ratings have been done, these ratings are processed to provide a priority for each alternative. The priority represents a relative measure for each alternative with respect to particular criteria. Saaty proposes to calculate priorities using the exact or the approximate method (Saaty 2001).

Approximate method for evaluating priorities, as advocated by Saaty, consists of the following steps. Add the column elements and divide each column element by its total. As an example, consider Table 5.3, in which four Alternatives A_1, A_2, A_3 and A_4 were compared with respect to criteria X. Adding the column sum and dividing each column element by column sum for this table is shown in Table 5.9. This is called as the normalized matrix.

X	A_1	A_2	A_3	A_4
A_1	1/1.875	2/9	4/7.5	8/9.75
A_2	0.5/1.875	1/9	0.5/7.5	0.25/9.75
A_3	0.25/1.875	2/9	1/7.5	0.5/9.75
A_4	0.125/1.875	4/9	2/7.5	1/9.75

Table 5.9 Normalized matrix for AHP Approximate method

After obtaining a normalized matrix, average of each row is calculated and this average is the priority for each of the alternatives A_1, A_2, A_3 and A_4. The priorities for Table 5.9 are shown in Table 5.10. The total of priorities equals to 1.

X	A_1	A_2	A_3	A_4	Priority
A_1	1/1.875	2/9	4/7.5	8/9.75	0.50
A_2	0.5/1.875	1/9	0.5/7.5	0.25/9.75	0.13
A_3	0.25/1.875	2/9	1/7.5	0.5/9.75	0.14
A_4	0.125/1.875	4/9	2/7.5	1/9.75	0.23
		Total			1.00

Table 5.10 Calculating priorities in AHP Approximate method

The exact method (Saaty 2001) for evaluating priorities consists of multiplying the matrix several times with itself. Each time, the power of the matrix is increased by 1. For example, a matrix M is multiplied first as M*M, then M*M*M and so on. If the matrix is consistent (consistency is explained in the next subsection), there is no need to raise the power of matrix further. Every time the matrix is multiplied, each row sum is taken and then normalized by the total sum. This represents the priorities. The matrix multiplication is stopped only when the priorities obtained in the $(n+1)^{th}$ power is within the set accuracy of decimal places of the n^{th} power. Having obtained these n priorities, their average is taken to represent the priorities of the alternatives. In this thesis, this data processing is achieved using the Expert Choice software. The priorities obtained for Table 5.10 using Expert Choice software are shown in Table 5.11.

	Priorities
A_1	0.584
A_2	0.105
A_3	0.119
A_4	0.192
Total	1.000

Table 5.11 Priorities obtained using Expert Choice

For the walkthrough example of sensor selection, the priorities are obtained, both for the criteria and alternatives. For criteria, the priorities obtained with respect to the objective are listed in Table 5.12

7 Walkthrough example: Criteria priorities

Criteria	Priorities
Accuracy	0.333
Repeatability	0.140
Price	0.528

Table 5.12 Priorities for criteria in Sensor selection problem

Similarly, priorities for three alternatives PRT, T and TC are obtained and are shown in Table 5.13. These priorities of alternatives are called as local priorities.

8 Walkthrough example: Alternative priorities

Alternative	Criteria		
	Accuracy	Repeatability	Price
PRT	0.709	0.726	0.163
T	0.179	0.172	0.540
TC	0.113	0.102	0.297

Table 5.13 Local priorities for alternatives in Sensor selection problem

Calculating Overall priorities

To find the overall priorities (also called as Global priorities) of the alternatives, SAW (section 3.4.2) is used as a scoring method. In Table 5.13, the priorities of alternatives represent the elements x_{ij} of a decision matrix. The priorities in Table 5.12 represent he weight w_i of the criteria and the overall priority for each alternative is obtained using the formula:

$$F(A_j) = \sum_{i=1}^{m} w_i x_{ij} \quad (5.2)$$

The overall priorities calculated for the three alternatives are shown in Table 5.14. From the priorities, it can be concluded that Platinum Resistance Thermometer would be the first choice for the University's Thermodynamics Laboratory. This is followed by Thermistor and then by Thermocouple.

A note on consistency evaluation in AHP

One of the important advantages of AHP, the reason it has been adopted as a part of the methodology proposed in this research, is the consistency issue.

Consistency in providing relative measures indicates the behaviour of the decision maker. AHP provides a measure to predict as to how much consistent the decision maker has been in providing his ratings.

9 Walkthrough example: Overall Alternative priorities

Sensor selection problem	Overall Priority
Platinum Resistance Thermometer	0.423
Thermistor	0.368
Thermocouple	0.208

Table 5.14 Overall priorities for alternatives in Sensor selection problem

Consistency can be measured in AHP because the decision maker is asked to provide some redundant relative data. The decision maker can decide not to provide this redundant data and still the priorities could be calculated. But this redundancy of ratings from the decision maker helps to evaluate the consistency. To understand consistency issues, consider an example of a matrix shown in Table 5.15 which consists of three Alternatives A_1, A_2 and A_3 and the comparison is done with respect to criteria X.

X	A_1	A_2	A_3
A_1	1	3	6
A_2	1/3	1	2
A_3	1/6	1/2	1

Table 5.15 A completely consistent comparison matrix

Table 5.15 is an example of a completely consistent comparison matrix. The matrix is declared completely consistent because of the following reasons. Consider second row of the matrix. A_1 provides 3 times more merits than A_2. Similarly, A_1 provides 6 times more merits than A_3. Expressing it in quantitative terms,

$$A_1 \equiv 3\,(A_2) \tag{5.3}$$

and $A_1 \equiv 6(A_3)$ (5.4)

It follows from Equations (5.3) and (5.4) that

$$A_2 \equiv 2(A_3) \quad (5.5)$$

Note that in Table 5.15, row three and column 4, A_2 provides 2 times more merits than A_3, which was also concluded from Equations (5.3) and (5.4). Hence, the matrix is declared consistent and that the decision maker is said to have been consistent in providing the comparison ratings. Consistency condition in a matrix is represented by:

$$x_{ij} \equiv x_{ik} * x_{kj} \quad (5.6)$$

Having discussed this, it is not always necessary that the decision maker has to be consistent in providing the relative ratings. This happens especially when there are a large number of alternatives to compare. In that case, it may not be possible for the decision maker to maintain consistency. Inconsistency "seeps into" the comparison ratings provided by the designer and AHP helps to provide a quantitative measure of the degree of inconsistency.

The quantitative estimate that reveals the amount of inconsistency is called the Consistency Ratio (CR). CR is a ratio of Consistency Index (CI) for the matrix in question and the Consistency Index (CI_{random}) of a randomly generated matrix. This random matrix represents a matrix when random judgements had been made using the scale in Table 5.4.

$$CR = \frac{CI}{CI_{random}} \quad (5.7)$$

The value of CI_{random} has been established by Saaty (Saaty 2001) and is listed in Table 5.16 for matrices of various sizes

Size of matrix	*1*	*2*	*3*	*4*	*5*	*6*	*7*	*8*	*9*	*10*
CI_{random}	0.00	0.00	0.52	0.89	1.11	1.25	1.35	1.40	1.45	1.49

Table 5.16 CI_{random} values

Since CI_{random} values are available, CR can be evaluated once CI value is available. CI can be calculated as follows. Consider a matrix in Table 5.17. It consists of 3 alternatives and the relative ratings for them have been provided. This is an inconsistent matrix as it does not satisfy Equation (5.6). Inconsistency is now calculated for this matrix using the prescribed procedure proposed by Saaty.

X	A_1	A_2	A_3
A_1	1	2	3
A_2	1/2	1	3
A_3	1/3	1/3	1

Table 5.17 An inconsistent matrix

Using these ratings, the priorities are calculated. The priorities are shown in Table 5.18.

X	A_1	A_2	A_3	Priorities
A_1	1	2	3	0.528
A_2	.50	1	3	0.333
A_3	.33	.33	1	0.140

Table 5.18 Priorities for an inconsistent matrix

Using these priorities, column A_1 is multiplied by the priority of A_1, column A_2 by the priority of A_2 and so on. The result is shown in Table 5.19.

X	A_1	A_2	A_3	Row Total
A_1	0.52	0.66	0.42	1.6
A_2	0.26	0.33	0.42	1.01
A_3	0.17	0.10	0.14	.41

Table 5.19 Comparison matrix obtained after multiplying priorities with the columns

Once again, the row total is done. The row total is shown in Table 5.19. This row total is divided by the priorities obtained as follows:

$$\begin{pmatrix} 1.6 \\ 1.01 \\ .41 \end{pmatrix} \div \begin{pmatrix} .52 \\ .33 \\ .14 \end{pmatrix} = \begin{pmatrix} 3.07 \\ 3.06 \\ 2.92 \end{pmatrix}$$

Let this new matrix obtained be T,

$$\mathrm{T} = \begin{pmatrix} 3.07 \\ 3.06 \\ 2.92 \end{pmatrix}$$

Saaty (2000) proposes to calculate CI using the equation,

$$\mathrm{CI} = \frac{\lambda_{max} - n}{n-1} \qquad (5.8)$$

Where λ_{max} is the principle eigenvalue of the matrix and is calculated using,

$$\lambda_{max} = \sum_{i=1}^{n} t_{i1} / n \qquad (5.9)$$

In Equation (5.9), t_{i1} are the elements of column matrix T. So,

$$\lambda_{max} = \frac{3.07 + 3.06 + 2.92}{3}$$

$$\lambda_{max} \approx 3.02$$

Hence, $\mathrm{CI} = \dfrac{\lambda_{max} - n}{n-1} = 0.01$ (5.10)

CI_{random} from Table 5.16 for n = 3 is 0.52,

Hence, from Equation (5.7), CR = 0.02, which signifies a good consistency. Saaty prescribes that the value of CR to be less than 0.10. (Saaty 2000). Normally, the use of software Expert Choice makes it easier for data processing and directly provides the CR of the judgements. In this research, Expert Choice has been used for calculating the CR value.

5.2.1.3 Entropy Method for Calculating Weights

Entropy method (Sen and Yang 1998; Hwang and Yoon 1981) is a MADM method to calculate the weights of attributes. The roots of entropy method lie in the information theory by Shannon (1948). It utilizes the information content of the decision matrix to calculate the weights of the attributes and therefore it does not require any extra input for evaluating weights. The entropy V_i of the set of normalized outcomes of attribute i is given by

$$V_i = -\gamma \sum_{j=1}^{n} y_{ij} * (\ln y_{ij}) \qquad (5.11)$$

for all i, (i = 1 to m represents attribute and j = 1 to n represents alternatives) where γ is constant which is calculated using

$$\gamma = 1 / \ln (n) \qquad (5.12)$$

and y_{ij} is a normalized element of the decision matrix. The weights are then calculated using the equation

$$w_i = (1-V_i) / (\sum_{i=1}^{m} (1-V_i)) \qquad (5.13)$$

5.2.1.4 Relative Reliability Risk Assessment Methodology

Relative reliability risk methodology is revisited so as to explain the relationship of this methodology with the function modelling, AHP, entropy and SAW method.

Step 1 Consider function structure

Considering the function structure helps to identify the important functions that the product is intended to perform. Since reliability is about performance of function over time, then how a concept (being a potential product) would perform important functions over time would help to evaluate reliability of the concept. The idea of important functions is crucial here. Although main functions discussed earlier represent important functions that fulfil the objective function directly, auxiliary functions can be important too. Hence, the designer's role in identifying important functions is critical here and there are chances of subjectivity involved in this step.

Since use of function structure is not widespread in industry (Sridharan and Campbell 2005), there are chances that function structures might not have been developed by the designers. In case systematic methodology for generating function structures has not been followed, identification of important functions can also be done without the use of function structures. Function structures are proposed as a part of this methodology so as to provide ease of identifying the important functions. The important functions obtained are supplied to the Step 2 of methodology as criteria for AHP application.

Step 2 Apply AHP

Steps 2, 3 and 4 of Relative reliability risk assessment come into picture because AHP has been modified to suit to the requirements of this research. If only AHP were used, Step 2 was sufficient to indicate the final objective output. But the increase in number of steps does not mean that the information sought from the designer also increases. Instead, number of steps has been increased to reduce the amount of information sought from the designer.

AHP application has been explained in section 5.1.2.2. In this methodology, alternatives available to the designers are concepts and criteria here are the important functions from the function structure. Like AHP, alternatives are compared with respect to various criteria. But unlike AHP, criteria are not compared with respect to the overall objective.

The output of application of this step is the local priorities obtained for the concepts for various functions.

Step 3 Apply entropy method

Entropy method, as already discussed, is a weight assigning method. Entropy method is used in this methodology due to the following reasons:

1. First and foremost, entropy method can evaluate weights from the preference values directly without any extra input required from the designers.

2. Secondly, Sen and Yang (1998) mention that the experienced designer are capable of directly assigning weights to the attributes. But since this methodology is meant to benefit both the novice and experienced designers, entropy method is used to evaluate weights so that weights can be automatically calculated.

3. Thirdly, the number of ratings required during the AHP decreases if this method is adopted. The number of relative ratings a designer has to provide during AHP application is given by:

   $$N_{ratings} = m*n*(n-1)/2 + m*(m-1)/2 \quad (5.14)$$

   Where, m is the number of criteria and n the number of alternatives. Since entropy method can calculate weights using the decision matrix, the second part of Equation (5.14) on right hand side can be removed by taking the relative ratings only for the alternatives with respect to criteria. Designers then would be required to provide less information.

4. Finally, since it is the functions that represent criteria, the designer may find it more difficult to assign weights to them since they all may appear equally important to the designer.

The result of this step would be the weights w_i of the criteria (functions in this case). Although entropy method is logically seen as a solution for assigning weights in this methodology, other weight assigning techniques (see Appendix A.2) are also used as a part of this methodology while addressing the validation issues of this research in chapter 7.

Step 4 Provide objective output

After application of Step 3, the information available is processed using SAW to obtain an objective output. Although AHP also uses SAW to provide an objective output, it has been explicitly considered here as a separate step in this methodology. The final output is called as Relative Reliability Risk Index or R^3I (called as "R cubed I").

$$R^3I_j = \sum_{i=1}^{m} w_i * y_{ij} \text{ for all } j. \quad (5.15)$$

Consideration of important functions as criteria and evaluation of objective output on their basis represents an aggregrate contribution of all the important functions of a concept in satisfying the overall function. This is also discussed during the validation issues in the thesis in chapter 7. SAW method of providing an objective output is also compared to other methods in chapter 7. Since this methodology provides the final output as R^3I, the methodology is also called as R^3I approach or R^3I methodology. Next, an illustration of the application of R^3I methodology is done on the example of seat suspensions.

5.2.2 Example for Illustration of R^3I Methodology

An illustration of application of R^3I methodology is undertaken here. The example, shown in Figure 5.7, is the seat suspension mechanism for the off-highway vehicles. It has been taken from Hurst (1991). Hurst had considered this example to illustrate the effectiveness of using spreadsheets for concept selection. There are six concepts A, B, C, D, E and F as shown in Figure 5.7. The example represents a situation where concepts can only be evaluated using qualitative information. This example has also been discussed in Mamtani and Green (2006a).

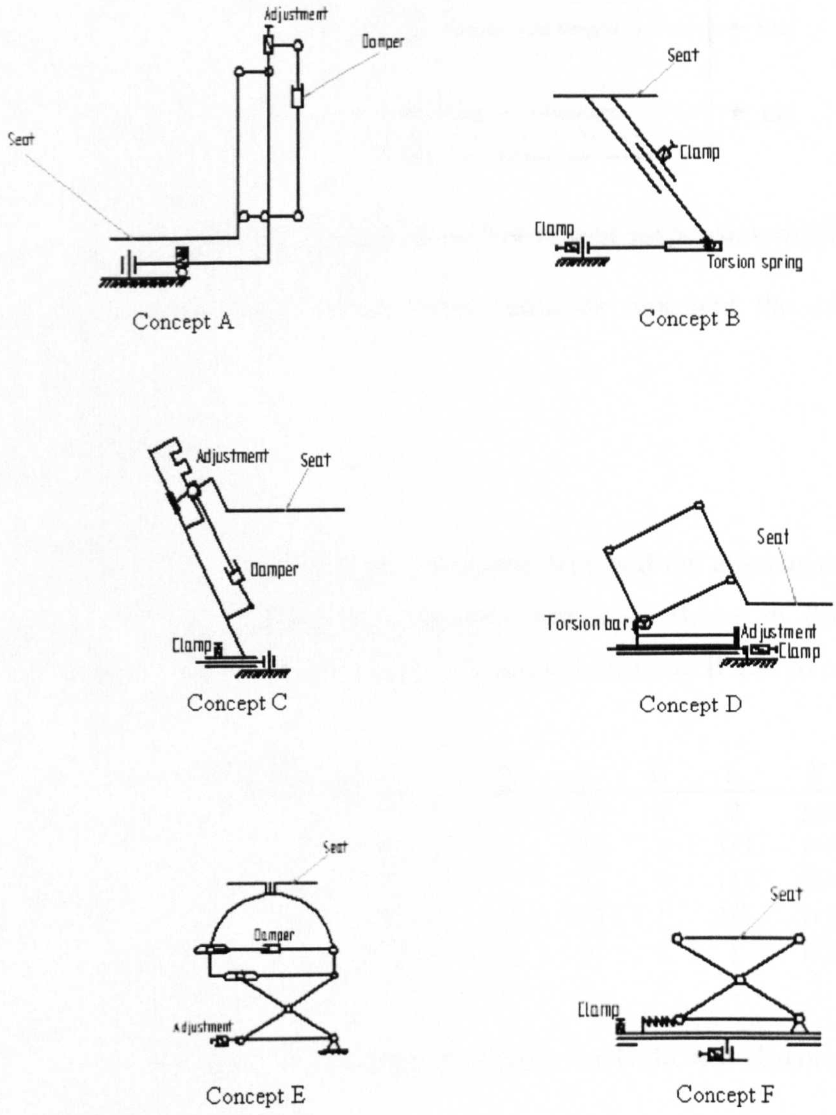


Figure 5.7 Concepts of seat suspensions for off-highway vehicles (after Hurst 1991)

Step 1 Consider function structure

The function structure established for seat suspensions is shown in Figure 5.8. Essentially, three important functions are considered in the structure. They are Hold seat, Dampen vibrations and Adjust seat height. The flow of matter, energy and signals

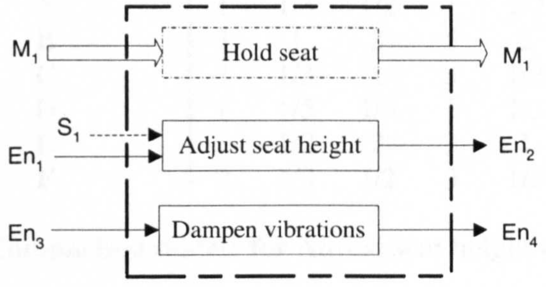


Figure 5.8 Function structure of seat suspension mechanism

is shown in the figure. These three functions represent the criteria during AHP application.

Step 2 Apply AHP

AHP is applied to the functions considered here and the alternatives are compared on the basis of each function. Comparison matrices are shown in Tables 5.20, 5.21 and 5.22. In the matrices, A, B etc refer to concept A, concept B and so on.

Hold seat	A	B	C	D	E	F
A	1	5	3	3	2	1/3
B	1/5	1	1/3	2	1/3	1/4
C	1/3	3	1	3	1/3	1/4
D	1/3	1/2	1/3	1	1/5	1/5
E	1/2	3	3	5	1	1/2
F	3	4	4	5	2	1

Table 5.20 Comparison matrix for Hold seat (Incon: 0.06)

Dampen vibrations	A	B	C	D	E	F
A	1	5	3	5	1/2	3
B	1/5	1	1/3	1	1/5	1/2
C	1/3	3	1	3	1/4	3
D	1/5	1	1/3	1	1/5	1/2
E	2	5	4	5	1	5
F	1/3	2	1/3	2	1/5	1

Table 5.21 Comparison matrix for Dampen vibrations (Incon: 0.03)

Adjust seat height	A	B	C	D	E	F
A	1	1/3	1/2	1	1/2	1/2
B	3	1	3	5	2	3
C	2	1/3	1	3	1/2	2
D	1	1/5	1/3	1	1/3	1/3
E	2	1/2	2	3	1	3
F	2	1/3	1/2	3	1/3	1

Table 5.22 Comparison matrix for Adjust seat height (Incon: 0.04)

A cell, say cell (2,3) where 2 refers to the row and 3 refers to the column of Table 5.20, of comparison matrix is filled using the following question:

With respect to performing the function "Holding seat" over time, how much is Concept A better/worse than Concept B?

All the comparisons are done using this question for the three functions considered. The inconsistencies are also laid down with each matrix considered (shown as Incon. in the table titles). After the application of AHP, a priority matrix is obtained (Table 5.23). These are the local priorities of the concepts.

	A	B	C	D	E	F
Hold seat	0.233	0.061	0.103	0.047	0.190	0.365
Dampen vibrations	0.271	0.053	0.145	0.053	0.396	0.082
Adjust seat height	0.082	0.352	0.157	0.061	0.229	0.119

Table 5.23 Priority matrix for seat suspension concepts

Step 3 Apply entropy method

The weights for the three functions are calculated using the information from Table 5.23. Entropy method is applied and Equations (5.11 – 5.13) are used to calculate the weights. The weights obtained after the application of the method are shown in Table 5.24.

Functions	Weight (w_j)
Hold seat	0.33
Dampen vibrations	0.41
Adjust seat height	0.25

Table 5.24 Weights obtained for seat suspension functions after applying entropy method

Step 4 Provide objective output

After calculating the weights and priorities, R^3I (Table 5.25) value is obtained using equation (5.15. As is evident from Table 5.25, concept E has the best R^3I value among all the available ones. Also the concepts that may be screened out from the further consideration are the ones that have low R^3I value, which are concepts B and D. A higher R^3I value indicates low risk in terms of reliability of the concept. Concepts are rank ordered as shown in Table 5.25.

	A	B	C	D	E	F
R^3I	0.209	0.130	0.133	0.052	0.283	0.184
Rank	2	5	4	6	1	3

Table 5.25 R^3I and ranks for seat suspensions concepts

A spinoff from R^3I methodology

Application of R^3I methodology also reveals the strengths or weaknesses of concepts with respect to functions. The priorities in Table 5.23 are used to plot a graph, called as Concept Functionality Graph (CFG). It is shown in Figure 5.9. The figure is meant to depict a clear picture of strengths and weaknesses of different concepts with respect to the functions considered. For example, concept E is very strong in dampening the vibrations whereas concept D is weak in satisfying this function.

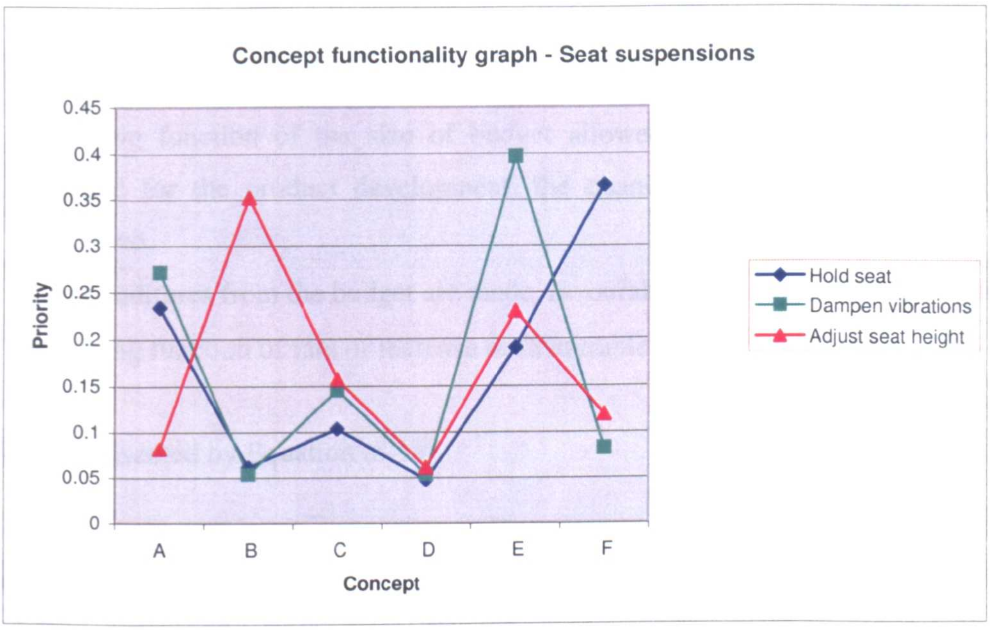


Figure 5.9 CFG for seat suspension concepts

5.3 Asimov's Physical Realizability

In section 4.5, physical realizability was defined and some models were discussed. Considering the generic Black box of reliability in Figure 5.2, the Black box of realizability should follow a similar model in which information input takes place, information is captured and processed, thereby providing an objective output. The constraints applicable to realizability methodology are similar to that of reliability methodology in section 5.1. An available methodology by Asimov (1962) has been adopted for realizability evaluation. The methodology is in agreement to the generic methodology of Figure 5.2. The derivation of the methodology is discussed here as follows.

5.3.1 Theory of Physical Realizability

Ease of realizing any alternative is denoted by Intensity of belief (L). It is the belief that a particular task can be accomplished successfully (here it is the belief that the alternative can be realized). Intensity of belief is a function of various factors. They are:

- Increasing function of favourable evidence that the sub problems can be resolved. The sub problems here referred to are the stumbling blocks that would pose difficulties to realize the alternative.
- Increasing function of the size of budget allowed. Of course, the more budget allocated for the product development, the chances are bright for realizing the alternative.
- As expenditures from the budget are made, favourable evidence will accumulate
- Increasing function of rate of increase of favourable evidence

This is represented by Equation (5.16)

$$L = f\left[E, X_B\left(\frac{dE}{dX}\right)_0\right] \tag{5.16}$$

Here,

E = Amount of favourable evidence

X = Current expenditure at any instant during a stage of product development

X_B = Allowed budget (in terms of time and money), and

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

This is a theoretical relationship of the Intensity of belief. A quantitative evaluation of ease of realization is now studied.

5.3.2 Quantitative Aspects of Physical Realizability

Mathematically, a probability is evaluated that represents ease of realization of an alternative. L is evaluated using Bayes probability theorem. L, in terms of probability is:

$$L = P(A_i \mid X_B) \tag{5.17}$$

P (A_i) is the probability that the "proposition" that alternative A_i is physically realizable is true. And P (A_i | X_B) refers to the conditional probability that alternative 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:

$$L = P(A_i \mid E\, X_B) \tag{5.18}$$

This equation refers to the proposition that A_i is true given the budget X_B and the evidence E. Using Bayes theorem of conditional probability, equation (5.18) can be expressed as:

$$P(A_iE \mid X_B) = P(A_i \mid EX_B) * P(E \mid X_B) = P(E \mid A_i\, X_B) * P(A_i \mid X_B) \tag{5.19}$$

Or,

$$P(A_i \mid EX_B) = P(A_i \mid X_B) * \frac{P(E|A_iX_B)}{P(E|X_B)} \tag{5.20}$$

Here,

$P(E|A_iX_B)$ = Probability that evidence E is true given the proposition that A_i is true and budget X_B, and

$P(E|X_B)$ = Probability that evidence E is true given the budget X_B

To make the equation manageable, the probabilities are changed to odds in favour. Odds in favour are represented by,

$$O(y) = \frac{P(y)}{P(\bar{y})} \tag{5.21}$$

O (y) represents the ratio of probability of success to probability of failure. Using Equation (5.21),

$$O\,(A_i \mid EX_B) = \frac{P(A_i \mid EX_B)}{P(\bar{A}_i \mid EX_B)} \tag{5.22}$$

So, Equation (5.20) becomes,

$$O\,(A_i \mid EX_B) = \frac{P(A_i \mid X_B)}{P(\bar{A}_i \mid X_B)} * \frac{P(E \mid A_i X_B) * P(E \mid X_B)}{P(E \mid \bar{A}_i X_B) * P(E \mid X_B)} \tag{5.23}$$

$$= O(A_i \mid X_B) * \frac{P(E \mid A_i X_B)}{P(E \mid \bar{A}_i X_B)} \tag{5.24}$$

To avoid using the multiplicative factors, logarithmic forms are used, which is represented by:

$$E_{V_{A_i}}\ (A \mid X) = 10 \log_{10} O\,(A \mid X) \tag{5.25}$$

$E_{V_{A_i}}$ is measured in decibels. Hence Equation (5.24) becomes:

$$E_{V_{A_i}}\ (A_i \mid EX_B) = E_{V_{A_i}}\ (A_i \mid X_B) + E_{V_{A_i}}\ (E \mid A_i X_B) \tag{5.26}$$

If many evidences $E_1, E_2 \ldots\ldots\ldots E_p$ are available then,

$$E_{V_{A_i}}\ (A_i \mid E_1 E_2 \ldots\ldots\ldots E_p\, X_B) = E_{V_{A_i}}\ (A_i \mid X_B) + \sum_{j=1}^{p} E_{V_{A_i}}\ (E_j \mid A_i X_B) \tag{5.27}$$

for an Alternative A_i. The expression on the left hand side of Equation (5.27) is called as Level of confidence. The evidence in decibels and the percent of Level of confidence are related as shown in Table 5.26.

Favourable		Unfavourable	
Evidence Decibels	**Level of Confidence Percent**	**Evidence Decibels**	**Level of Confidence Percent**
∞	100	- ∞	0
20	99	- 20	1
13	95	- 13	5
9.5	90	- 9.5	10
3	66	3	33
0	50	0	50

Table 5.26 Relation between Evidence and Level of confidence (after Asimov 1962)

5.3.3 Example for Illustration of Physical Realizability Methodology

To illustrate the methodology for physical realizability evaluation, the same example of seat suspensions (Figure 5.7) has been considered here. After observing the seat suspension concepts, a major problem identified in realizing any of the seat suspension concepts in Figure 5.7 would be realizing the linkages. This indicates that it is one of the major problems that one would face for realising seat suspension concept within the budget of cost and time. For the sake of simplicity, only one problem has been considered. To evaluate the Level of confidence, consider Equation (5.26)

$$E_{V_{A_i}} (A_i \mid EX_B) = E_{V_{A_i}} (A_i \mid X_B) + E_{V_{A_i}} (E \mid A_i X_B)$$

Here the left hand side of this equation would result in a Level of confidence in decibel values. The right hand side of this equation consists of two parts. The first part is $E_{V_{A_i}}$ $(A_i \mid X_B)$ and the second is $E_{V_{A_i}}$ $(E \mid A_i X_B)$. These both would be individually calculated to provide a final value of Level of confidence in decibels. For the sake of illustration, an assumption of the available budget is made. The budget X_B = 50000.00 £. This budget indicates the budget of cost and time of product development in terms of cost as a single scalar quantity and is arbitrarily selected for the sake of calculation. Let the first part be P_1,

$$P_1 = E_{V_{A_i}} (A_i \mid X_B) = 10 \log_{10} O(A \mid X) = 10 \log_{10} \frac{P(A_i \mid X_B)}{P(\bar{A}_i \mid X_B)}$$

To evaluate P_1, consider concept A. P (A_i | X_B) represents the probability that concept A is realizable with the allocated budget and

$$P(\bar{A}_i \mid X_B) = 1 - P(A_i \mid X_B)$$

and $P(A_i \mid X_B)$ = Probability that the concept is physically realizable with the allocated budget. For concept A, if

$$P(A_i \mid X_B) = 0.9$$

$$P(\bar{A}_i \mid X_B) = 0.1$$

$$P_1 = 10 \log_{10} \frac{0.9}{0.1} = 9.5 \text{ decibels}$$

Let the second part of Equation (5.27) be

$$P_2 = E_{V_{A_i}} (E \mid A_i X_B) = 10 \log_{10} O(E \mid A_i X_B) = 10 \log_{10} \frac{P(E \mid A_i X_B)}{P(E \mid \bar{A}_i X_B)}$$

And $P(E \mid A_i X_B)$ for concept A is evaluated by asking the question: Imagine that the prototype built of concept A linkage passes the test (A_i in budget X_B), what would be the probability of linkage in concept A passing the laboratory test in earlier stages? For simplicity, this probability is assumed to be equal to 1 because normally when the prototype (in future) would pass the test, the sample is earlier stages would pass the test as well.

$P(E \mid \bar{A}_i X_B)$ can be calculated by asking the following question: Imagine that the prototype built of concept A linkage fails ($\bar{A}_i$ in budget X_B), what would be the probability of linkage in concept A still passing the laboratory test in earlier stages?

For concept A, if this probability is 0.1, then

$$P_2 = 10 \log_{10} \frac{1.0}{0.1} = 10 \text{ decibels}$$

Hence for Concept A, $E_{V_{A_i}}$ (A_i | EX_B) for concept A is given by,

$$E_{V_{A_i}} (A_1 \mid EX_B) = P_1 + P_2 = 9.5 + 10 = 19.5 \text{ decibels}$$

From Table 5.26, this is equivalent to a probability of 99% Level of confidence, which is considered high. It shows that concept A has got high chances of being realised within the allocated Budget of 50000 £.

Similarly for other concepts, Table 5.27 lists various probabilities, final Level of confidence percentages and the ranks of the concepts for seat suspensions. Here all the probability values and inputs are provided for the sake of calculations only and have been provided by the author for methodology illustration.

	A	B	C	D	E	F
$P(A_i \mid X_B)$	0.9	0.6	0.4	0.5	0.8	0.9
$P(\bar{A}_i \mid X_B)$	0.1	0.4	0.6	0.5	0.2	0.1
$P(E \mid \bar{A}_i X_B)$	0.1	0.5	0.7	0.5	0.2	0.2
$E_{V_{A_i}}$ (A_i | EX_B) (db)	19.5	4.8	-0.2	3	13	16.5
L	**99%**	**73%**	**27%**	**33%**	**95%**	**97%**
Rank	**1**	**4**	**6**	**5**	**3**	**2**

Table 5.27 Physical realizability values for seat suspensions concepts

5.4 Limitations of the Methodologies

Both, R³I and physical realizability evaluation by Asimov offer certain limitations. They are discussed here for each methodology individually.

5.4.1 Limitations of R^3I Methodology

- Time consumption

Application of AHP requires numerous relative inputs from the decision maker. This may have an overall effect of increasing the time taken by the decomposed design evaluation approach. As discussed in section 1.6, the decomposed evaluation methodology may have an effect of increasing the time locally of design evaluation in conceptual design phase but it is the total calendar time of product development that is significant to the companies.

Lindahl (2005) states that a method should reduce the total calendar time of product development to be accepted by the companies. Although R^3I might have a tendency to slightly increase the time locally in the conceptual design phase, the methodology is hoped to decrease the total calendar time of the product development. This is because a structured evaluation method results in a decreased ambiguity, faster communication and fewer false starts (Ulrich and Eppinger 2000).

- Function structures

Functional modelling is based on systematic prescription of design and it forms the first step in R^3I methodology. Since functional modelling is not extensively used in industry, it may act as a limitation to the use of this methodology. But it has already been discussed (section 5.2.1.1) that the goal of this step is to identify important functions, which can also be done even if functional modelling has not been explicitly performed.

- Problem of Condorcet n tuple in paired component comparisons

Saari and Sieberg (2004) have raised issues concerning the reliability of pairwise comparisons. They show that various ranks obtained using pairwise comparisons change due to the presence of what is called the condorcet n tuple. Condorcet n tuple for 3 alternatives A_1, A_2 and A_3 is formed by,

$A_1 > A_2 > A_3$,

$A_2 > A_3 > A_1$ and

$A_3 > A_1 > A_2$

for three criteria where n = 3. This is because each of the available alternatives ranks the best for one criterion. This has an effect of creating a tie among the ranks for these three alternatives.

The presence of condorcet n tuple induces errors into the decision making process and thereby leads to arriving at false rank orders of the alternatives. Saari has proposed to solve this problem using a method equivalent to calculating the borda count. The method requires calculating the effect of each of the individual pairs with respect to a criterion. Dym et al (2002) have also realised a similar situation and proposed to use Pairwise Comparison Charts, called as PCC, for removing the effect of condorcet tuples from the decision making process.

The problem of condorcet tuple is not recognised here as being applicable to this methodology, although it might have effects in other pairwise comparison methods. This is because of the following reasons. In the above situations, all the weights of criteria are considered to have an equal importance so that a nullification of effects of an alternative can occur while considering the holistic picture. Secondly, here the preferences do not have any intensity associated with them so that that condorcet tuples can occur. But in R^3I methodology, AHP has intensities associated with the preference so that a nullification effect cannot occur in the above manner.

- Problem of rank reversal in AHP

AHP has been criticized for the phenomenon of rank reversal (Dyer 1990). Rank reversal means that rank orders obtained by using AHP change when alternatives are added or deleted from the decision making problem. Dyer (1990) proposes to formulate a supermatrix to solve this problem of rank reversal. But Dyer quotes that this supermatrix "requires responses from the decision maker that are numerous and ambiguous", henceforth this would not be a good way of solving this problem.

Saaty (1990) has also addressed the problem of rank reversal and proposed methods to preserve ranks so that the ranks do not change when an alternative is introduced or deleted from the scenario. The methods for rank preservation are:

1. By using an ideal mode of AHP relative measurement:

This is based on the reasoning by Salo and Hamalainen (1997) that "the fundamental reason for the occurrence of rank reversals in the relative measurement mode is that the local priorities at the lowest level of the hierarchy are normalized so that they add up to one". In the ideal mode, the local priorities of alternatives obtained for each criterion are divided by the maximum local priority available (of ideal alternative). Once this has been done, any new alternative added could be compared to this ideal alternative so that the ranks are preserved. But this still does not appear to be a proper cure to the problem.

2. By using the absolute measurement mode:

In this measurement mode, scales similar to the one used in Pahl and Beitz's evaluation process (section 3.4.3) are used for measuring intensities. Their verbal equivalents can be derived. But then no relative measurements are done. The ratings are obtained on the basis of scales (although these scales are derived using relative measurements itself) to perform an absolute measurement of all alternatives with each criteria. But obtaining scale has been prescribed as a task for the experienced decision makers and again the information capture is not easy in this case.

Since convergence and divergence activity (like Pugh's method discussed in section 3.4.1) does not form a part of this methodology, alternatives have not been added or deleted to the decision problem in hand. Hence, the problem of rank reversal has been avoided. Still, if alternatives are added or deleted, then the ideal mode of relative measurement is suggested to solve the problem of rank reversal to some extent.

5.4.2 Limitations of Physical Realizability Assessment Methodology

- Allocation of budget X_B

As noticed from Equation (5.26) for evaluating the Level of confidence, X_B is the budget allocated for the product development. Although this is a vector quantity of cost and time, Asimov suggests converting it into a scalar quantity by converting time into cost. But this parameter offers two problems:

1. Firstly, in any environment, industrial or laboratory, conversion of time into costs is not an easy activity. This might involve to consider resources used during the product development activity and hence it is a tedious task to be undertaken.

2. Secondly, in case of laboratory experiments, providing a numeric value for this parameter can be very problematic (although a value of X_B has been assumed for illustration of application of this methodology on the seat suspension example).

- Providing evidences as probabilities

One of the probabilities to be provided by the Designer during the application of physical realizability methodology is $P(E \mid A_i X_B)$. This is obtained by asking the question: Imagine that the prototype built of concept passed the test (A_i in Budget X_B), what would be the probability of concept experimental set up passing the laboratory test in earlier stages? Answering to provide this probability can be tough because normally one would expect that if the prototype finally worked then the experiment in the initial stages of design would have definitely worked. Here this probability value has been assumed to be 1.

- Defining problems

During the application of this methodology on an example in section 5.3.3, the problem considered was realizing of linkage. This is on the grounds of assumption that this problem would be a common problem for all the concepts to be realizable. However, Asimov suggests exploring each concept and finding problems of realizing it in a tree structure following the problems with solutions, solutions with sub problems and so on. Here, the problems are defined as those common problems that would be faced by all the concepts in being realized.

5.5 Closing Remarks

In this chapter, Relative reliability risk assessment and physical realizability methodologies have been explored. The requirements that a method should ideally satisfy have been listed. Both the methodologies are studied and applied to the example of seat suspension concepts. Their limitations are discussed and solutions to the limitations are suggested, wherever possible. After studying both the methodologies, following inference can be made with respect to the requirements listed in section 5.1:

1. The methodologies have been logically derived from the rules of reliability, realizability and engineering design and so they intend to satisfy the requirements of the purpose. Validation issues of the methodologies in chapter 7 also address this issue.

2. The methodologies make use of qualitative information with the designers.

3. These methodologies show potential to be incorporated into a computer environment. AHP has already been incorporated into Expert Choice software. Also, neither methodology requires a prior knowledge of the decision making methods for applying them.

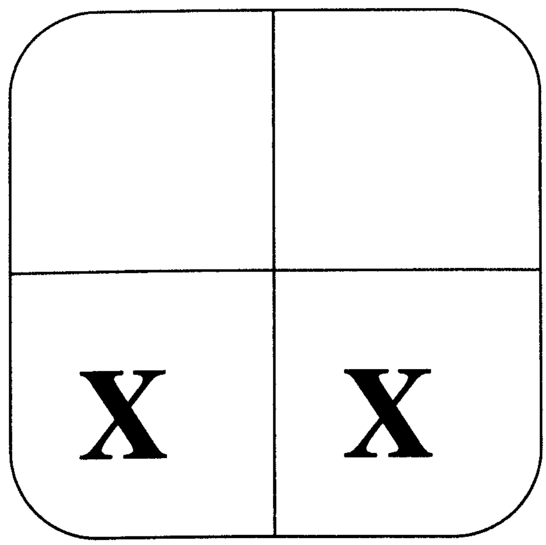
4. The methodologies provide an objective output to rank order the concepts on the basis of subjective inputs from the designers.

5. The methodologies can process the complexity, when the number of alternatives is large. This is again due to the decomposed design evaluation approach.

6. The methodologies have the potential to be applied to all the types of designs as they demand only qualitative data.

7. These methodologies have been derived considering the engineering design rules.

Although both the methodologies satisfy the requirements stated in section 5.1, their ease of application can be fully tested only when they are applied to an industrial context by the designers.



Validation Square

DRM
Descriptive Study II

Chapter 6

Verification of Relative Reliability Risk Methodology

Relative reliability risk assessment methodology is applied on various examples in this chapter. The chapter has been titled as Verification and not Validation because it does not ideally tests or evaluates the Reliability risk evaluation methodology proposed in chapter 5. The validation issues are considered separately in chapter 7. The methodology is applied on four examples in this chapter. Three of these examples are the designs developed by students in the university and one example represents an industry problem from Terex, Scotland. Each of the examples is studied in detail and methodology is applied on all of them. The outcome of methodology application for each example is discussed and finally, a discussion on methodology application is done. In this chapter, Steps 3, 4 and 5 of Validation Square are followed. The chapter also represents a part of the DRM, DS II.

6.1 Examples from the University Laboratory

An overview of the examples considered in this chapter is as follows. The three examples of design developed in the university workshop are Carr pack, Positive chair and Ab board. Carr pack is a design of a carrier and packer system that has been proposed to help the dentists place and pack the powder substance into the root canal. Positive chair is a design of a flexible support for the elderly. Though there are chairs available in the market that help the elderly in providing comforts, this design is a step forward and the product has been proposed after studying the market trends in this area.

Ab board is an example from the sports area in which the product is intended to be used along with the ubiquitous swiss ball for an effective use of swiss ball for workouts. Ab board represents a similar design like Carr pack and its requirements were felt after a strong observation of the daily chores of life.

Carr pack and Ab board represent examples of original designs. Positive chair reflects an adaptive design. All of these products have been designed by novices (students here) who have gained knowledge through literature and interviews with the related people in their respective product areas of work. Many illustrations of these examples are included in this chapter. They all represent the novices' thoughts and views of conceptual design.

6.2 Industry Example

An example from industry has also been considered in this chapter for the application of R^3I approach. This is an example from Terex, a manufacturing company in Scotland. Terex is a manufacturer of earth moving rigid and articulated trucks. Terex usually designs products using the proprietary items available in the market. This is similar to the catalog design discussed in section 4.3.

Designers at Terex faced a problem of selecting a transmission system for one of their trucks. Number of transmission system options available to them was three. They performed the selection process using Pugh's approach. To do so, various criteria were listed. One of the important criteria for selection was reliability. Since, the designers' already had the field data for reliability of these three transmissions; they could provide the preference values for reliability criterion with ease.

The availability of field data provides a scope for applying the R^3I approach on this example and comparing it with the data. Since the transmission systems are proprietary items the application of methodology on this example does not ideally tests it. The transmission systems are treated as conceptual designs. Important functions of transmissions were listed after discussion with the company designer and methodology was then applied.

The failure data for these three transmission system was obtained from Terex. Again, the definition of failure here refers to the one undertaken in this thesis (section 4.2). Hence, the failure data of Transmission systems when their function performance started degrading was collected from Terex designers. The results are discussed in section 6.7. All of the examples considered reflect the diversity of application of this methodology. The examples are listed in Table 6.1.

Example	Experiment environment	Application area	Design type	Designer
Carr pack	Laboratory	Medical	Original	Novice
Positive chair	Laboratory	Medical	Adaptive	Novice
Ab board	Laboratory	Sports	Original	Novice
Transmissions	Industry	Mechanical	Catalog	Novice/Experienced

Table 6.1 Examples used for Verification of R^3I methodology

6.3 Purpose of Verifying the R^3I Methodology

The application of the methodology on the examples considered in this chapter is hoped to transpire the following characteristics of the methodology:

- Simplicity of applying the methodology
- Ease of data capture using designer's qualitative information
- Generic nature of the methodology to be applied to various areas

A good rapport with the designers was established before applying the methodology. Their design concepts were studied. A definition of Reliability was provided before the designers applied the methodology. They were only asked to provide the relative inputs for the comparison matrices in R^3I methodology and the whole method was not explained to them. The ease of data capture and simplicity of method could be perceived through observation of designers' actions and inputs.

6.4 Carr Pack

Carr pack stands for a Carrier packer system. This is a design of a small medical product to be used by the dentists. This design project was undertaken by a student in the final year of B Eng, Product Design Engineering. The product has been proposed to help dentists place the calcium hydroxide powder or MTA (Mineral Trioxide Aggregate) into the root canal and pack the same efficiently and effectively. Currently it is done using a dovegan carrier, which though carries the powder into the root canal, does not help in packing the powder. The use of gutta percha tips (small sticks) and tweezers help pack the powder into the root canal. This whole procedure creates lot of problems for dentists. This is because firstly, loading the powder into dovegan carrier is not easy. Secondly, the small size of these "sticks" poses a problem of fitting into the root canal and then manoeuvre there. Due to all these difficulties, a tool was designer to load, carry and pack the powder into the root canal.

6.4.1 Carr Pack Concepts

Four concepts were generated for the design of Carr pack. Concept A for Carr pack is shown in Figure 6.1. In this concept, a rod acts as a ram to push the powder in a small curved cylinder. The pusher rod is a cored wire which has sufficient strength to pack the powder and is flexible enough to bend at the curve. The curved neck of the device is meant to help easily transfer the material from the device to the root canal. The eye-rings at the neck of this device help the users to conveniently hold the device and push the rod to pack the powder. Loading of the powder in this design is done using a hole provided at the ejector side of the device (shown in Figure 6.2). The powder can be manually filled and a sliding cover is provided to close the hole. The device converges into a tip at its front end to provide ease of placing it into the targeted area.

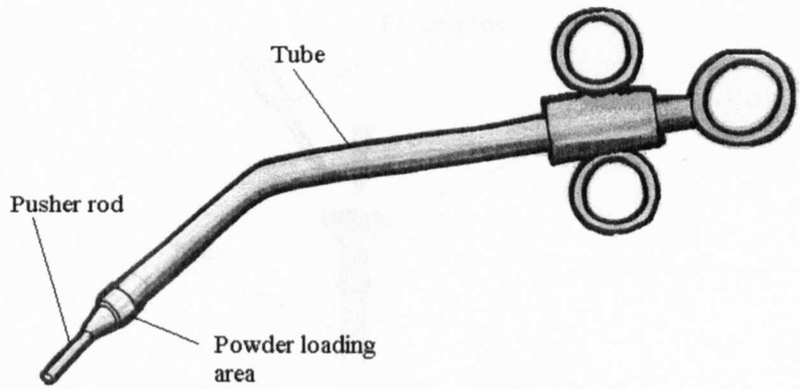


Figure 6.1 Concept A for Carr pack

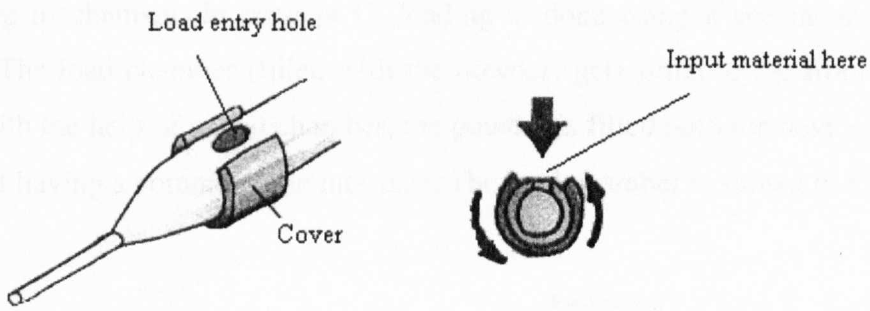


Figure 6.2 Twist cover loading entry for Carr pack concept A

Concept B is shown in Figure 6.3. It consists of a pusher rod that acts as a ram to pack the powder. It is similar to a medical syringe except for a curve at the front end of the tube. The loading of the device is done through the holding end of the pusher rod as shown in the Figure 6.4. A funnel can be used to fill the powder.

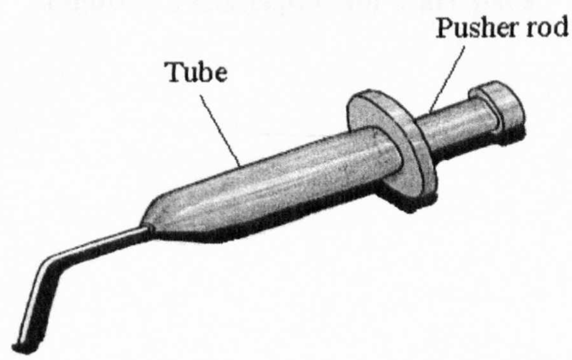


Figure 6.3 Concept B for Carr pack

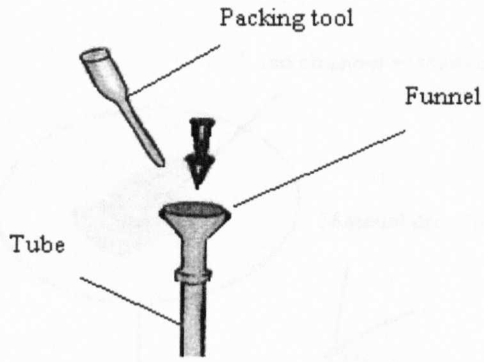


Figure 6.4 Loading device for Carr pack concept B

The idea of concept C (Figure 6.5) is similar to concept B, the only difference being in the loading mechanism. In concept C, loading is done using a special modular load chamber. The load chamber (filled with the powder) gets fitted to the front end of the device. With the help of a load chamber, the powder is filled onto the device through an attachment having a common hole interface. The load chamber is shown in Figure 6.6.

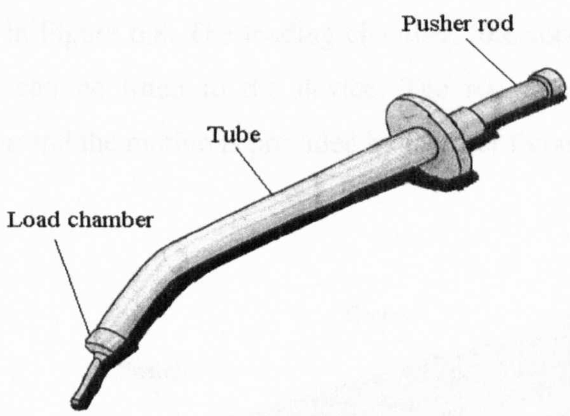


Figure 6.5 Concept C for Carr pack

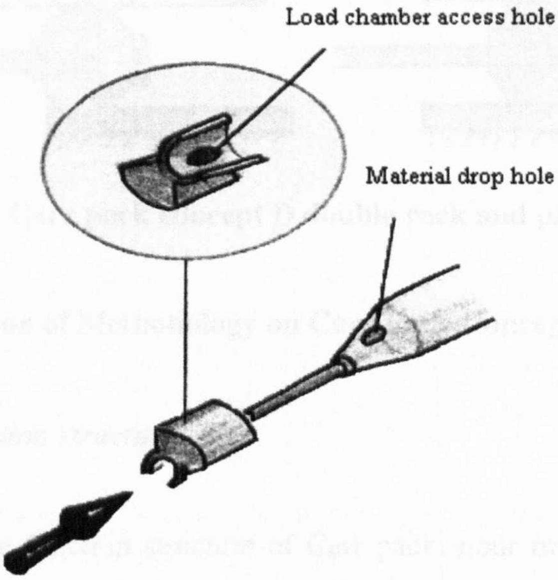


Figure 6.6 Loading method for Carr pack concept C

Concept D (see Figure 6.7) works on the principle of rack and pinion mechanism. The rack and pinion provides an advantage of doubling the users' motion to the rod. The mechanism is shown in Figure 6.8. The loading chamber, like concept C, is a separate modular unit, which can be fitted to the device. The rod that works as a "ram" reciprocates in a sleeve and the motion is provided by the user through the switch on top of the device.

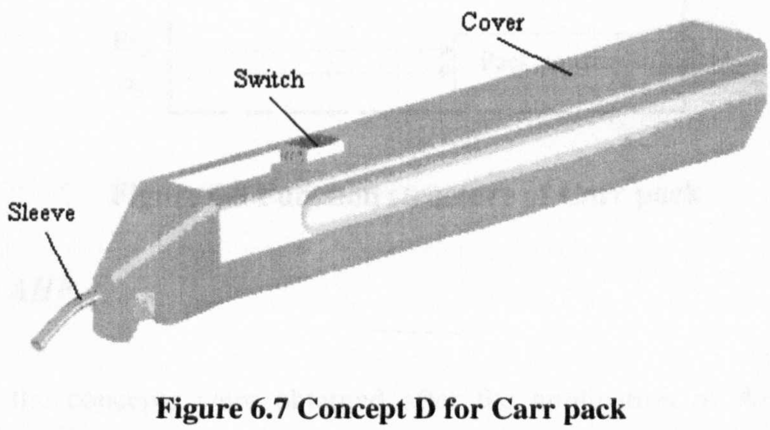


Figure 6.7 Concept D for Carr pack

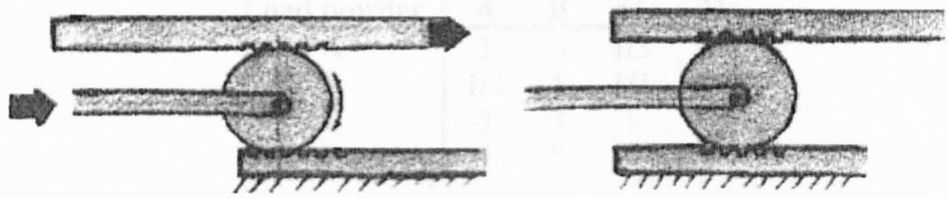


Figure 6.8 Carr pack concept D double rack and pinion system

6.4.2 Application of Methodology on Carr Pack Concepts

Step 1 Consider function structure

Figure 6.9 depicts the function structure of Carr pack. Four important functions were considered. They are Load powder (powder/MTA here), Hold powder, Pack powder and Fill powder. The conversion of mass, energy and signals are shown in Figure 6.9. These functions were considered after discussion with the designer of Carr pack. They were deemed as important functions by the designer.

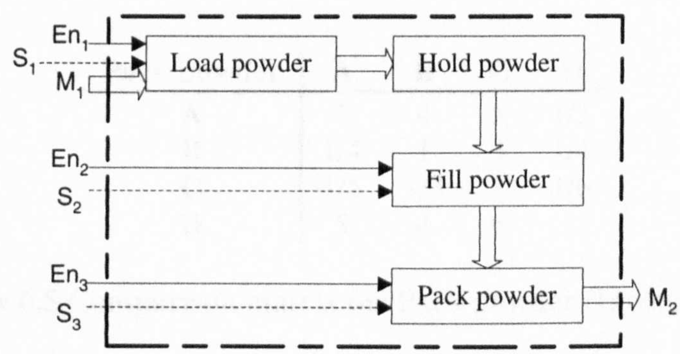


Figure 6.9 Function structure of Carr pack

Step 2 Apply AHP

Priorities of the concepts were obtained after the application of AHP. The novice designer was asked to provide the relative values of the concepts using the verbal scale of AHP (Table 5.4) for each function. The comparison matrix for Load material, Hold material, Fill material and Pack material are shown in Tables 6.2, 6.3, 6.4 and 6.5 respectively.

Load powder	A	B	C	D
A	1	3	1/3	1/4
B	1/3	1	1/3	1/5
C	3	3	1	1/4
D	4	5	4	1

Table 6.2 Comparison matrix for Load powder (Incon: 0.09)

Hold powder	A	B	C	D
A	1	3	1	1/5
B	1/3	1	1/3	1/7
C	1	3	1	1/5
D	5	7	5	1

Table 6.3 Comparison matrix for Hold powder (Incon: 0.03)

Fill powder	A	B	C	D
A	1	1/3	3	1/4
B	3	1	3	1/4
C	1/3	4	1	1/5
D	4	4	5	1

Table 6.4 Comparison matrix for Fill powder (Incon: 0.09)

Pack powder	A	B	C	D
A	1	4	5	1/5
B	1/4	1	3	1/4
C	1/5	1/3	1	1/6
D	5	4	6	1

Table 6.5 Comparison matrix for Pack powder (Incon: 0.14)

Steps 3 & 4 Apply entropy and SAW method

Priorities, R^3I values and ranks obtained for the concepts are shown in Table 6.6.

	A	B	C	D	Weight
Load powder	0.134	0.072	0.233	0.562	0.218
Hold powder	0.151	0.062	0.151	0.635	0.292
Fill powder	0.134	0.233	0.072	0.562	0.218
Pack powder	0.246	0.110	0.054	0.590	0.271
R^3I	**0.169**	**0.114**	**0.125**	**0.590**	
Rank	**2**	**4**	**3**	**1**	

Table 6.6 Priorities, R^3I and ranks for Carr pack concepts

Observations

The ranks obtained in Table 6.6 show that concept D has less risk associated with it in terms of reliability. The R^3I for concept D, 0.590, outweighs any other with a huge margin. Actually, the application of this methodology took place after the designer finished the concept design stage and had selected this concept for further design. The novice designer found it easier to input information using relative scale of AHP. Also the relative qualitative preference provided by the designer was in the range from Equal importance (1) to Very strong importance (7). Very strong importance was only used once during the whole evaluation. The inconsistency of providing the qualitative information was under limits except for one function i.e. Pack powder in Table 6.5. The inconsistency for this function is 0.14, which is a little higher than the acceptable limit.

6.5 The Positive Chair

The Positive chair is a design of a flexible support addressing the needs of elderly. It is a fully adjustable piece of dynamic, therapeutic equipment, that offers the users a range of healthy adjustable postures, minimizes musculo-skeletal damage and other health problems including pressure sore risk for chair bound users, which most chairs on the market inflict on their users. A student in B Eng Product Design Engineering undertook this design project. The concepts that were generated by the student are presented in the next sub section.

6.5.1 Positive Chair Concepts

Concept A of Positive chair is shown in Figure 6.10. This type of chair can offer various positions to a user. The positions are shown in Figure 6.11. Note a central pivot in the chair in Figure 6.11. The rotation takes place about this pivot. The chair is controlled by the cables in tension fixed to drum with spring to constrain motion. The rotation of the drum is responsible for various positions of the chair. Clockwise motion of the drum will recline the chair and vice versa. The mechanism is shown in Figure 6.12. Sitting to standing transfer is smooth in this chair.

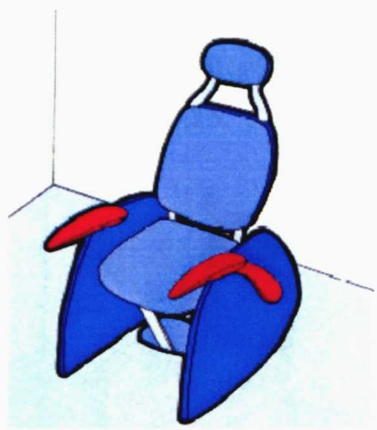


Figure 6.10 Concept A for Positive chair

Figure 6.11 Positions offered by Positive chair concept A

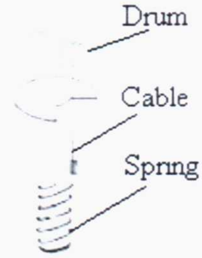


Figure 6.12 Mechanism in Positive chair concept A

Concept B is shown in Figure 6.13. This concept is developed with the help of linkages using an actuator and spring. Various positions are offered by this concept (Figure 6.14). The mechanism is shown in Figure 6.15.

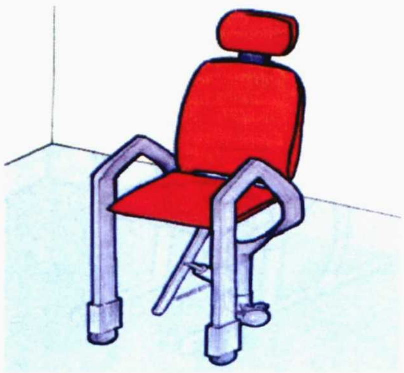


Figure 6.13 Concept B for Positive chair

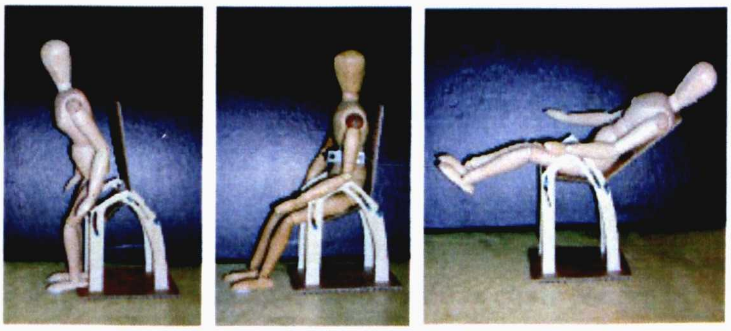


Figure 6.14 Positions offered by Positive chair concept B

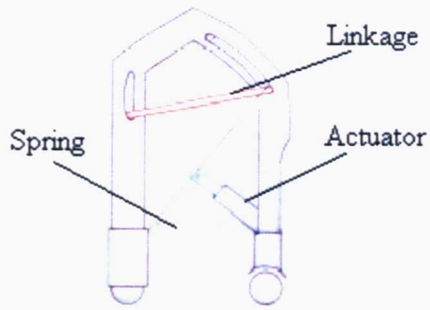


Figure 6.15 Mechanism in Positive chair concept B

Concept C (Figure 6.16) is mainly advantageous for locking the seat into various positions. Its linkage design can be seen in Figure 6.17. Again, like concept B, it has an actuator and a linkage to control its movement.

Figure 6.16 Concept C for Positive chair

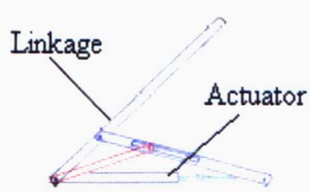


Figure 6.17 Mechanism in Positive chair concept C

Concept D (shown in Figure 6.18) is a chair in which the users can take different postures by shifting their body weight. By displacing the centre of mass, the users can take different positions by the requisite amount of movement of the chair. Various positions have been shown in Figure 6.19.

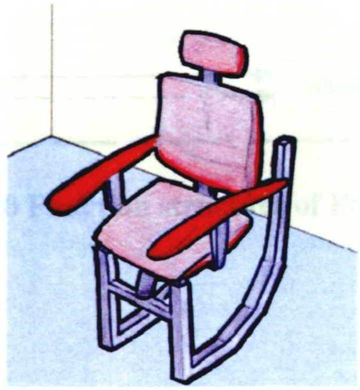


Figure 6.18 Concept D for Positive chair

Figure 6.19 Positions offered by Positive chair concept D

6.5.2 Application of Methodology on Positive Chair Concepts

Step 1 Consider function structure

Figure 6.20 depicts the function structure of Positive chair. The important functions considered are Provide comfort (comfortable support), Adjust (adjusting chair), Recline and Sitting to standing transfer. The conversion of mass, energy and signals are shown in Figure 6.20. These functions were considered after discussion with the designer of Positive chair.

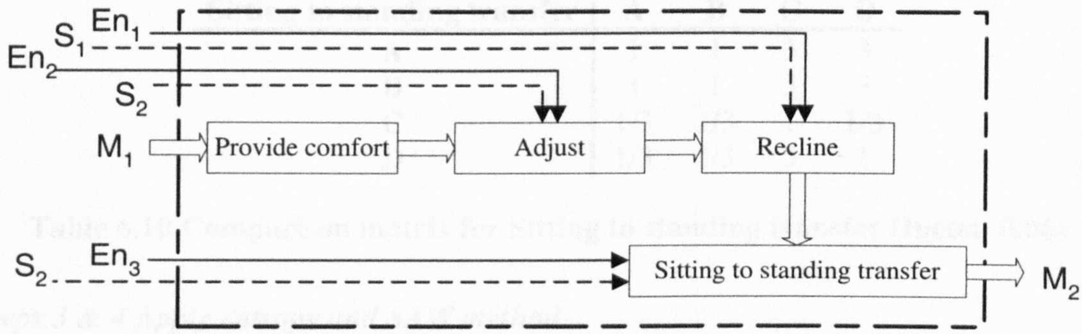


Figure 6.20 Function structure of Positive chair

Step 2 Apply AHP

Priorities of the concepts were obtained using the application of AHP. The novice designer was asked to provide the relative values of the concepts using the verbal scale of AHP for each function. The comparison matrices for the functions are shown in Tables 6.7, 6.8, 6.9 and 6.10.

Provide comfort	A	B	C	D
A	1	2	2	3
B	1/2	1	1	1
C	1/2	1	1	1
D	1/3	1	1	1

Table 6.7 Comparison matrix for Provide comfort (Incon: 0.01)

Adjust	A	B	C	D
A	1	1/3	1/5	1/4
B	3	1	1/4	1/4
C	5	4	1	1
D	4	4	1	1

Table 6.8 Comparison matrix for Adjust (Incon: 0.05)

Recline	A	B	C	D
A	1	1	3	4
B	1	1	3	3
C	1/3	1/3	1	1
D	1/4	1/3	1	1

Table 6.9 Comparison matrix for Recline (Incon: 0.00)

Sitting to standing transfer	A	B	C	D
A	1	1	3	3
B	1	1	3	3
C	1/3	1/3	1	1/3
D	1/3	1/3	3	1

Table 6.10 Comparison matrix for Sitting to standing transfer (Incon: 0.06)

Steps 3 & 4 Apply entropy and SAW method

Priorities, R^3I values and ranks of concepts after the application of entropy and SAW method are shown in Table 6.11.

Observations

The ranks obtained in Table 6.11 indicate that concept A has less risk associated with it in terms of reliability if it is selected for the next stage of design. The R^3I for concept A is 0.270.

	A	B	C	D	Weight
Provide comfort	0.434	0.195	0.165	0.177	0.145
Adjust	0.071	0.132	0.407	0.390	0.359
Recline	0.369	0.367	0.122	0.114	0.266
Sitting to standing transfer	0.368	0.368	0.096	0.169	0.228
R^3I	**0.270**	**0.257**	**0.228**	**0.234**	
Rank	**1**	**2**	**4**	**3**	

Table 6.11 Priorities, R^3I and ranks for Positive chair concepts

But this is very close to the R^3I value for concept B. Also concepts C and D are not far behind concepts B. The novice designer was comfortable using the verbal assessment scale of AHP. The relative qualitative preference provided by the designer was in the range from Equal importance (1) to Strong importance (5). These preferences also indicate that the concepts rated were strong competitors and R^3I values of concepts confirm the same.

6.5 Ab Board

Ab board is a design of an exercise frame that can work as an accompaniment with the swiss ball. Swiss ball has become a very popular fitness product in health industry. It is an inflatable abdominal exercise ball. There is a long training period required to use swiss ball as a standalone entity. This is because one needs to learn how to balance and use the ball simultaneously. In many instances, people fall while using it. This opens up a potential of designing a frame that can accompany this product and allow the users to leverage the use of swiss ball without any fear of falling. A student during his 5-year M Eng in Product Design Engineering undertook this project.

6.6.1 Ab Board Concepts

Concept A (Figure 6.21) is a simple frame that uses elastic bands for constraining the ball. By using bands, the position can be varied depending on the user's stability and requirement. The frame can be folded for easy storage. The elastic band would hold the ball properly and would also provide a safe movement to the user without much of the ball's lateral movement.

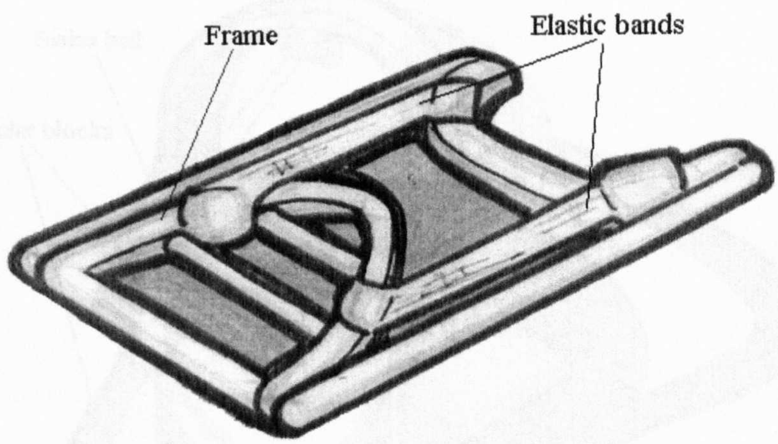


Figure 6.21 Concept A for Ab board (folded position)

Concept B uses a horizontal bar that is perpendicular from the rest. This would provide a simple way of attaching a belt. This belt would then help secure the ball and the belt can be adjusted passing through the loophole. The concept is shown in Figure 6.22.

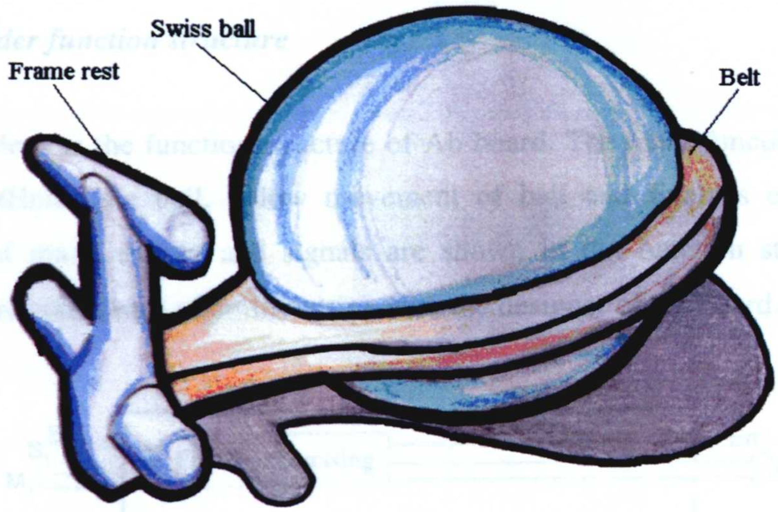


Figure 6.22 Concept B for Ab board

Concept C is made up of simple modular blocks, which can be manufactured in various sizes and can be attached to the ball. This might be advantageous with respect to the ball movements and storage point of view. The concept is shown in Figure 6.23.

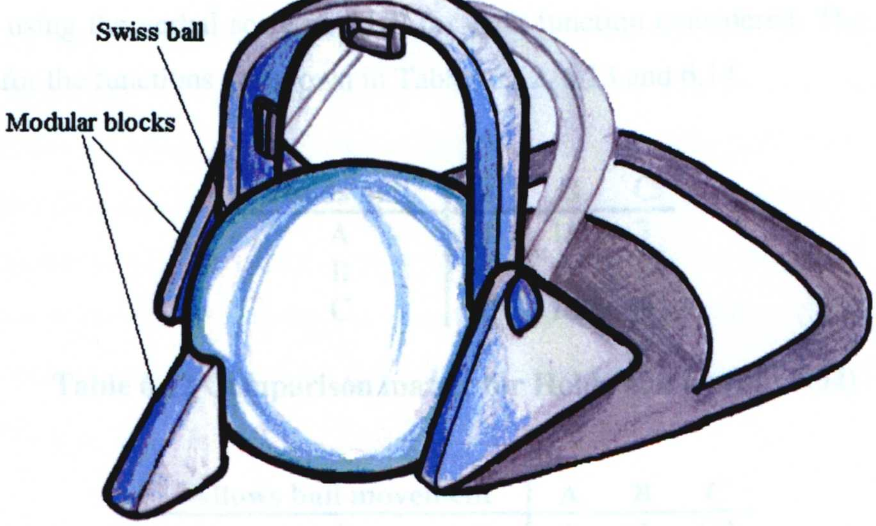


Figure 6.23 Concept C for Ab board

6.6.2 Application of Methodology on Ab Board Concepts

Step 1 Consider function structure

Figure 6.24 depicts the function structure of Ab board. The main functions considered are Stabilise/Holds the ball, Allow movement of ball and Enables exercising. The conversion of mass, energy and signals are shown in the function structure. These functions were considered after discussion with the designer of Ab board.

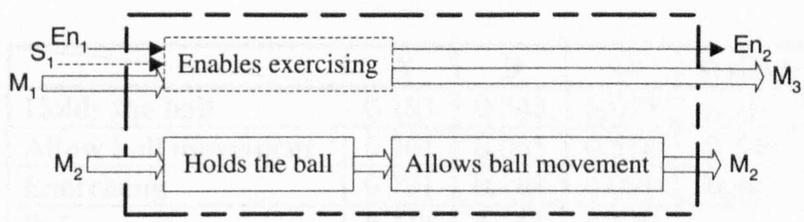


Figure 6.24 Function structure of Ab board

Step 2 Apply AHP

Priorities of the concepts with respect to various functions were obtained after applying the AHP. The novice designer was asked to provide the relative preference values of the concepts using the verbal scale of AHP for each function considered. The comparison matrices for the functions are shown in Tables 6.12, 6.13 and 6.14.

Holds ball	A	B	C
A	1	1/5	3
B	5	1	8
C	1/3	1/8	1

Table 6.12 Comparison matrix for Holds ball (Incon: 0.04)

Allows ball movement	A	B	C
A	1	7	1/2
B	1/7	1	1/7
C	2	7	1

Table 6.13 Comparison matrix for Allows ball movement (Incon: 0.05)

Enables exercising	A	B	C
A	1	5	7
B	1/5	1	3
C	1/7	1/3	1

Table 6.14 Comparison matrix for Enables exercising (Incon: 0.06)

Steps 3 & 4 Apply entropy and SAW method

Priorities, R^3I values and ranks of concepts obtained using entropy and SAW methods are listed in Table 6.15.

	A	B	C	Weight
Holds the ball	0.183	0.742	0.075	0.165
Allow ball movement	0.361	0.065	0.574	0.149
Exercising	0.731	0.188	0.081	0.592
R^3I	**0.514**	**0.247**	**0.139**	
Rank	**1**	**2**	**3**	

Table 6.15 Priorities, R^3I and ranks for Ab board concepts

Observations

The ranks obtained in Table 6.15 show that concept A has less risk associated with it in terms of reliability. The R^3I for concept A is 0.514. The R^3I for this concept, 0.514, outweighs any other with a huge margin. The relative qualitative preference provided by the designer, like that of Carr pack, was in the range from Equal importance (1) to Very strong importance (7). The designer was very inconsistent during the initial run of AHP comparison matrices. Hence, he was asked to provide the relative values again. The inconsistencies during the second run of AHP application were well under the limits (0.04-0.06).

6.6 Industry Example: Selection of Transmissions

An example from industry involves the selection of a transmission system, on the basis of reliability, for use in earth moving equipment produced by Terex in Scotland.

Let the transmissions available be A, B and C. Transmissions A and B are shown in Figures 6.25 and 6.26 respectively. The placement of transmission in the power train system of an earth moving truck is shown in Figure 6.27.

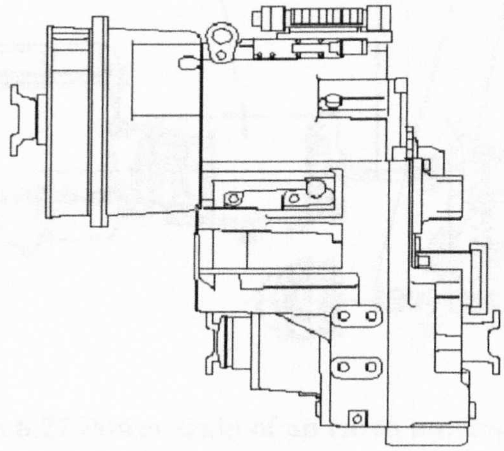


Figure 6.25 Transmission A

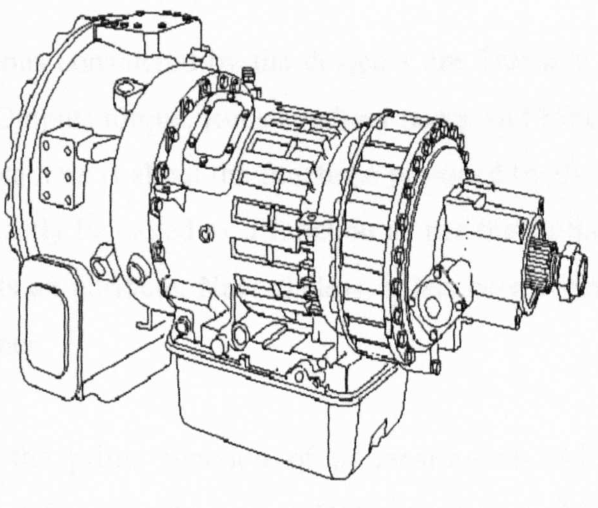


Figure 6.26 Transmission B

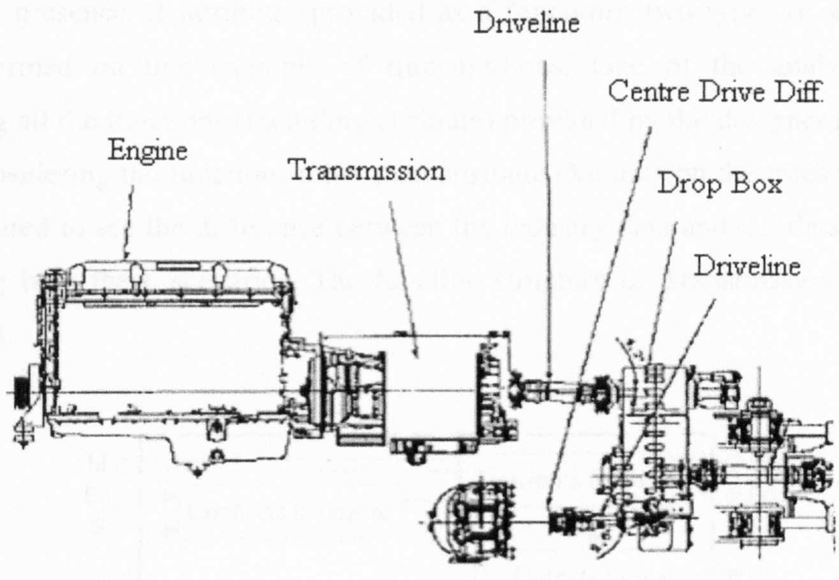


Figure 6.27 Power train of an earth moving truck

The methodology is applied on this example as follows.

Step 1 Consider function structure

The important functions considered by the designer are Transmit (or changes) torque, Connects to engine, Outputs torque, Runs auxiliary pump and Mounts on the truck. The important point to note here is about the functions provided by the designer. Mounts on the truck may not exactly be called as a function as per the earlier discussion (section 5.2.1.1) but represents an attribute. Nevertheless, it has been regarded as an important function by the designer.

Transmits torque is the prime function of a transmission. Along with this, other important functions are Connects to engine, Outputs torque and Running the auxiliary pump. Connection to engine in a Transmission is performed by the torque converter. Outputs torque is for providing number of torque outputs to the required devices (These devices may differ depending on the type of drives, for example 4 wheel drive or a 2 wheel drive). The transmission is also required to run an auxiliary pump for the hydraulic circuits in an earth moving truck. Mounts on the truck represents an assembly function of the transmission on the truck.

Due to the presence of attribute (provided as a function), two types of analysis have been performed on this example of transmissions. One of the analyses is done considering all the functions (including attribute) provided by the designer and the other is done considering the functions other than attribute (Mounts on the truck). The data is then compared to see the difference between the industry data and the data obtained by considering both these scenarios. The function structure of Transmission is shown in Figure 6.28.

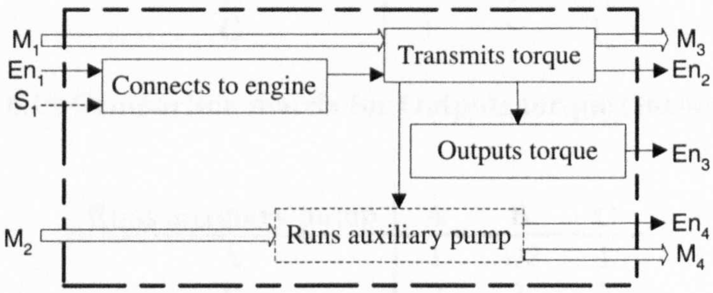


Figure 6.28 Function structure of Transmission system

Step 2 Apply AHP

Priorities of the concepts with respect to various functions were obtained using the application of AHP. The designer was asked to provide the relative preference values of the concepts using the verbal scale of AHP for each function. The comparison matrices for the functions are shown in Tables 6.16, 6.17 and 6.18, 6.19 and 6.20.

Transmits torque	A	B	C
A	1	1/5	1/3
B	5	1	3
C	3	1/3	1

Table 6.16 Comparison matrix for Transmits torque (Incon: 0.04)

Mounts on truck	A	B	C
A	1	3	1
B	1/3	1	1/3
C	1	3	1

Table 6.17 Comparison matrix for Mounts on truck (Incon: 0.00)

Connects to engine	A	B	C
A	1	1/3	1
B	3	1	4
C	1	1/4	1

Table 6.18 Comparison matrix for Connects to engine (Incon: 0.01)

Outputs torque	A	B	C
A	1	7	1
B	1/7	1	1/5
C	1	5	1

Table 6.19 Comparison matrix for Outputs torque (Incon: 0.00)

Runs auxiliary pump	A	B	C
A	1	1/2	1
B	2	1	2
C	1	1/2	1

Table 6.20 Comparison matrix for Runs auxiliary pump (Incon: 0.00)

Steps 3 & 4 Apply entropy and SAW method

Case 1: When 'Mounts on truck' is considered as a function

Priorities, R^3I values and ranks of concepts using the entropy and SAW methods for this case are listed in Table 6.21. This case is also discussed in Mamtani and Green (2006b).

	A	B	C	Weight
Transmits torque	0.105	0.637	0.258	0.290
Mounts on truck	0.429	0.143	0.429	0.120
Connects to engine	0.192	0.634	0.174	0.240
Outputs torque	0.487	0.078	0.435	0.240
Runs auxiliary pump	0.250	0.500	0.250	0.080
R^3I	**0.270**	**0.420**	**0.300**	
Rank	**3**	**1**	**2**	

Table 6.21 Priorities, R^3I and ranks for Transmission concepts: Case 1

Case 2: When 'Mounts on truck' is not considered as a function

Priorities, R^3I values and ranks of concepts using the entropy and SAW methods for this case are listed in Table 6.22.

	A	B	C	Weight
Transmits torque	0.105	0.637	0.258	0.341
Connects to engine	0.192	0.634	0.174	0.282
Outputs torque	0.487	0.078	0.435	0.282
Runs auxiliary pump	0.250	0.500	0.250	0.100
R^3I	**0.252**	**0.468**	**0.284**	
Rank	**3**	**1**	**2**	

Table 6.22 Priorities, R^3I and ranks for Transmission concepts: Case 2

Observations

General Observation:

The relative qualitative preference provided by the designer was in the range from Equal importance (1) to Very strong importance (7). The values of the inconsistencies (0.00-0.04) show that the designer was highly consistent during the evaluation activity. This may be attributed to some years of industrial experience of the designer.

Case 1:

The ranks obtained in Table 6.21 show that concept B has less risk associated with it in terms of reliability. The R^3I for concept B is 0.420. The ratio of R^3I values obtained for A, B and C is 1:1.55:1.1.

Case 2:

The ranks obtained in Table 6.22 show that concept B has less risk associated with it in terms of reliability. The R^3I for concept B, 0.468, is slightly different from that of Case

1. B scores the highest amongst the available options. The ratio of R^3I values obtained for A, B and C is 1:1.85:1.1. The ranks of concepts remain unchanged in both the cases.

The ratios of R^3I values for Case 1 and Case 2 were compared with the actual ratios of reliability of concepts provided by the designer. The actual ratio is 1:2.5:1. Concept A and C are almost equal but designer still preferred concept C over concept A in terms of reliability. The ranks obtained in both the cases match the actual ranks. There is only a little difference in the ratios of the values, case 2 conforming more to the actual reliability data than case 1.

6.8 Closing Remarks

After the application of this methodology on the examples considered, the following can be concluded:

1. The designs considered in this chapter are examples of concept designs. It was noted that the information available during the conceptual design phase is mainly qualitative.

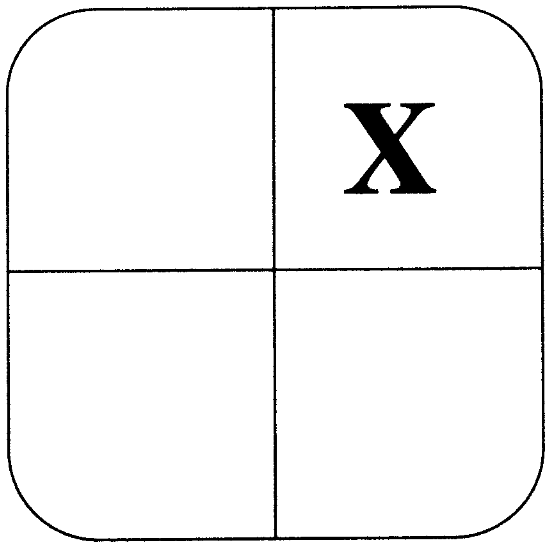
2. The novice designers (students here) found it easy to relatively rate the concepts on the basis of functions using their knowledge of the product and concepts.

3. Functions considered by the novices were not based on the knowledge of function structures. In fact, sometimes the functions listed are actually attributes (section 3.3).

4. The method does not require prior knowledge of decision making tools like AHP.

5. As expected, the designer from industry with a few years of experience was highly consistent as compared to the novice designers.

6. While comparing concepts using AHP, very high relative preferences i.e. 8, 9 were not noticed.



Validation Square

DRM
Descriptive Study II

Chapter 7

Validation Issues: Decomposed Design Evaluation

In chapter 2, the idea of decomposed design evaluation was introduced. Based on this idea, reliability and realizability were listed as important criteria under investigation. In chapter 5, methodologies for evaluating both of these criteria have been proposed. Chapter 6 threw light on the verification of Relative reliability risk methodology by considering examples from various areas of design. In this chapter, validation issues concerning decomposed design evaluation have been considered. To validate decomposed design evaluation, validation of its individual elements is done. The structure of this chapter is as follows. Firstly, impact model of this research is revisited in section 7.1. The validation strategy is discussed in section 7.2. The details of the experiment undertaken for validation are provided in section 7.3. Validation for R^3I and physical realizability methodologies are then undertaken in sections 7.4 and 7.5 respectively. Decomposed design evaluation is revisited in section 7.6. In section 7.7, both the methodologies are modified and applied on an example. Section 7.8 concludes this chapter. This chapter forms the Theoretical performance validity of Validation Square and DS II of DRM.

7.1 Revisiting Impact Model of Research

The Impact model of research discussed earlier (Figure 1.4) is reconsidered here. As it was discussed already, the decomposed design evaluation proposed in this thesis is expected to show a positive effect on the Quality of decision making. To mark any positive effects in improvement of Quality of decision making through decomposed design evaluation, each methodology should individually show an effect of improvement in the Quality of decision making. To measure an improvement in Quality of decision making in quantitative terms, a coefficient ρ (Rho) is calculated. This value of ρ (details on ρ in section 7.3.4) indicates whether an increase (if at all) in the Quality of decision making has been achieved.

7.2 Validation Strategy

The validation strategy followed is shown in Table 7.1. An experiment was conducted which included inputs from novices (novice designers) and experts (expert designers). Initially, the novices were asked to perform a pretest, which was applied without the introduction of the methodologies proposed in this thesis. Next, an independent variable X was introduced (X refers to the methodologies here) and then the novices were asked to perform a posttest after the introduction of the methodologies. The experts were then asked to perform a pretest. Hence, the novices' results of pretest and posttest, both could be compared to the experts' pre test results for each methodology.

	Pretest	Independent variable	Posttest
Novices	Yes	X	Yes
Experts	Yes		No

Table 7.1 Validation strategy

7.3 Experiment

7.3.1 Subjects Under Study

9 novices and 4 experts were studied for the validation of methodologies. The novices were students of the 3rd year Mechanical Design Engineering at Glasgow University. They were asked to generate concepts for an Electro mechanical car jack. The experts belonged to academia and were from different European Universities.

7.3.2 Example for the Experiment

The example under consideration was the design of an electro-mechanical car jack. This example was a part of the novices' design project. The requirements and objectives of the project were provided to the novices. They are included in Appendix A.3 of this thesis. The novices generated various concepts for the car jack. Eight concepts were selected out of all the generated concepts for this experiment. They are shown in Figure 7.1. The level of details provided by the novices has been captured in Figure 7.1.

7.3.3 Influence of Internal Factors on Experiment

The influence of various internal factors for novices could be minimized since the experiment was conducted on students of the same course and year. Most of the novices were of same age. Also, most of them had similar educational backgrounds. These novices had already been lectured on the knowledge of various design phases.

7.3.4 A Note on Spearman's ρ (Rho) Coefficient

Spearman's rank correlation or Rho coefficient (Gibbons 1993) measures the association between non parametric measures. It is used to find the association between ordinal paired data. ρ between two sets of ordinal data is calculated using the following equation:

$$\rho = 1 - \frac{6\sum_{j=1}^{n} d_i^2}{n^3 - n} \qquad (7.1)$$

Here, j = 1 to n is the number of alternatives, and
d = difference between each pair j of ordinal ranks.

The value of ρ varies between -1 and 1. ρ value of -1 indicates negative correlation, 0 indicates no correlation and 1 indicates absolute positive correlation.

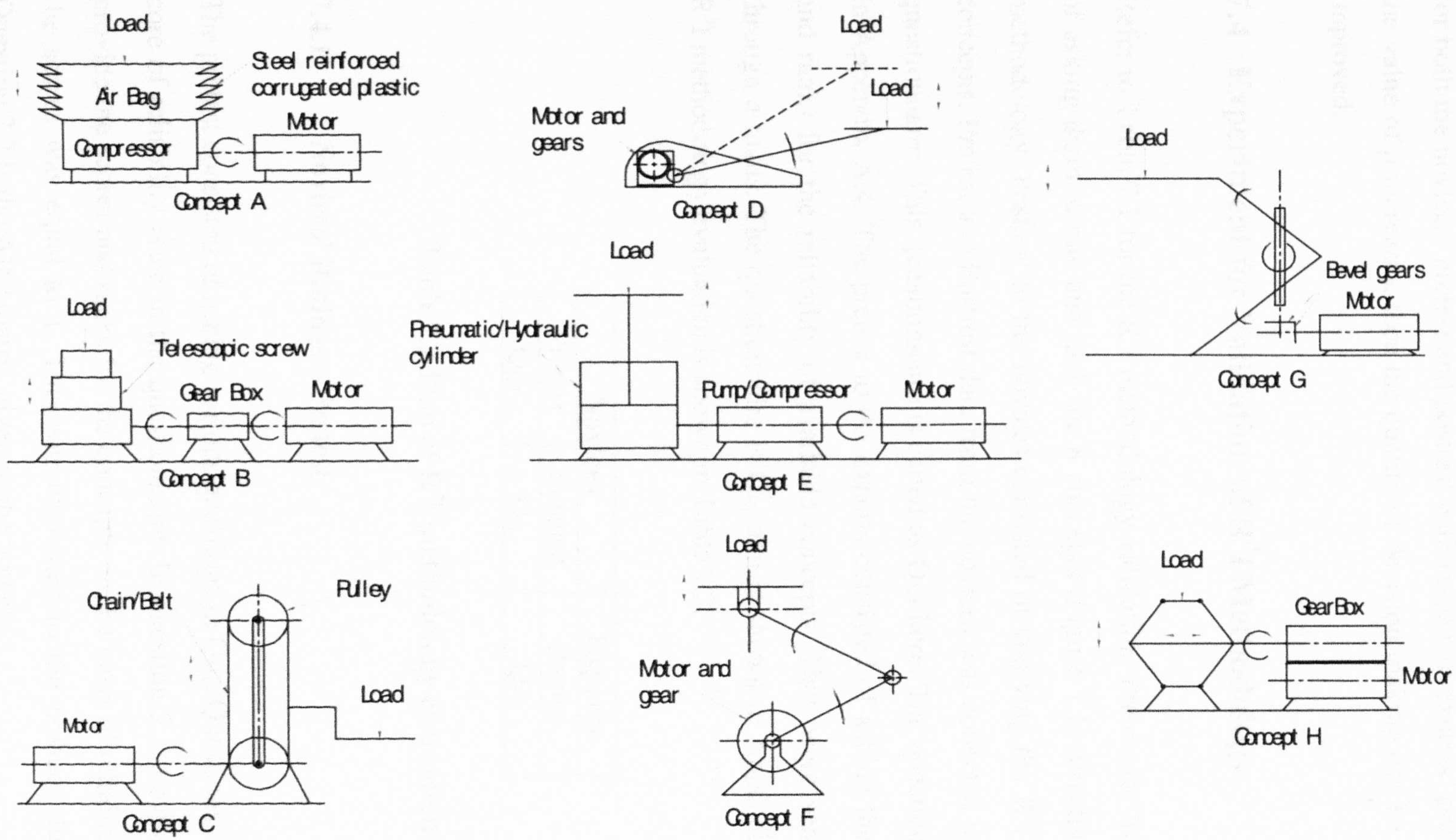


Figure 7.1 Car jack concepts generated by novices

Improvement in quality of decision making has been associated with the value of ρ. ρ for both the novices' pretest and posttest with respect to experts' pretest is calculated. If the value of ρ increases, then the quality of decision making can be considered to have improved.

7.4 Experiment for Validation of R^3I Methodology

Refer to Table 7.1 for the R^3I methodology validation. Pretest for the novices consisted of asking them to rate and rank the 8 concepts (Figure 7.1) directly without the aid of methodology. Posttest to the novices consisted of applying the R^3I methodology on 8 concepts. Pretest and Posttest data from the novices was collected using interviews and questionnaire. This questionnaire is called as Q_{N1} here. The questionnaire can be found in Appendix A.4. The pretest to the experts consisted of asking them the direct rating and ranks for the reliability of available concepts. They were sent the questionnaire through e-mails. The questionnaire is Q_{E1} and is shown in Appendix A.6. The plan of R^3I methodology evaluation is shown in Table 7.2.

Novices		Experts
Pretest	Posttest	Pretest
Q_{N1}	Q_{N1}	Q_{E1}

Table 7.2 Plan of R^3I methodology evaluation

7.4.1 Novices' Ratings – Pretest

The pretest consisted of asking various questions in Q_{N1}. Questions 2.1 and 2.7 form the core of reliability issue in the questionnaire. In question 2.1, novices were required to provide the scores and ranks for the concepts on the basis of reliability. The total for all the scores was equal to 1. This was explained to the novices during the interview. Question 2.7 is the AHP matrix given to the novices.

The terms were sufficiently explained in questionnaire Q_{N1} to the novices before recording their answers. General questions in the questionnaire were meant to give an easy start to the questionnaire. It represents an inverted funnel type structure of the questionnaire.

7.4.2 Novices' Ratings – Posttest

Posttest consisted of applying the R^3I methodology on the example.

Step 1 Consider function structure

The important functions of a car jack considered are Lift car, Support the car at raised level and React to the ground. A simplified function structure of car jack is shown in Figure 7.2. A more detailed function structure could be established but the number of functions is kept to three so as to provide ease of obtaining the data at this stage. Also, the novices were asked if they thought any other function(s) should be included as a part of this evaluation. Most of them concurred to these functions and a few provided functions which were actually attributes. For the sake of comparison of results from all novices, only the above three functions have been considered as a part of this methodology.

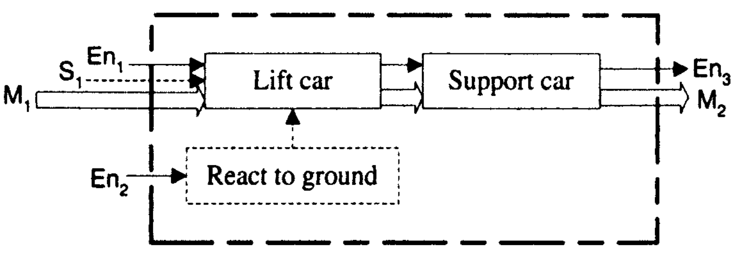


Figure 7.2 Function structure of Car jack

Step 2 Apply AHP

AHP comparison matrices are filled using question 2.7 of questionnaire Q_{N1}. All the comparison matrices obtained from the 9 novices are shown in Appendix A.8.

Steps 3 & 4 Apply entropy and SAW method

Entropy method is employed for evaluating weights of the functions considered. Apart from the weights obtained using the entropy approach, the novices were also asked to provide the direct weights for these functions. These direct weights were recorded so that sensitivity analysis on the final results could be performed. After the application of entropy and SAW method, the R^3I value and the ranks obtained for each novice is calculated (listed in Appendix A.8).

Observations after methodology application

Extreme relative scores for AHP were not frequently used by the novices. Novice 8 & 9 used these scores and in the entire range (equal importance i.e. 9 to extreme importance .e. 1). The inconsistencies could not be calculated in the real time and henceforth they were calculated after the data had been recorded. The inconsistencies for comparison matrices were within the limits for most of the novices. Novice 5 was found to have a very high inconsistency. The inconsistencies for all the novices are given in Table 7.3. In Table 7.3, N1, N2 etc represent Novice 1, Novice 2 and so on.

Function	**Inconsistency**								
	N1	**N2**	**N3**	**N4**	**N5**	**N6**	**N7**	**N8**	**N9**
Lift	0.04	0.08	0.03	0.12	0.33	0.07	0.21	0.16	0.03
Support	0.02	0.07	0.02	0.18	0.07	0.04	0.06	0.13	0.04
React	0.00	0.04	0.01	0.21	0.15	0.02	0.03	0.13	0.00

Table 7.3 Inconsistencies of novices for comparison matrices of Car jack functions

7.4.3 Experts' Ratings – Pretest

The experts' scores and ranks were gathered from a questionnaire Q_{E1} (Appendix A.6) sent to them. This questionnaire asked them to provide scores and ranks for the car jack concepts. The geographically distributed experts' views were combined and the concepts could be ranked with ease due to harmony in their ranks. The ranks from 4 experts and their majority rank are shown in Table 7.4.

Concept	Experts' rank	Majority rank
A	4,6,4,3	4
B	1,3,1,1	1
C	7,5,6,6	6
D	8,2,8,8	8
E	3,4,2,4	3
F	5,3,7,7	7
G	6,4,5,2	5
H	2,2,3,5	2

Table 7.4 Ranks for Car jack concepts by experts with respect to reliability

7.4.4 Comparison of Ranks

To compare and understand various ranks and scores, following notations have been used:

R_{R1N} = of a concept with respect to reliability, directly provided by the novice (R1 in the subscript denotes reliability and N denotes novice).

R^{e}_{R1N} = Rank of a concept with respect to reliability, obtained after applying R^3I approach.

R_{R1E} = Rank of a concept with respect to reliability, directly provided by the expert (considering the majority view shown in Table 7.4 as majority rank).

Considering experts' rank as the correct ranks of concepts in terms of reliability, a ρ coefficient can be calculated which will provide a correlation between R_{R1N} and R_{R1E}, and R^{e}_{R1N} and R_{R1E}. The increase/decrease in the correlation coefficient would provide a measure as to how effective R^3I methodology is.

To explain how this analysis is undertaken, an example of analysis for novice 1 is explained. Ranks R_{R1N} and R^{e}_{R1N} for novice 1 are listed in Table 7.5. ρ for direct ranks by novice 1, R_{R1N} with respect to the expert ranks R_{R1E} (of Table 7.4) is obtained as

0.690. This means that the correlation between the direct ranks provided by novice 1 and that of experts is 0.690. Now ρ for the ranks obtained using R^3I methodology for novice 1 is calculated, and the value is 0.857. This shows that for novice 1, the correlation of the ranks obtained after the methodology application to the experts' ranks is stronger than that obtained from the direct ranks.

	A	B	C	D	E	F	G	H	ρ
R_{R1N}	3	5	8	7	2	6	4	1	0.690
R^e_{R1N}	3	2	8	6	4	7	5	1	0.857

Table 7.5 Ranks obtained/calculated from novice 1's inputs

The graph between R_{R1N}, R^e_{R1N} and R_{R1E} for novice 1 is shown in Figure 7.3. Notice that the ranks obtained from the application of methodology are closer to the experts' ranks than the direct ranks provided by novice 1. In Figure 7.3, direct ranks are R_{R1N}, ranks using method are R^e_{R1N} and experts ranks are R_{R1E}.

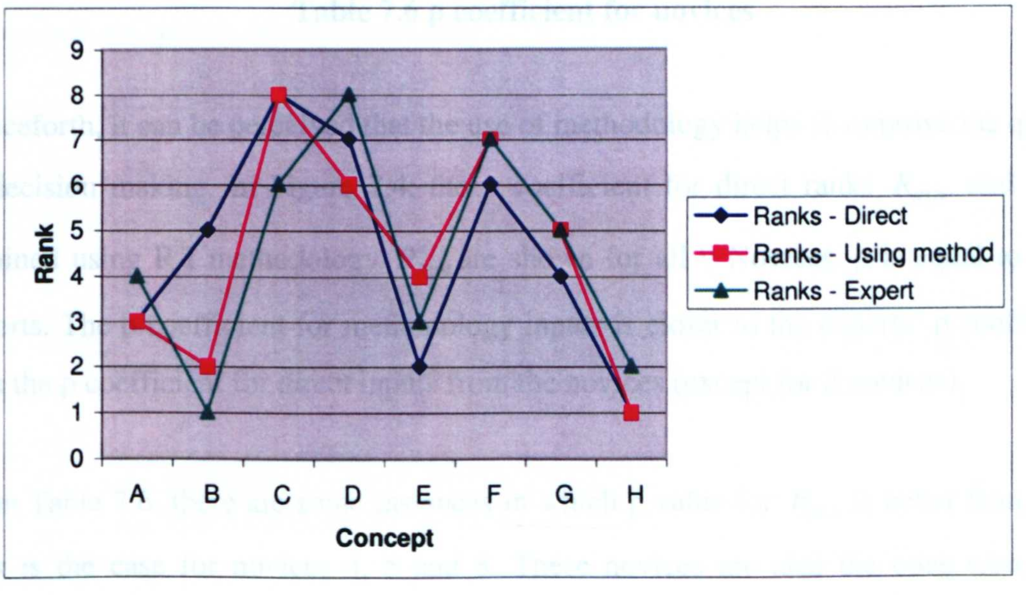


Figure 7.3 Comparing ranks of concepts with respect to reliability for novice 1

The ρ coefficients for all the novices are calculated. The ρ values obtained for other novices are listed in Table 7.6. The average ρ value for R^{e}_{RIN} is more than the average ρ value for R_{RIN}.

Novice	ρ (R_{RIN})	ρ (R^{e}_{RIN})
Novice 1	0.690	0.857
Novice 2	0.523	0.880
Novice 3	0.226	0.761
Novice 4	0.738	0.571
Novice 5	0.571	-0.11
Novice 6	-0.47	0.285
Novice 7	0.380	0.952
Novice 8	0.785	0.738
Novice 9	0.452	0.738
Average	**0.432**	**0.629**

Table 7.6 ρ coefficient for novices

Henceforth, it can be perceived that the use of methodology helps to improve the quality of decision making. In Figure 7.4, the ρ coefficient for direct ranks R_{RIN} and ranks obtained using R^3I methodology R^{e}_{RIN} are shown for all 9 Novices. ρ is equal to 1 for experts. The ρ coefficient for methodology inputs is closer to the experts' ρ coefficient than the ρ coefficient for direct inputs from the novices (except for 2 novices).

From Table 7.6, there are some instances in which ρ value for R_{RIN} is better than R^{e}_{RIN}. This is the case for novices 4, 5 and 8. These novices are also the ones who were inconsistent during the AHP application in providing the relative ratings. There inconsistencies can be noticed from Table 7.3.

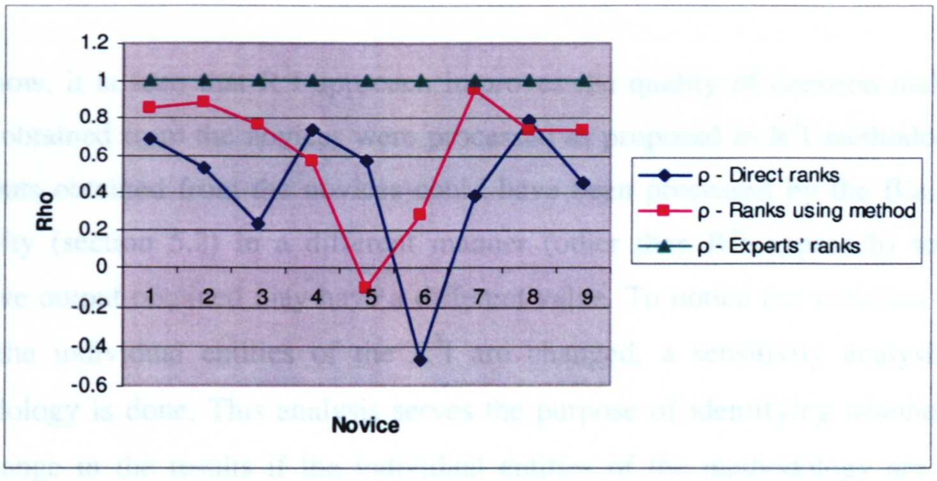


Figure 7.4 ρ coefficient comparisons for novices. ρ is calculated for direct input, R³I methodology and experts' input.

If these inconsistent novices were dropped from further consideration, the average value of ρ for R_{R1N} (direct ranks) is 0.300 and R^{e}_{R1N} (R³I ranks) is 0.745. In Figure 7.5, the ρ coefficient for direct ranks R_{R1N} and ranks obtained using R³I methodology R^{e}_{R1N} are shown for all 6 novices who were consistent. All the consistent novices show an increase in the quality of decision making.

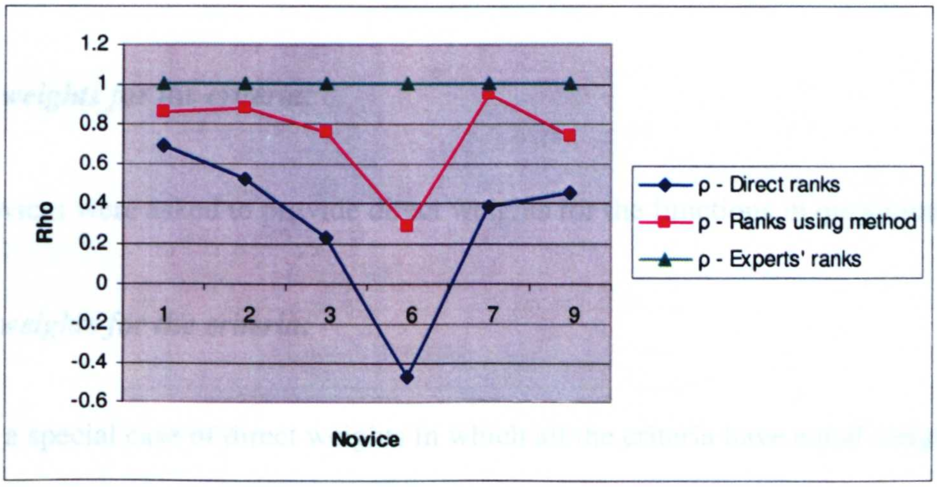


Figure 7.5 ρ coefficient comparisons for novices (except novice 4, 5 and 8 who were inconsistent in AHP ratings). ρ is calculated for direct input, R³I methodology and experts' input.

7.4.5 Sensitivity Analysis

Until now, it is seen that R^3I approach improves the quality of decision making. The inputs obtained from the novices were processed as proposed in R^3I methodology. But the inputs obtained from the novices could have been processed by the Black box of reliability (section 5.2) in a different manner (other than R^3I approach) so that the objective output obtained may have a different value. To notice the variation of results when the individual entities of the R^3I are changed, a sensitivity analysis for the methodology is done. This analysis serves the purpose of identifying whether there is any change in the results if the individual entities of the methodology are changed. Also, some methods have been considered here that are not exact equivalents of the methodology but are considered for the sake of comparison. The elements of R^3I methodology (except function structures and AHP) are replaced with other elements. Other weight assigning techniques and information processing techniques are used. They are discussed as follows:

7.4.5.1 Change in Weight Assigning Technique

In R^3I methodology, entropy analysis has been proposed to calculate the weights. Here 2 simple weight assigning techniques are also used. They are:

Direct weights for the criteria:

The novices were asked to provide direct weights for the functions in questionnaire Q_{N1}.

Equal weights for the criteria:

This is a special case of direct weights in which all the criteria have equal weights

7.4.5.2 Change in Scoring Method

SAW was proposed to be used during the R^3I methodology, but other scoring methods could be used for processing the available data. The methods used here are:

Weakest link method

Reliability is usually mentioned in terms of weakest link of the system. Taking this analogy, the alternative with the weakest/lowest local priority (or preference value) for any function is rated as the worse alternative and.

Reciprocal method

This is similar to the method for processing the preference values during the DPI calculation (section 3.4.7). Following formula can be used instead of Equation (3.1):

$$1/S_j = \sum_{i=1}^{m} w_i / y_{ij} \qquad (7.2)$$

where S is the total score for an alternative.

7.4.5.3 Analysis

8 logical combinations can be derived when considering the above weight assigning techniques and scoring methods. They are shown in Table 7.7.

Step 1	Step 2	Step 3	Step 4	Case
Function structure	**AHP**		Direct input	Case 1
		Entropy	SAW	Case 2 (R^3I approach)
			Reciprocal	Case 3
		Direct weights	SAW	Case 4
			Reciprocal	Case 5
		Equal weights	SAW	Case 6
			Reciprocal	Case 7
			Weakest link	Case 8

Table 7.7 Various cases derived from combinations of weight assigning techniques and scoring methods

Step 1 and Step 2 of methodology remain the same. Step 3 and Step 4 have been changed to check the influence of weight assigning techniques and scoring methods. As a result of combinations, various cases are arrived at. In section 7.4.4, Case 1 (Direct input) and Case 2 (R^3I approach) were compared. Case 3 uses entropy method for weight assessment and reciprocal method for scoring method. Case 4 uses direct weights and Equation (3.1) for scoring. Case 5 uses direct weights from the novices and Equation (7.1) for scoring. Case 6 uses equal weights and Equation (3.1). Case 7 uses equal weights and Equation (7.1). Case 8 represents the weakest link method discussed above.

With these 8 combinations, new ranks are obtained for all the novices. The ranks arrived at after the application of each case for all 9 novices are listed in Appendix A.8. With these ranks, the value of ρ is found for all the novices in each case. The results of the ρ values for each case for novices are listed in Table 7.8.

ρ coefficient	Case							
	1	2	3	4	5	6	7	8
Novice 1	0.690	0.857	0.880	0.857	0.857	0.880	0.857	0.857
Novice 2	0.523	0.880	0.809	0.809	0.738	0.809	0.738	0.523
Novice 3	0.226	0.761	0.761	0.761	0.785	0.785	0.738	0.595
Novice 4	0.738	0.571	0.571	0.595	0.571	0.642	0.571	0.595
Novice 5	0.571	-0.119	0	0.047	0.119	-0.095	0	0.095
Novice 6	-0.476	0.285	0.523	0.309	0.404	0.452	0.404	0.404
Novice 7	0.380	0.952	0.833	0.880	0.809	0.952	0.809	0.714
Novice 8	0.785	0.738	0.738	0.761	0.761	0.667	0.738	0.738
Novice 9	0.452	0.738	0.690	0.690	0.690	0.690	0.690	0.690
Average	0.432	0.629	0.645	0.634	0.637	0.642	0.616	0.579

Table 7.8 ρ coefficient values obtained for novices for various cases

From Table 7.8, it can be noticed that novice 5 has a high level of random ρ values. Also, Case 1 and Case 8 have a very low average value of ρ. Case 2 (R^3I approach) has an average ρ value of 0.629. Case 2, 3, 4, 5 and 6 have got very little difference in their average ρ values. Since novice 5 was highly inconsistent in providing AHP relative ratings, if novice 5 is dropped from consideration then the average values of ρ obtained are shown in Table 7.9.

ρ coefficient	Case							
	1	2	3	4	5	6	7	8
Average	0.415	0.723	0.726	0.708	0.702	0.735	0.693	0.639

Table 7.9 Average ρ coefficient values for novices for various cases (except novice 5)

When novice 5 is dropped from consideration, the average value of ρ for case 1 (direct ratings by novices) falls to 0.415. For Case 2 (R^3I approach), the average value of ρ increases to 0.723. The average ρ values for Case 2 (0.723), Case 3 (0.726) and Case 6 (0.735) are almost equal to each other and better than rest of the cases. The graph for these average values of ρ in Table 7.9 for various cases are shown in Figure 7.6.

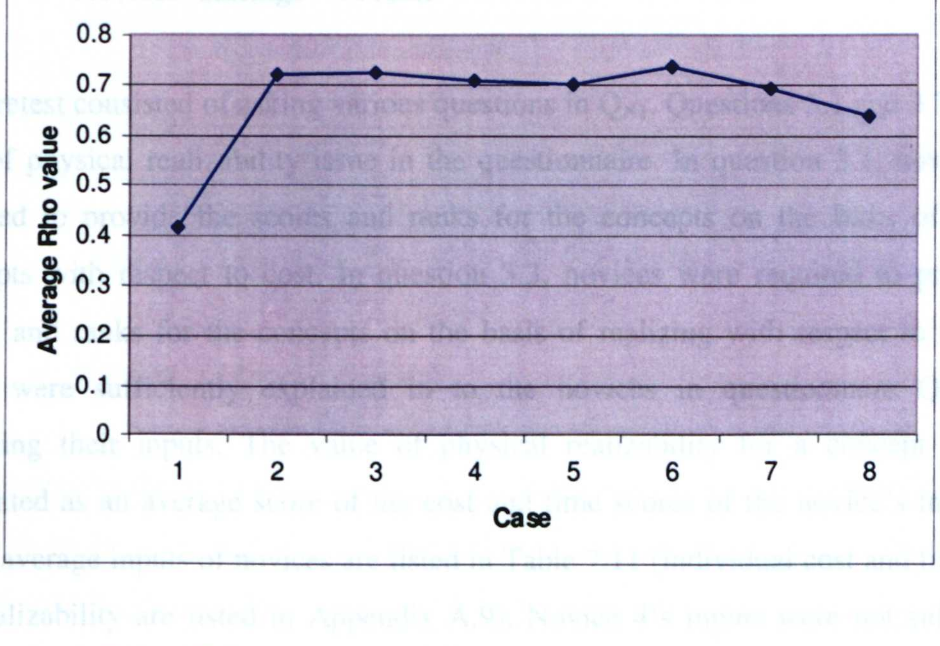


Figure 7.6 Average ρ coefficient values for various cases

7.5 Experiment for Validation of Physical Realizability Methodology

Referring back to Table 7.1 for the validation of physical realizability methodology, Pretest to the novices consisted of asking them to rate and rank the 8 concepts (Figure 7.1) directly without the aid of methodology. Posttest to the novices consisted of applying Asimov's physical realizability methodology on 8 concepts. Pretest and posttest were collected using interviews and questionnaire from the novices.

Questionnaire for the pretest to novices was Q_{N1} and posttest was Q_{N2}. Both the questionnaires are attached in Appendix A.4 and A.5 respectively. The pretest to the experts consisted of asking them to directly rate and rank the physical realizability of the available concepts. They were sent the questionnaire through e-mails. The Questionnaire is Q_{E1} and is attached in Appendix A.6. The plan of physical realizability methodology evaluation is shown in Table 7.10.

Novices		Experts
Pretest	Posttest	Pretest
Q_{N1}	Q_{N2}	Q_{E1}

Table 7.10 Plan of physical realizability methodology evaluation

7.5.1 Novices' Ratings – Pretest

The pretest consisted of asking various questions in Q_{N1}. Questions 3.1 and 3.3 form the core of physical realizability issue in the questionnaire. In question 3.1, novices were required to provide the scores and ranks for the concepts on the basis of realizing concepts with respect to cost. In question 3.3, novices were required to provide the scores and ranks for the concepts on the basis of realizing with respect to time. The terms were sufficiently explained in to the novices in questionnaire Q_{N1} before recording their inputs. The value of physical realizability for a concept was then calculated as an average score of the cost and time scores of the novice's inputs. The direct average inputs of novices are listed in Table 7.11 (individual cost and time scores for realizability are listed in Appendix A.9). Novice 4's inputs were not sufficient to calculate an average score; hence his inputs are not listed here. Also, notations used in Table 7.11 are as follows:

S^{da}_{R2N} = Average of the direct (cost & time) scores provided by the novice for physical realizability of a concept

R^{da}_{R2N} = Ranks for the score S^{da}_{R2N}.

		A	B	C	D	E	F	G	H
Novice 1	S^{da}_{R2N}	0.10	0.10	0.10	0.15	0.07	0.12	0.17	0.17
	R^{da}_{R2N}	5	5	5	3	6	4	2	1
Novice 2	S^{da}_{R2N}	0.05	0.07	0.10	0.12	0.12	0.15	0.20	0.17
	R^{da}_{R2N}	8	7	6	5	4	3	1	2
Novice 3	S^{da}_{R2N}	0.05	0.11	0.12	0.09	0.09	0.12	0.06	0.17
	R^{da}_{R2N}	8	4	3	5	6	2	7	1
Novice 5	S^{da}_{R2N}	0.12	0.10	0.15	0.15	0.15	0.10	0.10	0.17
	R^{da}_{R2N}	4	5	3	3	2	6	5	1
Novice 6	S^{da}_{R2N}	0.11	0.08	0.06	0.17	0.16	0.14	0.12	0.12
	R^{da}_{R2N}	6	7	8	1	2	3	4	5
Novice 7	S^{da}_{R2N}	0.06	0.06	0.12	0.03	0.03	0.06	0.27	0.35
	R^{da}_{R2N}	6	5	3	7	8	4	2	1
Novice 8	S^{da}_{R2N}	0.04	0.10	0.14	0.04	0.17	0.07	0.19	0.21
	R^{da}_{R2N}	7	5	4	7	3	6	2	1
Novice 9	S^{da}_{R2N}	0.03	0.06	0.10	0.14	0.12	0.14	0.19	0.19
	R^{da}_{R2N}	8	7	6	3	5	4	2	1

Table 7.11 Novices' Pretest inputs for physical realizability

7.5.2 Novices' Ratings – Posttest

The posttest to the novices consisted of a questionnaire Q_{N2} in which questions were asked so as to apply the physical realizability methodology. The questionnaire was handed over to the novices to submit at a later date. The questions and their inputs are discussed while the application of methodology. Only novices 2, 3 and 6 submitted the questionnaire results.

Application of Asimov's physical realizability methodology

The major problem in realizing any electro-mechanical car jack concept (Figure 7.1) would be realizing the technology as shown in the concept sketches. This is one of the major problems that one would be faced with for realizing a car jack concept within the budget of cost and time. Technology would be a major cause of differentiating between the concepts. For example, concept A has corrugated plastic with pneumatic technology while concept B has mechanical elements like telescopic screw to realise. For the sake of simplicity and ease of applying of methodology with the novices (students), only one problem has been considered.

Here, an example of calculating physical realizability for novice 2 is undertaken.

To evaluate the Level of confidence, consider Equation (5.26)

$$E_{V_{A_i}}(A_i \mid EX_B) = E_{V_{A_i}}(A_i \mid X_B) + E_{V_{A_i}}(E \mid A_iX_B)$$

The right hand side of this equation is broken into two parts. The first part is $E_{V_{A_i}}(A_i \mid X_B)$ and the second is $E_{V_{A_i}}(E \mid A_iX_B)$. These both would be individually calculated to provide a final value of Level of confidence in decibels for novice 2. For the sake of illustration, an assumption of the available budget is made. It is known that X_B is not involved in calculations but only provides a numeric figure to base conditional probabilities upon. A value of X_B is mentioned in context to the budget of the companies for product development in terms of cost and time. Since novices did not have any industrial experience, providing such a numeric figure for X_B is expected to confuse them. Such a figure of budget would not "ring any bell" to them. Henceforth, a budget cost of 50 £ as the final production cost of an electro-mechanical car jack has been assumed for realising the concept and questions were asked based on this budget.

Consider the first part of Equation (5.26), called as P_1,

$$P_1 = E_{V_{A_i}}(A_i \mid X_B) = 10 \log_{10} O(A \mid X) = 10 \log_{10} \frac{P(A_i \mid X_B)}{P(\bar{A}_i \mid X_B)}$$

To evaluate P_1, consider concept A.

$P(A_i \mid X_B)$ = Probability that the concept is physically realizable with the allocated budget. Inputs from novice 2 for this probability for concept A is:

$P(A_i \mid X_B) = 0.01$

and

$P(\bar{A}_i \mid X_B) = 1 - P(A_i \mid X_B)$

$P(\bar{A}_i \mid X_B) = 0.99$

$$P_1 = 10 \log_{10} \frac{0.01}{0.99} = -19.9 \text{ decibels}$$

Let the second part of Equation (5.27) be

$$P_2 = E_{V_{A_i}} (E \mid A_i X_B) = 10 \log_{10} O(E \mid A_i X_B) = 10 \log_{10} \frac{P(E \mid A_i X_B)}{P(E \mid \bar{A}_i X_B)}$$

And $P(E \mid \bar{A}_i X_B)$ for concept A is evaluated by asking the question: "Imagine we implemented the technology (pneumatic and corrugated plastic) in concept A and the prototype failed and was not physically realisable, what is the probability that this technology implemented and tested in earlier stages (before the prototype is built) would have still passed the tests?"

$P(E \mid A_i X_B)$ is assumed to be equal to 1 (section 5.3.3) because normally when the prototype (in future) would pass the test, the sample is earlier stages would pass the test as well.

For novice 2 inputs' for concept A, this probability is 0.5, so

$$P_2 = 10 \log_{10} \frac{1.0}{0.5} = 3 \text{ decibels}$$

Hence for concept A, $E_{V_{A_i}}$ (A_i | EX_B) is given by,

$E_{V_{A_i}}$ (A_1 | EX_B) = P_1 + P_2 = -19.9 + 3 = -16.9 decibels, which is equal to only a 2.71% Level of confidence in realising this concept.

Based on the above method for evaluating the final probabilities for the concepts, the results of methodology application for novices 2, 3 and 6 are listed in Table 7.12.

		A	B	C	D	E	F	G	H
Novice 2	**L**	-16.9	-13.5	10	2.22	6	5.22	4	7
	L (%)	2.71	4.71	90.7	61.8	77	74.2	69.6	80.7
	R^{l}_{R2N}	7	8	1	6	3	4	5	2
Novice 3	**L**	1.55	0.96	2.21	-3.22	6.70	5.90	-4.47	5.90
	L (%)	59	55	61.8	32	79.67	76.7	27.8	76.7
	R^{l}_{R2N}	4	5	3	7	1	2	6	1
Novice 6	**L**	3.30	-2.04	-5.56	3	-1.46	4.65	7.66	4.77
	L (%)	67	38.6	24	61.8	41.7	72.10	83.10	72.54
	R^{l}_{R2N}	4	7	8	5	6	3	1	2

Table 7.12 Asimov's Level of confidence values and ranks of concepts for novices

In Table 7.12, rank R^{l}_{R2N} is the rank obtained after the application of Asimov's approach for novices (R2 in the subscript is for physical realizability and N for novice. l in superscript is for Asimov's measure of belief).

Observations after methodology application

Only 3 novices turned in the questionnaires. This affects the data collected and indicates that the novices could have faced difficulty in providing the probability values in the Questionnaire Q_{N2}. For each concept, 2 probability questions were asked. Hence, the novices were required to provide 16 probabilities (for 8 concepts) values. Perhaps the novices did not find it easy to provide the probability values and this could have been the reason that held them back from submitting the questionnaires.

7.5.3 Experts' Ratings – Pretest

The experts' scores and ranks were also gathered from a questionnaire sent to them. This questionnaire asked them to provide scores and ranks for the 8 concepts generated by the novices.

The pretest consisted of asking various questions in Q_{E1}. Questions 2.1 and 2.3 form the core of physical realizability issue in the questionnaire. In question 2.1, experts were required to provide the scores and ranks for the concepts on the basis of realizing concepts with respect to cost. In question 2.3, experts were required to provide the scores and ranks for the concepts on the basis of realizing with respect to time. The value of physical realizability was then taken as an average score of cost and time scores by the experts. These average scores are listed in Table 7.13.

		A	B	C	D	E	F	G	H
Expert 1	S^{da}_{R2E}	0.05	0.09	0.06	0.07	0.21	0.15	0.12	0.24
	R^{da}_{R2E}	8	5	7	6	2	3	4	1
Expert 2	S^{da}_{R2E}	0.12	0.07	0.10	0.17	0.10	0.15	0.07	0.15
	R^{da}_{R2E}	3	5	4	1	4	2	5	2
Expert 3	S^{da}_{R2E}	0.05	0.09	0.22	0.11	0.15	0.10	0.09	0.17
	R^{da}_{R2E}	7	6	1	4	3	5	6	2
Expert 4	S^{da}_{R2E}	0.22	0.27	0.07	0.05	0.10	0.05	0.15	0.07
	R^{da}_{R2E}	2	1	5	6	4	6	3	5

Table 7.13 Experts' Pretest inputs for physical realizability

The notations used in Table 7.13 are as follows:

S^{da}_{R2E} = Average of the direct (cost & time) scores provided by the experts for physical realizability evaluation

R^{da}_{R2E} = Ranks for the scores S^{da}_{R2E}.

Clearly, from Table 7.13, no majority can be obtained from the experts' ranks. This is very surprising because there is no harmony in the experts' inputs. All of them perceive a concept to take different ranks with respect to ease of realizability. Although, the terms were sufficiently explained in the questionnaire, the ranks of concepts vary substantially. This might be due to established views on the terminology of ease of physical realizability of a concept.

Since there is no unanimity in the scores and ranks of the experts', an average of experts' scores is calculated and ranks are obtained. The scores and ranks obtained in this manner are shown in Table 7.14.

	A	B	C	D	E	F	G	H
S^{da}_{R2E}	0.11	0.13	0.11	0.10	0.14	0.11	0.10	0.15
R^{da}_{R2E}	6	3	5	8	2	4	7	1

Table 7.14 Average scores and ranks of the experts' ratings for physical realizability of concepts

7.5.4 Comparison of Ranks

This comparison strategy is very similar to the strategy adopted in section 7.4.4 for the comparison of ranks for reliability data.

An example of analysis for novice 2 is undertaken to explain how the comparison of data is done. Ranks R^{da}_{R2N} and R^{l}_{R2N} for novice 2 are listed in Table 7.15. ρ for direct ranks by novice 2, R^{da}_{R2N} with respect to the expert ranks (of Table 7.15) is obtained as 0.142. This means that the correlation of ranks between the direct ranks provided by the novice and that of experts is 0.142. This value of ρ is very low i.e. the correlation value between both the ranks is very low. When ρ calculation for ranks obtained using the physical realizability methodology is done, the value obtained is 0.380. This shows the correlation between ranks obtained after the methodology application is better than that obtained from the direct ranks of the novices. Nevertheless, the value of ρ is still low.

	A	B	C	D	E	F	G	H	ρ
R_{R2N}^{da}	8	7	6	5	4	3	1	2	0.142
R_{R2N}^{l}	7	8	1	6	3	4	5	2	0.380

Table 7.15 Ranks obtained/calculated from novice 2's inputs for physical realizability evaluation

ρ values for all novices who took part in physical realizability experiment (novice 2, 3 and 6) are shown in the Figure 7.7. Although there is no substantial increase in ρ values from direct values to values obtained through method, there has been some improvement in the value. This is a measure of increase in the quality of decision making by using the methodology of physical realizability evaluation by Asimov. But there are still lot of answers unravelled by the Asimov's approach. There had been a lot of assumptions made during this exercise for applying this methodology. Also, since only 3 novices answered the questionnaires makes, it makes one ponder on the ease of methodology application. These points have already been discussed during the discussion of limitations posed by Asimov's methodology (section 5.4.2).

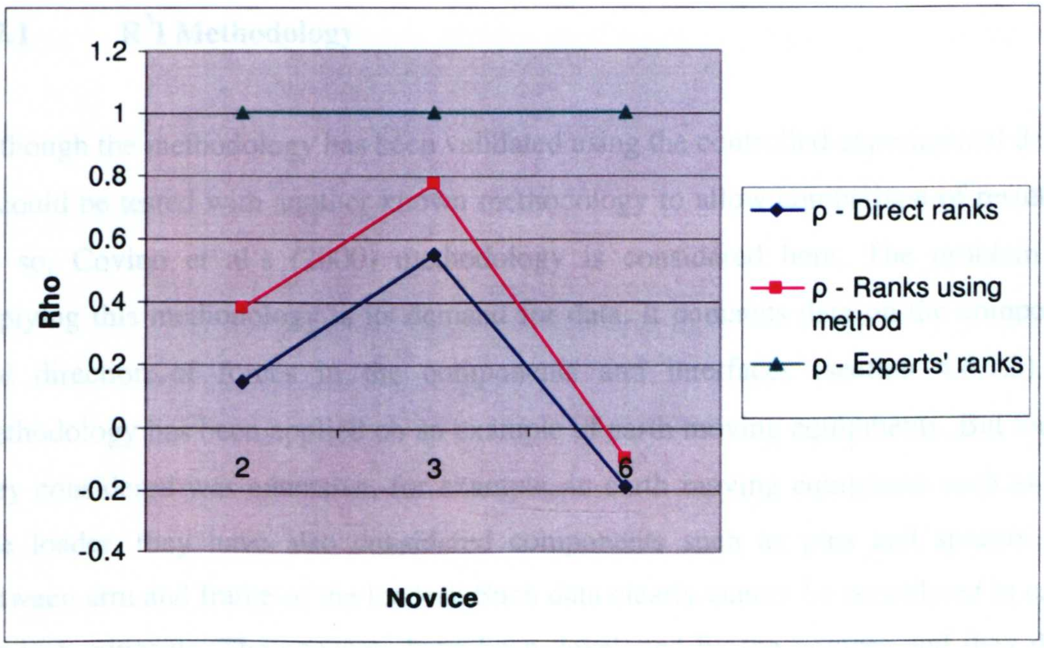


Figure 7.7 ρ coefficient comparisons for novices. ρ is calculated for direct input, Realizability methodology and experts' input.

7.6 Decomposed Design Approach

Returning back to the decomposed design evaluation approach discussed in section 2.4, it can now be asserted that decomposed design evaluation also helps to increase the quality of decision making since its individual components increase the quality of decision making. A typical decision matrix of decomposed design approach for novice 2 is shown in Table 7.16.

X	w	A	B	C	D	E	F	G	H
Reliability	--	0.13	0.20	0.06	0.08	0.17	0.06	0.12	0.15
Ease of Realizability	--	2.71	4.71	90.7	61.8	77	74.2	69.6	80.7
----	--	---	---	---	---	---	---	---	---
X_m		---	---	---	---	---	---	---	---

Table 7.16 Decision matrix for novice 2 with inputs using the decomposed design evaluation approach

7.7 Modifying the Methodologies

7.7.1 R^3I Methodology

Although the methodology has been validated using the controlled experimental design, It could be tested with another known methodology to allow comparison of results. To do so, Covino et al's (2000) methodology is considered here. The problem with applying this methodology is its demand for data. It demands data on the components and direction of forces in the components and interfaces (section 4.4.1.3). The methodology has been applied on an example of earth moving equipments. But the data they considered was extensive, for example, in earth moving equipment such as Back hoe loader, they have also considered components such as pins and spacers (used between arm and frame of the loader). Such data clearly cannot be considered in case of car jack concepts. The concepts have been developed by the novices and they do not show any such details at this point during the design process.

Since this methodology cannot be applied on car jack example of Figure 7.1, it has been modified with the application of AHP. The modification has been done in the following manner. Covino et al (2000) have proposed to identify "Black Box" components. These are the components due to which interference between functions occur. To reiterate, they have found that if there is interference between the functions, then there are chances of less clarity, which indicates chances of low reliability. Extracting the idea of interference between functions in R^3I approach, it could be modified and compared using the following methodology.

Step 1 Consider function structure

This step is similar to the R^3I approach.

Step 2 Apply AHP

In R^3I approach, AHP was applied with respect to various functions. But in this case, AHP would be applied considering the interference between various functions. Hence the criteria are not the functions themselves, but interference between functions. This is denoted here by $\cap$. As an example, if there are 2 functions F_1 and F_2, the criteria would be $F_1 \cap F_2$.

Step 3 Provide objective output

In this case, total interference would be obtained by adding the local priorities of individual interference for each concept.

One of the experts was requested to provide relative ratings of AHP. The expert was aware of the Covino et al's work and provided the ratings. For simplicity, only first 5 concepts were considered. The first 5 concepts (Table 7.4) on the basis of reliability were concept A, B, E, G and H.

Step 1 Consider function structure

This was already considered (Figure 7.2) for the application of R^3I approach.

Step 2 Apply AHP

Let F_1 be Lift Car, F_2 be Support car and F_3 be React to ground. Hence the AHP matrices, considering function interferences are shown in Table 7.17, 7.18 and 7.19.

$F_1 \cap F_2$	A	B	E	G	H
A	1	1	1/2	1/3	1
B	1	1	1/2	3	1/2
E	2	2	1	3	2
G	3	1/3	1/3	1	3
H	1	2	1/2	1/3	1

Table 7.17 Comparison matrix for $F_1 \cap F_2$ (Incon: 0.03)

$F_2 \cap F_3$	A	B	E	G	H
A	1	2	2	2	2
B	1/2	1	1	2	1
E	1/2	1	1	1/2	1
G	1/2	1/2	2	1	1/2
H	1/2	1	1	2	1

Table 7.18 Comparison matrix for $F_2 \cap F_3$ (Incon: 0.05)

$F_3 \cap F_1$	A	B	E	G	H
A	1	2	2	2	1
B	1/2	1	1	2	2
E	1/2	1	1	2	2
G	1/2	1/2	1/2	1	1/2
H	1	1/2	2	2	1

Table 7.19 Comparison matrix for $F_3 \cap F_1$ (Incon: 0.05)

Step 3 Obtain objective output

Priorities, scores and ranks for concepts are obtained for concepts. They are shown in Table 7.20.

	A	B	E	G	H
$F_1 \cap F_2$	0.192	0.170	0.339	0.075	0.225
$F_2 \cap F_3$	0.322	0.190	0.146	0.152	0.190
$F_3 \cap F_1$	0.293	0.216	0.216	0.106	0.170
Score	**0.807**	**0.576**	**0.701**	**0.333**	**0.585**
Rank	**5**	**2**	**4**	**1**	**3**

Table 7.20 Priorities, scores and ranks for 5 Car jack concepts using the modified approach for reliability evaluation

ρ coefficient for these ranks of Table 7.20 with the experts' majority ranks of Table 7.4, is obtained as 0. This means there is no correlation between these ordinal ranks and those by the experts. Hence the use of interference between the functions as an indicator of reliability does not show any correlation with the experts' inputs. This low correlation could also have been obtained due to the difference in the consideration of types and abstraction levels of the functions.

7.7.2 Physical Realizability Methodology

The proposed methodology by Asimov has been discussed earlier and applied on the example of car jacks. Although results show an increase in the quality of decision making, it has limitations because of which it may be difficult in application. Henceforth, using the questionnaires provided to the experts and some literature, there is a lot of scope for improvement in this methodology. The limitations of this methodology include considering sub problems and asking questions which can confuse the designers. So, to get around this problem, question 3.2 in questionnaire Q_{N2} and question 2.2 in questionnaire Q_{E1} were considered. Both these questions asked the novices and experts about the reasons of selecting a concept with respect to physical realizability. The answers received were random but they all fall into the following 3 broad categories.

Category 1: Use of standard components

Category 2: Harnessing the technology

Category 3: Prediction of simplest geometry of the product

Henceforth, these 3 categories can be considered to provide a measure of ease of realizability of a concept. A questionnaire Q_{E2} (attached in Appendix A.7) was sent to the experts to rate and rank the car jack concepts on the basis of these 3 categories. Although the questionnaire was fairly simple, unfortunately only 1 out of 4 experts answered the questionnaire. The questions asked in questionnaire Q_{E2} are as follows:

Question 1. Which of the concepts encapsulates the simplest technology?

Question 2. Which of the concepts would require the least number of non-standard components?

Question 3. Which of the concepts would exhibit the simplest geometry of individual parts and assembly?

The answers to the above 3 Questions from the expert are listed in Table 7.21

Ranks	A	B	C	D	E	F	G	H
Rank (Question 1)	5	4	6	7	2	8	3	1
Rank (Question 2)	6	4	5	7	2	8	3	1
Rank (Question 3)	3	2	6	7	1	8	5	4

Table 7.21 Ranks of Car jack concepts by expert for questions in Q_{E2}

Unfortunately, the results from only 1 expert do not lead to any conclusion. The improved methodology would require another controlled experimental design to test its validity. Due to limitations in time and other resources, this experimental study is not carried out in this project.

Chapter 8

Conclusions

8.1 Conclusion

Design evaluation has been considered as an important activity in conceptual design phase because many resources are committed during this activity. A novel design evaluation approach is proposed in this thesis that is intended to help designers take better decisions. Reliability and realizability have been identified as important criteria considered during design evaluation. Hence research on decomposed design evaluation is undertaken considering these two criteria. The final deliverables of the thesis are two methodologies for evaluating Reliability and Realizability in the conceptual design phase. For reliability evaluation, a methodology, called as R^3I has been proposed. It is applied using the steps shown in Figure 8.1 (section 5.2.1).

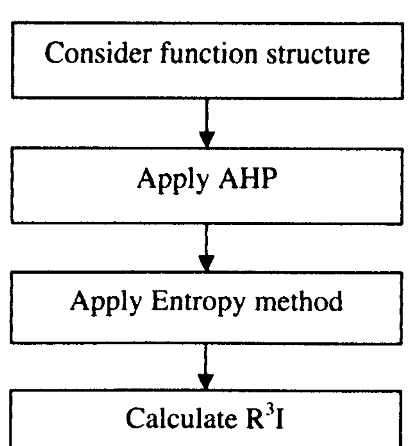


Figure 8.1 Steps to calculate R^3I

Realizability evaluation has been undertaken using the methodology by Asimov (1962), as shown in Figure 8.2 (section 5.3.2).

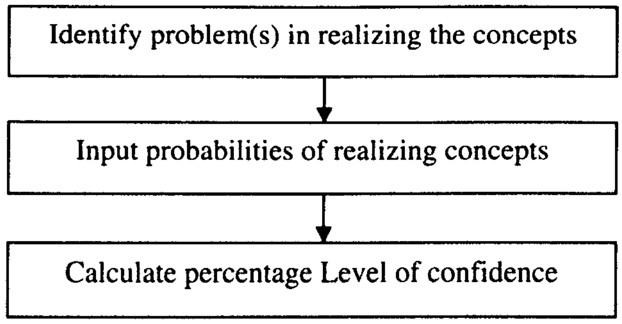


Figure 8.2 Steps to calculate Physical realizability

This research was guided by the following hypothesis:

The use of decomposition strategy in design evaluation during conceptual design phase would improve the Quality of decision making, especially for the original designs, and for novice designers when compared with that of experienced designers. This decomposition approach would also be able to handle the complexity of decision making in the desirable case when a large number of concepts are generated.

The hypothesis is true and it has been demonstrated, perhaps for the first time in chapter 7 that the Quality of decision making indeed improves when decomposed design evaluation strategy is adopted by the designers. Also, decomposed design evaluation helps break the problem into individual entities which makes it capable of handling the complexity of the evaluation problem.

The thesis set some objectives in chapter 1 and they have been fulfilled in the following manner:

- Various decision making tools and their information capture procedure have been discussed.
- Various reliability and realizability tools have been classified and discussed.

- A novel methodology for reliability has been proposed and Asimov's realizability evaluation has been adopted in this research.
- Validation is carried out on both the above methodologies using controlled experimental design.
- Both the methodologies are applicable in conceptual design phase. These methodologies create a link with various other methods that can be used in other phases of design.

In chapter 1, it is confirmed that experienced designers tend to use decomposed problem solving strategy whereas novices tend to use holistic methods. Decomposed design evaluation is then proposed to help designers evaluate design concepts using decomposition strategy. It is hypothesized that design evaluation through decomposed evaluation strategy would lead to better decision making. The research guidance by Design Research Methodology (Blessing and Chakrabarti 2002) has been accepted and is explained in the chapter. Validation issues in design research are discussed and Validation Square is considered in this thesis. Design research lacks a suitable validation methodology. However Validation Square and controlled experimental design do help to address this problem. Impact model of research is derived and a measurable criterion of success in this research is established. Quality of decision making has been established as a measurable criteria and its measurement in quantitative terms is defined.

Chapter 2 focuses on introducing the background of design evaluation. Some design processes are discussed and the importance of design evaluation in industry is explored. The results of the questionnaire surveys provide sufficient proof of a need for new evaluation methods. For decomposed evaluation, the questionnaire surveys and interviews with the company personnel helped identify the elements of decomposed design approach to focus upon. Reliability and realizability criteria have been identified for further investigation in this thesis.

To understand decomposed design evaluation, various decision making methods are studied in chapter 3. Decision making, in general and relating to engineering design is discussed. The study of decision making methods helps to understand the phenomenon of information capture during this activity. Information capture in decision making is considered important here because conceptual design phase is an information poor phase. Generally, the information present during this phase is qualitative or "soft" and so decision making methods are studied with respect to their information capture.

Since reliability and realizability criteria have been identified as important elements of decomposed design evaluation in chapter 2, individual studies of literature for reliability and realizability are covered in chapter 4. For reliability, a review on various reliability methods in all phases of design is undertaken. Attention is also given to some reliability methods that use decision making tools. The review reveals that there is no existing method that evaluates reliability in conceptual design phase for all types of design. The types of designs identified are original, adaptive, variant and catalog. For realizability, Asimov's (1962) physical realizability evaluation is found to serve the purpose and is adopted for further research.

With an understanding of decision making, reliability and realizability from chapters 3 and 4, the methodologies for evaluating reliability and physical realizability have been proposed in chapter 5. In the case of reliability evaluation, it is found that reliability cannot be calculated due to the lack of information availability in conceptual design phase. Hence a Relative reliability risk evaluation methodology has been proposed. It has been called relative because it captures relative data for various alternatives using the Analytic Hierarchy Process. Also, it provides a risk in terms of reliability of going ahead with a concept. Physical realizability evaluation has actually been proposed to provide an indication of the cost criterion. Again, due to a dearth of information available during the conceptual design phase, Asimov's physical realizability evaluation has been adopted in this thesis. Both of the methodologies are explained in detail. Their application is illustrated using an example problem from the available literature. Both of the methodologies do have some limitations and they are listed in this chapter.

Chapter 6 represents an important part of Validation Square. Validation Square has been used in this thesis on Relative reliability risk methodology to underpin confidence in using it. Four examples have been considered on which the methodology is applied. Three examples are from the student projects and one example is from industry. The examples are from various application areas and represent different types of designs. The results show ease of application of methodology and its generic nature of application on various types of designs. The industry example made it possible to compare the existing reliability data with the company and the results of the methodology application. The results of methodology application on the industry example were found positive.

Validation issues for both the methodologies in this thesis have been covered in chapter 7. Controlled experimental design from social science research is followed. Validation is achieved using novices' and experts' views. Novices' views were recorded with and without the application of the methodologies. Both of these views were compared with the experts' views. The change in the novices' results is noted. Improvement in Quality of decision making is measured using a Rho coefficient that measures the correlation between the paired ordinal data. The results obtained for both the methodologies are positive. For Relative reliability risk assessment methodology, a substantial increase in Quality of decision making has been observed. In case of physical realizability, little improvement in Quality of decision making was found. Physical realizability methodology has not indicated an ease of its application and hence, an improvement of this methodology has been suggested. Limitations of time factors and other resources did not allow another exploratory research to be carried out to test this improved methodology. Thus, the decomposed design evaluation improves the quality of decision making at the same time.

8.2 Recommendations on Future Research

8.2.1 Decomposed Design Evaluation Approach

Decomposed design evaluation approach has been followed in this thesis for reliability and realizability criteria. It has been demonstrated that decomposed design evaluation has a positive effect on decision making in conceptual design phase. But a rigorous investigation of this approach requires to be tested in industry once it has been captured in a computer environment. The research is conducted in this thesis with respect to reliability and realizability. Other criteria, that are also important to industry designers can be investigated and their Black boxes investigated in a similar manner as reported in chapter 5 for reliability and realizability.

8.2.2 Relative Reliability Risk Assessment Methodology

As discussed in section 5.4.1, there are certain limitations associated with Relative reliability risk evaluation methodology. This is due to the application of AHP and functional modelling that form a part of this methodology.

More research is required on identification of "important functions" considered during the application of this methodology. Pahl and Beitz mention that main functions in a function structure contribute directly to the achievement of the objective function and hence can be considered important. But auxiliary functions can be important too. Along with this, research is also required to identify the abstraction level of the function structure that should be considered for applying this methodology.

The methodology can also be improved if AHP application is incorporated along with fuzzy logic. Research is being conducted on the combination of AHP and fuzzy logic (Yeo et al 2004) for selection decisions and this could help improve the methodology.

8.2.3 Physical Realizability Methodology

Physical realizability methodology by Asimov (1962) was found to have some limitations, see section 5.4.2. Due to these limitations, physical realizability methodology by Asimov also needs to be tested rigorously in an industrial environment. An improved methodology to evaluate physical realizability was proposed in section 7.7.2. Its application has been illustrated by an example but this methodology needs refinement and another experimental design for its validation.

Given the positive results of the research described in this thesis it is now clear that if the decomposed design evaluation approach is integrated within a Computer Aided Design environment future designers will be able to take better decisions. This is particularly important with respect to the need to increase the productivity of the design process by enabling designers to evaluate large numbers of concept designs in an efficient manner. Equally the methodology described in this thesis offers the possibility for geographically distributed teams of multidisciplinary experts to undertake group evaluation of emerging design ideas.

Appendix A.1 Questionnaire to the Companies

Importance of Conceptual design and Evaluation

This research aims at developing a CAD tool that will help designers to evaluate the design concepts with respect to various criteria under consideration. Conceptual design is that phase of design, which takes a statement of a design problem and generates schemes. Concept design evaluation (or Design evaluation) is a process of selecting the best scheme or concept generated during this phase.

Name of the Organisation: ☐

Some facts about yourself:

Name: ☐

Age: ☐

Designation: ☐

No. of years in the organisation: ☐

Section I

1. Which design phase do you think is most important? Please prioritise the following phases:

☐ Generation of Product design specification

☐ Concept design

☐ Detail design

2. Out of the following departments, which one(s) are involved in the conceptual design phase? (Tick all those that apply)

☐ Design ☐ Marketing ☐ Production

☐ Maintenance ☐ Finance ☐ Quality

If others, please specify.....................................

3. Which criteria do you think is most important? Please prioritise the following criteria:

Criteria	Rank
Quality	
Reliability	
Maintainability	
Manufacturability	
Ease of Assembly	
Performance	
Cost	

Section II:

1. Which of the following CAD tools is/are used in your company?

☐ I-DEAS ☐ Pro/E ☐ Solidworks

☐ AutoCAD ☐ SolidEdge ☐ Catia

If others, please specify......................................

2. Do you keep most of your components/assembly/product in CAD environment?

☐ Yes ☐ No

Section III

1. Do you use Computer Aided tools for evaluation of the following criteria?

Criteria	Yes	No	If yes, please specify the tool
Reliability			
Maintainability			
Manufacturability			
Ease of assembly			
Performance			
Cost			

2. If the answer to the above is Yes, how satisfied are you with that tool?

☐ Highly Satisfied ☐ Satisfied ☐ Dissatisfied

3. Do you draw/model/assemble the concepts in CAD environment?

☐ Yes ☐ No

4. Do you desire to have a tool for Evaluation embedded in some conventional CAD environment?

Definitely No 1 2 3 4 5 6 7 8 9 10 Definitely Yes

Please encircle the one that applies. 1 = Definitely No and 10 = Definitely Yes

Section IV

How many persons get involved during the conceptual design phase?

☐ Less than 3 ☐ 3 to 7 ☐ 7 to 10

☐ 10 to 15 ☐ More than 15

2. What percentage of the Total design time do you spend on conceptual design?

☐ Less than 20% ☐ 20 to 40% ☐ 40 to 60%

If other, please specify.......................................

Section V

Please add comments that you would like to share about the current Evaluation activity followed in your company:

Thank you very much for your cooperation.

Appendix A.2 Weight Assigning Methods, Normalising Techniques and Scales

A.2.1 Weight Assigning Methods

Various weight assigning methods (or techniques) can be used to evaluate weights. To understand them, consider a decision matrix in Table A.2.1.

Attribute	Weight	Alternatives			
		A_1	A_2	...	A_n
X_1	w_1	x_{11}	x_{12}	...	x_{1n}
X_2	w_2	X_{21}	x_{22}	...	x_{2n}
...	...	...	...	...	...
X_m	w_m	x_{m1}	x_{m2}	...	x_{mn}
Score		S_1	S_2	...	S_n

Table A.2.1 Decision matrix

1. Direct weight assigning

Experienced designers find it easy to directly assign the weights to the attributes. They can directly do so as they can perceive the importance of attributes. This is represented by:

$$W = [w_1\ w_2\ w_3 \ldots\ldots\ w_m] \qquad \text{(A.2.1)}$$

where $\sum w_i = 1$

These weights are also called as true weights.

2. Rank sum weights

In this case, the m attributes available are ranked by the decision maker. Rank sum weights for attributes can be obtained (Eckenrode 1965) using the following formula:

$$w_i = \frac{m - R_i + 1}{\sum_{j=1}^{m} m - R_j + 1} \qquad \text{(A.2.2)}$$

m is the number of attributes and R_i is the rank of attribute j.

3. Rank reciprocal weights

These weights can be obtained using the normalized reciprocals of the ranks with the help of following formula:

$$w_i = \frac{1/R_i}{\sum_{j=1}^{m} 1/R_j} \qquad \text{(A.2.3)}$$

A.2.2 Normalising Techniques

Preference values x_{ij} of Decision matrix Table A.1.1 cannot be processed together to obtain a final score. This is because of the difference in units of measures of various attributes. To bring them to a similar platform of so as to combine/process them, Normalisation is done. Types of Normalising techniques are:

1. Vector normalization:

$$y_{ij} = \frac{x_{ij}}{\sqrt{\sum_{i=1}^{m} x_{ij}^2}} \qquad \text{(A.2.4)}$$

2. Linear scale transformation:

For benefit attributes (These are the attributes in which benefit derived is directly proportional to the preference value),

$$y_{ij} = \frac{x_{ij}}{x_i^{max}} \qquad \text{(A.2.5)}$$

For cost attributes (These are the attributes in which benefit derived is inversely proportional to the preference value),

$$y_{ij} = 1 - \frac{x_{ij}}{x_i^{max}} \qquad \text{(A.2.6)}$$

Following formulas can also be used for linear scale transformations:

For benefit attributes

$$y_{ij} = \frac{x_{ij} - x_i^{min}}{x_i^{max} - x_i^{min}} \qquad \text{(A.2.7)}$$

For cost Attributes,

$$y_{ij} = \frac{x_i^{max} - x_{ij}}{x_i^{max} - x_i^{min}} \qquad (A.2.8)$$

x_i^{max} is the maximum preference value of an attribute and x_i^{min} is the minimum preference value of an attribute.

A.2.3 Scales of Measurement

1. Nominal scale

Nominal scales are assigned to arbitrary data for example Gender, True/False, category etc. It does not carry any numeric meaning and hence cannot process data like numbers. This is simply for classifying the data. Also called as Categorical scale.

2. Ordinal scale

These scales are for the ordered data but the differences/interval between the values are not important and are indeterminate for example University rankings, Manufacturing company rankings etc

3. Interval scale

This scale represents an ordered constant scale. But there is no natural 0 in this scale. The differences are logical although ratios are not. Examples are temperature scales F, say the difference between $50^{\circ} - 20^{\circ}$ is same as $70^{\circ} - 40^{\circ}$.

4. Ratio scale

This is an ordered constant scale with a natural 0. The ratios in this scale are equivalent. Examples include Height, Weight, Length etc.

Appendix A.3 Design of Electro-Mechanical Car Jack

Engineering Product Design Project DWD3
Dr. G. Green

Introduction:
You are required to design an electro-mechanical car jack that can be powered from a standard lighter socket. The car jack must be designed (styled) for a particular (4x4) make of car. The jack is to be sold with the car.

The aim is to develop and integrate the design and engineering skills/knowledge that you have acquired to date. Students may share the results from user and technology research but must produce their own specific design solution for their selected vehicle and manufacturer.

Objectives:
The objectives of this project are:
- To allow students to exercise and refine their developing visual communication and rendering skills
- To allow students to apply their acquired industrial design skills
- To develop their understanding and control of a modern concurrent design process
- To integrate engineering and manufacturing considerations to their design process

Deliverables:
Students are required to submit the following piece of work for assessment and subsequent retention within their portfolios:
- A3 Folio containing ten A3 sheets comprising: selected concept sketch sheets, hand rendered perspective views, user/market research, product graphics, human factors (including photos of any physical models used) and 2 x A3 presentation sheets visually summarising the design development and the technical analysis.

Appendix A.4 Questionnaire Q_{N1}

Reliability and Physical Realizability Evaluation in Conceptual Design phase

By:
Girish Mamtani,
3rd year – PhD,
Mechanical engineering,
Glasgow University,
UK

Supervised by:
Dr. Graham Green

Notes

Please refer to the following notes before answering the questions:

1. This Questionnaire is not a part of your class assessment. It is for your better understanding and research on Design evaluation during the Conceptual design phase.
2. Please do not hesitate in answering and expressing your views. Your views and active participation are very important for this research project.
3. The information you provide will be kept confidential and will remain with Mr. Girish Mamtani and Dr. Graham Green.
4. This is a part of research project – Evaluation of Reliability and Physical Realizability in Conceptual Design phase.
5. The important goals of the Questionnaire are:
   - Validation issues and assessment of Reliability risk assessment and Physical realizability methodology.
   - Physical realizability exploratory study to explore the factors that lead to judging the concept(s) on the basis of Physical realizability.
   - Understanding the importance of Design evaluation and various criteria considered during Design evaluation.

Terms used in the Questionnaire and their Definitions

Reliability:
The definition of Reliability according to BS47778 is: "The ability of an item to perform a required function under stated conditions for a stated period of time". (BS 47778 1990)

In this Questionnaire, Reliability is meant to address the issues of function breakdown as well and not only the actual breakdown of a part or the whole system. If the performance of function in the item is affected, the Reliability of an item is affected as well. For e.g. If a car brake is manufactured to stop a car running at 50 Km/hr in about 25 metres, and if it doesn't do so then its Reliability is low (than it is supposed to be) though the brakes are still working and haven't actually broken down.

Conceptual design:
The part of engineering design process whereby the initial ideas and concepts are generated and evaluated. At the end of the Conceptual design process, one decides the final concept to pursue through the rest of the design process.

Design evaluation:
A Decision making activity whereby various concepts are evaluated so as to select one (or more) out of them.

Criteria:
During design evaluation, the concepts are evaluated against various attributes of the product being designed. These are called as criteria e.g. Reliability, Aesthetics, Cost and so on.

Physical realizability:
It is the realising of idea or concept into a final product within the allotted Budget of cost and time. This may include for example Ease of manufacture, Ease of implementing the technology.

Main functions (functions):
Any product, which is designed, has to perform certain functions that are the very important part of its existence and working. These are called as Main functions.

Original designs:
Designs that incorporate new solution principles are termed as Original designs. "These are realised either by selecting and combining known principles and technology or by inventing completely new technology" (Pahl & Beitz 1996).

Design phases:
Following are 3 important phases of design:

1. Conceptual design phase
2. Embodiment design phase
3. Detail design phase

Questions: General

Please refer to Concepts (Concept A to Concept H) for answering the following questions.

1.1 Which Concept do you think is the most innovative one? (Tick the one you think is applicable.)

☐ Concept A ☐ Concept B ☐ Concept C ☐ Concept D

☐ Concept E ☐ Concept F ☐ Concept G ☐ Concept H

1.2 Which Concept out of the chosen ones would you finally select to manufacture? (Tick the one you think is applicable.)

☐ Concept A ☐ Concept B ☐ Concept C ☐ Concept D

☐ Concept E ☐ Concept F ☐ Concept G ☐ Concept H

1.3 Out of the 3 Design phases, which one do you think is the most important one? (Tick the one you think is applicable.)

☐ Concept Design

☐ Embodiment Design

☐ Detail Design

1.4 What criteria do you think are critical while deciding the final Concept to pursue? (Say Cost, aesthetics, Compactness etc...). In other words, on what basis did you select the Concept in Question 1.2 above?

1.5 Which brand of the car (if any) did you pick for designing the Car Jack?

Questions: Reliability

Please refer to Concepts (Concept A to Concept H) for answering the following questions.

2.1 Please rank the concepts from 1 to 8 with regard to Reliability. 1 refers to the Best concept out of the available ones with respect to Reliability and 8 refers to vice versa (Encircle the numbers against each Concept). Also provide the weights for the Concepts so that the total of weights for all the concepts equals to 1.

Concept	**Rank**								**Weight**
Concept A	1	2	3	4	5	6	7	8	
Concept B	1	2	3	4	5	6	7	8	
Concept C	1	2	3	4	5	6	7	8	
Concept D	1	2	3	4	5	6	7	8	
Concept E	1	2	3	4	5	6	7	8	
Concept F	1	2	3	4	5	6	7	8	
Concept G	1	2	3	4	5	6	7	8	
Concept H	1	2	3	4	5	6	7	8	
Total									1.0

2.2 Why do you think the Concept you have ranked as first (1) in Question 2.1 is the most Reliable Concept?

2.3 Please list any assumptions you made when coming to your conclusion about the Reliability of the concepts e.g. the structure of Concepts, prior in-depth knowledge of concept, layout of Concept and so on...

2.4 The Main functions (or Important functions) for a Car Jack are:

A: Lift the car
B: Support the car
C: React to the ground

Do you think there is any other function that is important and not listed above?

☐ Yes ☐ No

If your answer is Yes, please go to Question 2.5, else go to Question 2.6.

2.5 Please mention the function (s) that you think are fundamental to the operation of Car Jack and have not been considered in Question 2.4.

....
....
....
....

2.6 Please provide the weights for the Functions discussed in Question 2.4 and Question 2.5 (If new functions added) so that the total weight equals to 1. The weights here refers to the quantified importance of the function and show how much important a function is.

S. No.	Function	Weight
1	Lift the car	
2	Support the car	
3	React to the ground	
4	....	
5	....	
6	....	

2.7 Please fill in the matrix attached. This is the application of Analytic Hierarchy process for relative comparison of concepts under consideration. AHP is a Decision support tool that can be used in various areas including Design Evaluation. You shall also be guided to apply the same during the Interview.

Lift	Concept A	Concept B	Concept C	Concept D	Concept E	Concept F	Concept G	Concept H
Concept A	1							
Concept B		1						
Concept C			1					
Concept D				1				
Concept E					1			
Concept F						1		
Concept G							1	
Concept H								1

Support	Concept A	Concept B	Concept C	Concept D	Concept E	Concept F	Concept G	Concept H
Concept A	1							
Concept B		1						
Concept C			1					
Concept D				1				
Concept E					1			
Concept F						1		
Concept G							1	
Concept H								1

React	Concept A	Concept B	Concept C	Concept D	Concept E	Concept F	Concept G	Concept H
Concept A	1							
Concept B		1						
Concept C			1					
Concept D				1				
Concept E					1			
Concept F						1		
Concept G							1	
Concept H								1

Function	Concept A	Concept B	Concept C	Concept D	Concept E	Concept F	Concept G	Concept H
Concept A	1							
Concept B		1						
Concept C			1					
Concept D				1				
Concept E					1			
Concept F						1		
Concept G							1	
Concept H								1

Questions: Physical Realizability

3.1 Please rank the concepts from 1 to 8 with regard to Cost. 1 refers to the cheapest concept to realise out of the available ones and 8 refers to vice versa (Encircle the numbers against each Concept). Also provide the weights for the Concepts so that the total of weights for all the concepts equals to 1.

Concept	Rank								Weight
Concept A	1	2	3	4	5	6	7	8	
Concept B	1	2	3	4	5	6	7	8	
Concept C	1	2	3	4	5	6	7	8	
Concept D	1	2	3	4	5	6	7	8	
Concept E	1	2	3	4	5	6	7	8	
Concept F	1	2	3	4	5	6	7	8	
Concept G	1	2	3	4	5	6	7	8	
Concept H	1	2	3	4	5	6	7	8	
Total									1.0

3.2 Why do you think the Concept you have ranked as first (1) in Question 3.1 is the Cheapest Concept to realise?

3.3 Imagine you have to realise a Concept and you have fixed number of resources (Budget allotted, people, material etc) to do so, which Concept out of the available ones do you think would take the minimum amount of Time to realise? Please rank the concepts from 1 to 8 for the same and provide the weights.

Concept	Rank								Weight
Concept A	1	2	3	4	5	6	7	8	
Concept B	1	2	3	4	5	6	7	8	
Concept C	1	2	3	4	5	6	7	8	
Concept D	1	2	3	4	5	6	7	8	
Concept E	1	2	3	4	5	6	7	8	
Concept F	1	2	3	4	5	6	7	8	
Concept G	1	2	3	4	5	6	7	8	
Concept H	1	2	3	4	5	6	7	8	
Total									1.0

3.4 Why do you think the Concept you have ranked as first (1) in Question 3.3 shall take minimum Time to realise?

3.5 We think that the important factors to consider while evaluating Physical Realizability of a Concept are:

A: Realising the Concept in allocated time
B: Ease of manufacture
C: Harnessing and implementing the technology

Do you think there is any other factor that is important and not listed above?

☐ Yes ☐ No

3.6 If your answer to Question 3.5 is Yes, please mention the factor(s) that you think are important to consider while evaluating Physical Realizability of a Concept fundamental to the operation of Car Jack and have not been considered in Question 3.5.

....
....
....
....

Thank you very much for your efforts and cooperation.

Appendix A.5 Questionnaire Q_{N2}

Reliability and Physical Realizability Evaluation in Conceptual Design phase

By:
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Supervised by:
Dr. Graham Green

Notes

Please refer to the following Notes before answering the Questions:

6. This Questionnaire is not a part of your class assessment. It is for your better understanding and research on Design evaluation during the Conceptual design phase.

7. Please do not hesitate in answering and expressing your views. Your views and active participation are very important for this research project.

8. The information you provide will be kept confidential and will remain with Mr. Girish Mamtani and Dr. Graham Green.

9. This is a part of research project – Evaluation of Reliability and Physical Realizability in Conceptual Design phase.

10. The important goals of the Questionnaire are:
    - Validation issues and assessment of Reliability Risk Assessment and Physical Realizability methodology.
    - Physical Realizability Exploratory study to explore the factors that lead to judging the Concept(s) on the basis of Physical Realizability.
    - Understanding the importance of Design Evaluation and various Criteria considered during Design Evaluation.

Terms used in the Questionnaire and their Definitions

Conceptual design:
The part of Engineering Design process whereby the initial ideas and Concepts are generated and evaluated. At the end of the Conceptual Design process, one decides the final Concept to pursue through the rest of the Design process.

Physical realizability:
It is the realising of idea or Concept into a final product within the allotted Budget of Cost and Time. This may include for example Ease of manufacture, Ease of implementing the technology.

1. What is the probability that Concept A is Physically Realizable within the Budgeted cost of 50 £?

2. What is the probability that Concept B is Physically Realizable within the Budgeted cost of 50 £?

3. What is the probability that Concept C is Physically Realizable within the Budgeted cost of 50 £?

4. What is the probability that Concept D is Physically Realizable within the Budgeted cost of 50 £?

5. What is the probability that Concept E is Physically Realizable within the Budgeted cost of 50 £?

6. What is the probability that Concept F is Physically Realizable within the Budgeted cost of 50 £?

7. What is the probability that Concept G is Physically Realizable within the Budgeted cost of 50 £?

8. What is the probability that Concept H is Physically Realizable within the Budgeted cost of 50 £?

9. Imagine we implemented this Technology (In Concept A, it refers to the pneumatic and corrugated plastic) in Concept A and the prototype failed and was not Physically Realizable, what is the probability that this Technology implemented and tested in earlier stages (Before the prototype is built) would have still passed the tests?

10. Imagine we implemented this Technology (In Concept B, it refers to the telescopic screw) in Concept B and the prototype failed and was not Physically Realizable, what is the probability that this Technology implemented and tested in earlier stages (Before the prototype is built) would have still passed the tests?

11. Imagine we implemented this Technology (In Concept C, it refers to the Chain/belt and sprocket/pulley) in Concept C and the prototype failed and was not Physically Realizable, what is the probability that this Technology implemented and tested in earlier stages (Before the prototype is built) would have still passed the tests?

12. Imagine we implemented this Technology (In Concept D, it refers to the mechanical gearbox) in Concept D and the prototype failed and was not Physically Realizable, what is the probability that this Technology implemented and tested in earlier stages (Before the prototype is built) would have still passed the tests?

13. Imagine we implemented this Technology (In Concept E, it refers to the Hydraulic system) in Concept E and the prototype failed and was not Physically Realizable, what is the probability that this Technology implemented and tested in earlier stages (Before the prototype is built) would have still passed the tests?

14. Imagine we implemented this Technology (In Concept F, it refers to the gear and links) in Concept F and the prototype failed and was not Physically Realizable, what is the probability that this Technology implemented and tested in earlier stages (Before the prototype is built) would have still passed the tests?

15. Imagine we implemented this Technology (In Concept G, it refers to the screw and bevel gears) in Concept G and the prototype failed and was not Physically Realizable, what is the probability that this Technology implemented and tested in earlier stages (Before the prototype is built) would have still passed the tests?

16. Imagine we implemented this Technology (In Concept H, it refers to the Links and screw) in Concept H and the prototype failed and was not Physically Realizable, what is the probability that this Technology implemented and tested in earlier stages (Before the prototype is built) would have still passed the tests?

Appendix A.6 Questionnaire Q_{E1}

Reliability and Physical Realizability Evaluation in Conceptual Design phase

By:
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3rd year – PhD,
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UK

Supervised by:
Dr. Graham Green

Notes

I have proposed a methodology for evaluating Reliability Risk evaluation and adopted Asimov's (Introduction to Design, Asimov 1962) methodology for Physical realizability of concepts. It has been applied to an example of Electro mechanical Car jack (The same example used here) by the students. To validate the methodologies, I have prepared this Questionnaire for Experienced people in Design.

Please refer to the following Notes before answering the Questions:

1 The information you provide will be kept confidential and will remain with Mr. Girish Mamtani and Dr. Graham Green.

2 The goals of the Questionnaire are:

- Validation issues and assessment of Reliability Risk Assessment Methodology.
- Physical realizability study exploring the factors that lead to judging the concept(s) on the basis of Physical Realizability.

Terms used in the Questionnaire and their Definitions

Reliability:
The definition of Reliability according to BS47778 is: "The ability of an item to perform a required function under stated conditions for a stated period of time". (BS 47778 1990)

In this Questionnaire, Reliability is meant to address the issues of function breakdown as well and not only the actual breakdown of a part or the whole system. If the performance of function in the item is affected, the Reliability of an item is affected as well. For e.g. If a car brake is manufactured to stop a car running at 50 Km/hr in about 25 metres, and if it doesn't do so then its Reliability is low (than it is supposed to be) though the brakes are still working and haven't actually broken down.

Conceptual design:
The part of engineering design process whereby the initial ideas and concepts are generated and evaluated. At the end of the Conceptual design process, one decides the final concept to pursue through the rest of the design process.

Design evaluation:
A Decision making activity whereby various concepts are evaluated so as to select one (or more) out of them.

Criteria:
During design evaluation, the concepts are evaluated against various attributes of the product being designed. These are called as criteria e.g. Reliability, Aesthetics, Cost and so on.

Physical realizability:
It is the realising of idea or concept into a final product within the allotted Budget of cost and time. This may include for example Ease of manufacture, Ease of implementing the technology.

Main functions (functions):
Any product, which is designed, has to perform certain functions that are the very important part of its existence and working. These are called as Main functions.

Original designs:
Designs that incorporate new solution principles are termed as Original designs. "These are realised either by selecting and combining known principles and technology or by inventing completely new technology" (Pahl and Beitz 1996).

Design phases:
Following are 3 important phases of design:

4. Conceptual design phase
5. Embodiment design phase
6. Detail design phase

General Questions

Name:

Age (Optional):

Number of years of Experience:

Questions: Reliability

Please refer to Concepts (Concept A to Concept H) for answering the following questions.

1.1 Please rank the concepts from 1 to 8 with regard to Reliability. 1 refers to the Best concept out of the available ones with respect to Reliability and 8 refers to vice versa (Encircle the numbers against each Concept). Also provide the weights for the Concepts so that the total of weights for all the concepts equals to 1.

Concept	**Rank**								**Weight**
Concept A	1	2	3	4	5	6	7	8	
Concept B	1	2	3	4	5	6	7	8	
Concept C	1	2	3	4	5	6	7	8	
Concept D	1	2	3	4	5	6	7	8	
Concept E	1	2	3	4	5	6	7	8	
Concept F	1	2	3	4	5	6	7	8	
Concept G	1	2	3	4	5	6	7	8	
Concept H	1	2	3	4	5	6	7	8	
Total									1.0

1.2 Why do you think the Concept you have ranked as first (1) in Question 1.1 is the most Reliable Concept?

1.3 Please list any assumptions you made when coming to your conclusion about the Reliability of the concepts e.g. the structure of Concepts, prior in-depth knowledge of concept, layout of Concept and so on...

Questions: Physical Realizability

2.1 Please rank the concepts from 1 to 8 with regard to Cost. 1 refers to the cheapest concept to realise out of the available ones and 8 refers to vice versa (Encircle the numbers against each Concept). Also provide the weights for the Concepts so that the total of weights for all the concepts equals to 1.

Concept	Rank								Weight
Concept A	1	2	3	4	5	6	7	8	
Concept B	1	2	3	4	5	6	7	8	
Concept C	1	2	3	4	5	6	7	8	
Concept D	1	2	3	4	5	6	7	8	
Concept E	1	2	3	4	5	6	7	8	
Concept F	1	2	3	4	5	6	7	8	
Concept G	1	2	3	4	5	6	7	8	
Concept H	1	2	3	4	5	6	7	8	
Total									1.0

2.2 Why do you think the Concept you have ranked as first (1) in Question 2.1 is the Cheapest Concept to realise?

2.3 Imagine you have to realise a Concept and you have fixed number of resources (Budget allotted, people, material etc) to do so, which Concept out of the available ones do you think would take the minimum amount of Time to realise? Please rank the concepts from 1 to 8 for the same and provide the weights.

Concept	Rank								Weight
Concept A	1	2	3	4	5	6	7	8	
Concept B	1	2	3	4	5	6	7	8	
Concept C	1	2	3	4	5	6	7	8	
Concept D	1	2	3	4	5	6	7	8	
Concept E	1	2	3	4	5	6	7	8	
Concept F	1	2	3	4	5	6	7	8	
Concept G	1	2	3	4	5	6	7	8	
Concept H	1	2	3	4	5	6	7	8	
Total									1.0

2.4 Why do you think the Concept you have ranked as first (1) in Question 3.3 shall take minimum Time to realise?

Thank you very much for your efforts and co-operation.

Appendix A.7 Questionnaire Q_{E2}

Reliability and Physical Realizability Evaluation in Conceptual Design phase

By:
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Supervised by:
Dr. Graham Green

Notes

I have adopted Asimov's (Introduction to Design, Asimov 1962) methodology for evaluating the Physical realizability of Concepts. It has been applied to an example of Car jack by the students. This involves the second phase of research on this methodology. We believe that Physical realizability is a measure derived from the combination of some factors. They are:

1. Encapsulating the simplest Technology in the concept
2. Requirement of Least number of Non-standard components
3. Simple geometry of individual parts and assembly in the Concept

This Questionnaire is aimed to procure ranks for the concepts with respect to above factors. I have prepared this Questionnaire for Experienced people in Design. The information you provide will be kept confidential and will remain with Mr. Girish Mamtani and Dr. Graham Green.

General Questions

Name:

Age (Optional):

Number of years of Experience:

Questions: Physical Realizability

1. Which of the Concepts encapsulates the simplest Technology?
Please rank the Concepts from 1 to 8. 1 refers to the Concept encapsulating the simplest technology and 8 refers to vice versa. (Encircle the numbers against each Concept). Also provide the weightings for the Concepts so that the total of weightings for all the concepts equals to 1.

Concept	Rank								Weight
Concept A	1	2	3	4	5	6	7	8	
Concept B	1	2	3	4	5	6	7	8	
Concept C	1	2	3	4	5	6	7	8	
Concept D	1	2	3	4	5	6	7	8	
Concept E	1	2	3	4	5	6	7	8	
Concept F	1	2	3	4	5	6	7	8	
Concept G	1	2	3	4	5	6	7	8	
Concept H	1	2	3	4	5	6	7	8	
Total									1.0

2. Which of the Concepts would require the Least number of Non-standard components?
Please rank the Concepts from 1 to 8. 1 refers to the Concept that requires the least no of Non-standard components and 8 refers to vice versa. (Encircle the numbers against each Concept). Also provide the weightings for the Concepts so that the total of weightings for all the concepts equals to 1.

Concept	Rank								Weight
Concept A	1	2	3	4	5	6	7	8	
Concept B	1	2	3	4	5	6	7	8	
Concept C	1	2	3	4	5	6	7	8	
Concept D	1	2	3	4	5	6	7	8	
Concept E	1	2	3	4	5	6	7	8	
Concept F	1	2	3	4	5	6	7	8	
Concept G	1	2	3	4	5	6	7	8	
Concept H	1	2	3	4	5	6	7	8	
Total									1.0

3. Which of the Concepts would exhibit the Simplest geometry of individual parts and assembly?
   Please rank the concepts from 1 to 8. 1 refers to the Concept that exhibits the Simplest geometry of individual parts and components and 8 refers to vice versa. (Encircle the numbers against each Concept). Also provide the weightings for the Concepts so that the total of weightings for all the concepts equals to 1.

Concept	**Rank**								**Weight**
Concept A	1	2	3	4	5	6	7	8	
Concept B	1	2	3	4	5	6	7	8	
Concept C	1	2	3	4	5	6	7	8	
Concept D	1	2	3	4	5	6	7	8	
Concept E	1	2	3	4	5	6	7	8	
Concept F	1	2	3	4	5	6	7	8	
Concept G	1	2	3	4	5	6	7	8	
Concept H	1	2	3	4	5	6	7	8	
Total									1.0

Thank you very much for your efforts and co-operation.

Appendix A.8 Experiment Results for Reliability

In this Appendix, the results of controlled experimental design obtained from the novices and experts with respect to reliability evaluation methodology are laid down. For novices, comparison matrices are presented. Values for various "Cases" studied in chapter 7 have been evaluated and listed. For experts, their direct inputs for reliability are listed.

A.8.1 Results from Inputs of Novice Designers

Novice 1

Lift	A	B	C	D	E	F	G	H
A	1	1/2	5	4	1	3	1/2	1/3
B	2	1	5	3	2	4	2	1/2
C	1/5	1/5	1	1/2	1/4	1	1/3	1/4
D	1/4	1/3	2	1	1/2	1	1/2	1/3
E	1	1/2	4	2	1	3	2	1
F	1/3	1/4	1	1	1/3	1	1/2	1/3
G	2	1/2	3	2	1/2	2	1	1/2
H	3	2	4	3	1	3	2	1

Table A.8.1 Comparison matrix for Lift, Novice 1 (Incon: 0.04)

Support	A	B	C	D	E	F	G	H
A	1	1/2	2	2	1/3	2	1	1/3
B	2	1	3	3	1	2	2	1
C	1/2	1/3	1	1	1/2	1	1/2	1/3
D	1/2	1/3	1	1	1/2	1	1/2	1/3
E	3	1	2	2	1	3	2	1
F	1/2	1/2	1	1	1/3	1	1/2	1/4
G	1	1/2	2	2	2	2	1	1/2
H	3	1	3	3	4	4	2	1

Table A.8.2 Comparison matrix for Support, Novice 1 (Incon: 0.02)

React	A	B	C	D	E	F	G	H
A	1	1	1	1	1	1	1	1
B	1	1	1	1	1	1	1	1
C	1	1	1	1	1	1	1	1
D	1	1	1	1	1	1	1	1
E	1	1	1	1	1	1	1	1
F	1	1	1	1	1	1	1	1
G	1	1	1	1	1	1	1	1
H	1	1	1	1	1	1	1	1

Table A.8.3 Comparison matrix for React, Novice 1 (Incon: 0.00)

	A	B	C	D	E	F	G	H	w_p
Lift	0.134	0.206	0.039	0.061	0.155	0.052	0.123	0.231	0.30
Support	0.101	0.188	0.065	0.065	0.192	0.063	0.110	0.216	0.40
React	0.125	0.125	0.125	0.125	0.125	0.125	0.125	0.125	0.30
Score	0.118	0.174	0.075	0.081	0.160	0.078	0.118	0.193	
Rank	5	2	8	6	3	7	4	1	

Table A.8.4 Priorities, scores and ranks for direct weights w_p for Novice 1

	A	B	C	D	E	F	G	H	w_e
Lift	0.134	0.206	0.039	0.061	0.155	0.052	0.123	0.231	0.56
Support	0.101	0.188	0.065	0.065	0.192	0.063	0.110	0.216	0.43
React	0.125	0.125	0.125	0.125	0.125	0.125	0.125	0.125	0
Score	0.119	0.198	0.050	0.062	0.171	0.056	0.117	0.224	
Rank	3	2	8	6	4	7	5	1	

Table A.8.5 Priorities, R^3I scores and ranks for entropy weights w_e for Novice 1

Novice 1		A	B	C	D	E	F	G	H
Case 1	Score	0.150	0.150	0.025	0.025	0.150	0.100	0.150	0.200
Case 1	Rank	3	5	8	7	2	6	4	1
Case 2	Score	0.119	0.198	0.050	0.062	0.171	0.056	0.117	0.224
Case 2	Rank	3	2	8	6	4	7	5	1
Case 3	Score	0.117	0.197	0.047	0.062	0.169	0.056	0.117	0.224
Case 3	Rank	4	2	8	6	3	7	5	1
Case 4	Score	0.118	0.174	0.075	0.081	0.160	0.078	0.118	0.193
Case 4	Rank	5	2	8	6	3	7	4	1
Case 5	Score	0.116	0.167	0.061	0.074	0.155	0.068	0.117	0.180
Case 5	Rank	5	2	8	6	3	7	4	1
Case 6	Score	0.360	0.519	0.229	0.251	0.472	0.240	0.358	0.572
Case 6	Rank	4	2	8	6	3	7	5	1
Case 7	Score	0.039	0.055	0.020	0.025	0.050	0.023	0.039	0.058
Case 7	Rank	5	2	8	6	3	7	4	1
Case 8	Rank	5	2	8	6	3	7	4	1

Table A.8.6 Scores and ranks for various Cases for Novice 1

Novice 2

Lift	A	B	C	D	E	F	G	H
A	1	1/7	3	1/3	1/6	4	3	1/5
B	7	1	8	5	2	5	5	2
C	1/3	1/8	1	1/4	1/8	1	1/2	1/7
D	3	1/5	4	1	1/5	4	1	1/4
E	6	1/2	8	5	1	8	4	2
F	1/4	1/5	1	1/4	1/8	1	1/5	1/6
G	1/3	1/5	2	1	1/4	5	1	1/2
H	5	1/2	7	4	1/2	6	2	1

Table A.8.7 Comparison matrix for Lift, Novice 2 (Incon: 0.08)

Support	A	B	C	D	E	F	G	H
A	1	4	6	1	4	4	3	3
B	1/4	1	4	1/2	1	1/2	1/3	1/4
C	1/6	1/4	1	1/6	1/3	1/2	1/4	1/5
D	1	2	6	1	1	1	1/4	1/2
E	1/4	1	3	1	1	1	1/4	1/2
F	1/4	2	2	1	1	1	1/4	1/2
G	1/3	3	4	4	4	4	1	1/2
H	1/3	4	5	2	2	2	2	1

Table A.8.8 Comparison matrix for Support, Novice 2 (Incon: 0.07)

React	A	B	C	D	E	F	G	H
A	1	1/2	1/2	1	1/2	1/2	1/4	1
B	2	1	1/2	4	1	1	2	4
C	2	2	1	4	1	1	2	4
D	1	1/4	1/4	1	1/6	1/4	1/4	1/2
E	2	1	1	6	1	1	1/2	3
F	2	1	1	4	1	1	1	4
G	4	1/2	1/2	4	2	1	1	4
H	1	1/4	1/4	2	1/3	1/4	1/4	1

Table A.8.9 Comparison matrix for React, Novice 2 (Incon: 0.04)

	A	B	C	D	E	F	G	H	w_p
Lift	0.067	0.306	0.025	0.080	0.254	0.025	0.064	0.179	0.33
Support	0.286	0.059	0.029	0.111	0.070	0.073	0.194	0.178	0.33
React	0.064	0.167	0.199	0.039	0.152	0.159	0.170	0.050	0.33
Score	0.137	0.175	0.083	0.075	0.157	0.084	0.141	0.134	
Rank	4	1	7	8	2	6	3	5	

Table A.8.10 Priorities, scores and ranks for direct weights w_p for Novice 2

	A	B	C	D	E	F	G	H	w_e
Lift	0.067	0.306	0.025	0.080	0.254	0.025	0.064	0.179	0.48
Support	0.286	0.059	0.029	0.111	0.070	0.073	0.194	0.178	0.32
React	0.064	0.167	0.199	0.039	0.152	0.159	0.170	0.050	0.19
Score	0.135	0.200	0.060	0.081	0.175	0.066	0.125	0.153	
Rank	4	1	8	6	2	7	5	3	

Table A.8.11 Priorities, R^3I scores and ranks for entropy weights w_e for Novice 2

Novice 2		A	B	C	D	E	F	G	H
Case 1	Score	0.050	0.250	0.050	0.100	0.200	0.100	0.100	0.150
Case 1	Rank	8	1	7	4	2	5	6	3
Case 2	Score	0.135	0.200	0.060	0.081	0.175	0.066	0.125	0.153
Case 2	Rank	4	1	8	6	2	7	5	3
Case 3	Score	0.087	0.123	0.031	0.071	0.129	0.039	0.096	0.118
Case 3	Rank	5	2	8	6	1	7	4	3
Case 4	Score	0.137	0.175	0.083	0.075	0.157	0.084	0.141	0.134
Case 4	Rank	4	1	7	8	2	6	3	5
Case 5	Score	0.089	0.115	0.038	0.064	0.122	0.050	0.113	0.097
Case 5	Rank	5	2	8	6	1	7	3	4
Case 6	Score	0.417	0.532	0.253	0.23	0.476	0.257	0.428	0.407
Case 6	Rank	4	1	7	8	2	6	3	5
Case 7	Score	0.029	0.038	0.012	0.021	0.040	0.016	0.037	0.032
Case 7	Rank	5	2	8	6	1	7	3	4
Case 8	Rank	3	4	8	6	1	7	2	5

Table A.8.12 Scores and ranks for various Cases for Novice 2

Novice 3

Lift	A	B	C	D	E	F	G	H
A	1	1/2	1/4	1/2	1/4	1/5	1/2	1/5
B	2	1	1/2	3	1	1	3	1
C	4	2	1	4	1	2	2	1
D	2	1/3	1/4	1	1/2	1/3	1/2	1/4
E	4	1	1	2	1	1	2	1
F	5	1	1/2	3	1	1	2	1
G	2	1/3	1/2	2	1/2	1/2	1	1/4
H	5	1	1	4	1	1	4	1

Table A.8.13 Comparison matrix for Lift, Novice 3 (Incon: 0.03)

Support	A	B	C	D	E	F	G	H
A	1	1/4	1/2	1	1/2	1/2	1	1/2
B	4	1	2	4	1	2	3	1
C	2	1/2	1	2	1/2	1/2	2	1/2
D	1	1/4	1/2	1	1/4	1/4	1	1/4
E	2	1	2	4	1	2	4	1
F	2	1/2	2	4	1/2	1	4	1
G	1	1/3	1/2	1	1/4	1/4	1	1/4
H	2	1	2	4	1	1	4	1

Table A.8.14 Comparison matrix for Support, Novice 3 (Incon: 0.02)

React	A	B	C	D	E	F	G	H
A	1	1	2	2	1	2	2	1
B	1	1	2	2	1	2	2	1
C	1/2	1/2	1	1	1/2	1	1	1/2
D	1/2	1/2	1	1	1/2	1	1	1/2
E	1	1	2	2	1	1	2	1
F	1/2	1/2	1	1	1	1	2	1
G	1/2	1/2	1	1	1/2	1/2	1	1/2
H	1	1	2	2	1	1	2	1

Table A.8.15 Comparison matrix for React, Novice 3 (Incon: 0.01)

	A	B	C	D	E	F	G	H	w_p
Lift	0.040	0.145	0.200	0.053	0.151	0.150	0.073	0.187	0.20
Support	0.065	0.207	0.097	0.049	0.198	0.154	0.051	0.179	0.40
React	0.168	0.168	0.084	0.084	0.154	0.112	0.077	0.154	0.40
Score	0.101	0.179	0.112	0.063	0.171	0.136	0.065	0.170	
Rank	6	1	5	8	2	4	7	3	

Table A.8.16 Priorities, scores and ranks for direct weights w_p for Novice 3

	A	B	C	D	E	F	G	H	w_e
Lift	0.040	0.145	0.200	0.053	0.151	0.150	0.073	0.187	0.40
Support	0.065	0.207	0.097	0.049	0.198	0.154	0.051	0.179	0.45
React	0.168	0.168	0.084	0.084	0.154	0.112	0.077	0.154	0.15
Score	0.070	0.176	0.136	0.055	0.172	0.146	0.063	0.178	
Rank	6	2	5	8	3	4	7	1	

Table A.8.17 Priorities, R^3I scores and ranks for entropy weights w_e for Novice 3

Novice 3		A	B	C	D	E	F	G	H
Case 1	Score	0.060	0.130	0.150	0.050	0.100	0.230	0.050	0.230
Case 1	Rank	6	4	2	5	3	2	6	1
Case 2	Score	0.070	0.176	0.136	0.055	0.172	0.146	0.063	0.178
Case 2	Rank	6	2	5	8	3	4	7	1
Case 3	Score	0.056	0.171	0.118	0.054	0.169	0.144	0.061	0.177
Case 3	Rank	7	2	4	8	3	5	6	1
Case 4	Score	0.101	0.179	0.112	0.063	0.171	0.136	0.065	0.170
Case 4	Rank	6	1	5	8	2	4	7	3
Case 5	Score	0.073	0.175	0.101	0.059	0.168	0.133	0.063	0.169
Case 5	Rank	6	1	5	8	3	4	7	2
Case 6	Score	0.273	0.520	0.381	0.186	0.503	0.416	0.201	0.520
Case 6	Rank	6	1	5	8	3	4	7	2
Case 7	Score	0.021	0.056	0.036	0.019	0.055	0.045	0.021	0.057
Case 7	Rank	7	2	5	8	3	4	6	1
Case 8	Rank	8	3	5	7	2	4	6	1

Table A.8.18 Scores and ranks for various Cases for Novice 3

Novice 4

Lift	A	B	C	D	E	F	G	H
A	1	1/3	1/2	2	1/2	2	2	1/2
B	3	1	2	2	1/4	2	2	1/2
C	2	1/2	1	1/2	1/2	1/2	1/2	1/2
D	1/2	1/2	2	1	2	2	1/2	1/2
E	2	4	2	1/2	1	2	2	1/2
F	1/2	1/2	2	1/2	1/2	1	1/2	1/2
G	1/2	1/2	2	2	1/2	2	1	1
H	2	2	2	2	2	2	1	1

Table A.8.19 Comparison matrix for Lift, Novice 4 (Incon: 0.12)

Support	A	B	C	D	E	F	G	H
A	1	1/2	1/4	1	1/2	2	1/2	1/2
B	2	1	3	2	1/2	1/2	1	3
C	4	1/3	1	1/2	1/4	2	1/2	1/4
D	1	1/2	2	1	1	2	1/2	1/4
E	2	2	4	1	1	1	2	3
F	1/2	2	1/2	1/2	1	1	1/2	1/3
G	2	1	2	2	1/2	2	1	1/4
H	2	1/2	4	4	1/3	3	4	1

Table A.8.20 Comparison matrix for Support, Novice 4 (Incon: 0.18)

React	A	B	C	D	E	F	G	H
A	1	1/2	1/3	1/2	1/4	1	1/2	1/5
B	2	1	1	2	1	1/4	3	1
C	3	1	1	1/3	1/2	4	2	1/2
D	2	1/2	3	1	1/3	1	1/4	1/2
E	4	1	2	3	1	1	1/2	3
F	1	4	1/4	1	1	1	2	2
G	2	1/3	1/2	4	2	1/2	1	1/2
H	5	1	2	2	1/3	1/2	2	1

Table A.8.21 Comparison matrix for React, Novice 4 (Incon: 0.21)

	A	B	C	D	E	F	G	H	w_p
Lift	0.106	0.147	0.076	0.110	0.180	0.071	0.113	0.196	0.35
Support	0.071	0.161	0.082	0.092	0.203	0.088	0.112	0.191	0.35
React	0.049	0.127	0.145	0.100	0.170	0.152	0.121	0.137	0.30
Score	0.076	0.146	0.098	0.100	0.185	0.101	0.115	0.176	
Rank	8	3	7	6	1	5	4	2	

Table A.8.22 Priorities, scores and ranks for direct weights w_p for Novice 4

	A	B	C	D	E	F	G	H	w_e
Lift	0.106	0.147	0.076	0.110	0.180	0.071	0.113	0.196	0.33
Support	0.071	0.161	0.082	0.092	0.203	0.088	0.112	0.191	0.41
React	0.049	0.127	0.145	0.100	0.170	0.152	0.121	0.137	0.25
Score	0.077	0.147	0.095	0.099	0.187	0.098	0.114	0.179	
Rank	8	3	7	5	1	6	4	2	

Table A.8.23 Priorities, R^3I scores and ranks for entropy weights w_e for Novice 4

Novice 4		A	B	C	D	E	F	G	H
Case 1	Score								
Case 1	Rank	5	3	7	6	4	8	2	1
Case 2	Score	0.077	0.147	0.095	0.099	0.187	0.098	0.114	0.179
Case 2	Rank	8	3	7	5	1	6	4	2
Case 3	Score	0.070	0.146	0.089	0.099	0.186	0.090	0.114	0.175
Case 3	Rank	8	3	7	5	1	6	4	2
Case 4	Score	0.076	0.146	0.098	0.100	0.185	0.101	0.115	0.176
Case 4	Rank	8	3	7	6	1	5	4	2
Case 5	Score	0.069	0.144	0.091	0.100	0.184	0.091	0.114	0.172
Case 5	Rank	8	3	7	5	1	6	4	2
Case 6	Score	0.226	0.435	0.303	0.302	0.553	0.311	0.346	0.524
Case 6	Rank	8	3	6	7	1	5	4	2
Case 7	Score	0.022	0.047	0.031	0.033	0.061	0.031	0.038	0.056
Case 7	Rank	8	3	7	5	1	6	4	2
Case 8	Rank	8	3	6	5	1	7	4	2

Table A.8.24 Scores and ranks for various Cases for Novice 4

Novice 5

Lift	A	B	C	D	E	F	G	H
A	1	1/2	1	1	1/7	1	1/2	1/2
B	2	1	1	1	1/7	1/2	1/3	1
C	1	1	1	1	1/5	1	1	1
D	1	1	1	1	1/7	1/2	1	1
E	7	7	5	7	1	1/7	1/7	1/7
F	1	2	1	2	7	1	1	1
G	2	3	1	1	7	1	1	1
H	2	1	1	1	7	1	1	1

Table A.8.25 Comparison matrix for Lift, Novice 5 (Incon: 0.33)

Support	A	B	C	D	E	F	G	H
A	1	6	2	1	1	3	1	3
B	1/6	1	1/2	1/3	1/4	1	1/2	1/2
C	1/2	2	1	1	1/2	1	1	1/2
D	1	3	1	1	1	1/2	1/2	1
E	1	4	2	1	1	1	1/2	1/2
F	1/3	1	1	2	1	1	1	1
G	1	2	1	2	2	1	1	3
H	1/3	2	2	1	2	1	1/3	1

Table A.8.26 Comparison matrix for Support, Novice 5 (Incon: 0.07)

React	A	B	C	D	E	F	G	H
A	1	1	3	1	1/2	5	1	3
B	1	1	1	1/3	1	3	1/3	1
C	1/3	1	1	1/4	1	3	1	1/2
D	1	3	4	1	5	4	3	2
E	2	1	1	1/5	1	1/3	1/4	1/4
F	1/5	1/3	1/3	1/4	3	1	1/5	1/6
G	1	3	1	1/3	4	5	1	2
H	1/3	1	2	1/2	4	6	1/2	1

Table A.8.27 Comparison matrix for React, Novice 5 (Incon: 0.15)

	A	B	C	D	E	F	G	H	w_p
Lift	0.056	0.061	0.077	0.067	0.170	0.190	0.165	0.184	0.30
Support	0.209	0.053	0.095	0.111	0.127	0.112	0.175	0.117	0.60
React	0.167	0.087	0.078	0.245	0.075	0.051	0.166	0.131	0.10
Score	0.158	0.058	0.087	0.111	0.134	0.129	0.171	0.138	
Rank	2	8	7	6	4	5	1	3	

Table A.8.28 Priorities, scores and ranks for direct weights w_p for Novice 5

	A	B	C	D	E	F	G	H	w_p
Lift	0.056	0.061	0.077	0.067	0.170	0.190	0.165	0.184	0.44
Support	0.209	0.053	0.095	0.111	0.127	0.112	0.175	0.117	0.20
React	0.167	0.087	0.078	0.245	0.075	0.051	0.166	0.131	0.36
Score	0.126	0.068	0.081	0.138	0.127	0.125	0.167	0.151	
Rank	5	8	7	3	4	6	1	2	

Table A.8.29 Priorities, R^3I scores and ranks for entropy weights w_e for Novice 5

Novice 5		A	B	C	D	E	F	G	H
Case 1	Score	0.150	0.100	0.100	0.050	0.180	0.050	0.200	0.150
Case 1	Rank	4	5	6	7	2	8	1	3
Case 2	Score	0.126	0.068	0.081	0.138	0.127	0.125	0.167	0.151
Case 2	Rank	5	8	7	3	4	6	1	2
Case 3	Score	0.090	0.065	0.080	0.101	0.112	0.090	0.167	0.146
Case 3	Rank	5	8	7	4	3	6	1	2
Case 4	Score	0.158	0.058	0.087	0.111	0.134	0.129	0.171	0.138
Case 4	Rank	2	8	7	6	4	5	1	3
Case 5	Score	0.113	0.057	0.087	0.097	0.127	0.112	0.170	0.132
Case 5	Rank	4	8	7	6	3	5	1	2
Case 6	Score	0.432	0.201	0.250	0.423	0.372	0.353	0.506	0.432
Case 6	Rank	2	8	7	4	5	6	1	3
Case 7	Score	0.034	0.021	0.027	0.035	0.036	0.029	0.056	0.046
Case 7	Rank	5	8	7	4	3	6	1	2
Case 8	Rank	6	7	3	5	4	8	1	2

Table A.8.30 Scores and ranks for various Cases for Novice 5

Novice 6

Lift	A	B	C	D	E	F	G	H
A	1	1	1/2	2	1	1/3	1/2	1
B	1	1	2	1	2	1/2	1	1
C	2	1/2	1	1/2	1/2	1/3	1/2	1/2
D	1/2	1	2	1	2	1	3	3
E	1	1/2	2	1/2	1	1/2	1/2	1
F	3	2	3	1	2	1	3	2
G	2	1	2	1/3	2	1/3	1	2
H	1	1	2	1/3	1	1/2	1/2	1

Table A.8.31 Comparison matrix for Lift, Novice 6 (Incon: 0.07)

Support	A	B	C	D	E	F	G	H
A	1	1	2	1/2	1	1	1	1
B	1	1	2	2	1	2	1	1
C	1/2	1/2	1	1/2	1/3	1/2	1/2	1/2
D	2	1/2	2	1	1	1	1/2	1/2
E	1	1	3	1	1	2	1	1
F	1	1/2	2	1	1/2	1	2	1
G	1	1	2	2	1	1/2	1	1
H	1	1	2	2	1	1		1

Table A.8.32 Comparison matrix for Support, Novice 6 (Incon: 0.04)

React	A	B	C	D	E	F	G	H
A	1	1	4	3	1	2	1	1
B	1	1	4	2	1	2	1	1
C	1/4	1/4	1	1/2	1/2	1/3	1/3	1/4
D	1/3	1/2	2	1	1/2	1	1/2	1/2
E	1	1	2	2	1	2	2	1
F	1/2	1/2	3	1	1/2	1	1	1/2
G	1	1	3	2	1/2	1	1	1
H	1	1	4	2	1	2	1	1

Table A.8.33 Comparison matrix for React, Novice 6 (Incon: 0.02)

	A	B	C	D	E	F	G	H	w_p
Lift	0.106	0.121	0.076	0.176	0.086	0.219	0.125	0.090	0.34
Support	0.120	0.156	0.061	0.116	0.149	0.125	0.133	0.141	0.34
React	0.169	0.160	0.044	0.076	0.165	0.093	0.133	0.160	0.32
Score	0.130	0.145	0.060	0.123	0.132	0.146	0.130	0.129	
Rank	4	2	8	7	3	1	5	6	

Table A.8.34 Priorities, scores and ranks for direct weights w_p for Novice 6

	A	B	C	D	E	F	G	H	w_e
Lift	0.106	0.121	0.076	0.176	0.086	0.219	0.125	0.09	0.39
Support	0.120	0.156	0.061	0.116	0.149	0.125	0.133	0.141	0.16
React	0.169	0.160	0.044	0.076	0.165	0.093	0.133	0.16	0.44
Score	0.136	0.144	0.059	0.121	0.131	0.147	0.129	0.129	
Rank	3	2	8	7	4	1	5	6	

Table A.8.35 Priorities, R^3I scores and ranks for entropy weights w_e for Novice 6

Novice 6		A	B	C	D	E	F	G	H
Case 1	Score	0.076	0.102	0.020	0.230	0.102	0.205	0.128	0.128
Case 1	Rank	7	6	8	1	5	2	3	4
Case 2	Score	0.136	0.144	0.059	0.121	0.131	0.147	0.129	0.129
Case 2	Rank	3	2	8	7	4	1	5	6
Case 3	Score	0.130	0.141	0.055	0.105	0.119	0.126	0.129	0.120
Case 3	Rank	2	1	8	7	6	4	3	5
Case 4	Score	0.130	0.145	0.060	0.123	0.132	0.146	0.130	0.129
Case 4	Rank	4	2	8	7	3	1	5	6
Case 5	Score	0.126	0.143	0.057	0.110	0.122	0.129	0.130	0.122
Case 5	Rank	4	1	8	7	5	3	2	6
Case 6	Score	0.395	0.437	0.181	0.368	0.400	0.437	0.391	0.391
Case 6	Rank	4	1	8	7	3	2	5	6
Case 7	Score	0.042	0.047	0.019	0.036	0.040	0.042	0.043	0.040
Case 7	Rank	4	1	8	7	5	3	2	6
Case 8	Rank	3	2	8	7	6	4	1	5

Table A.8.36 Scores and ranks for various Cases for Novice 6

Novice 7

Lift	A	B	C	D	E	F	G	H
A	1	1/5	1/3	1	1/5	3	1/4	1/7
B	5	1	1/4	2	1/3	4	3	1/3
C	3	4	1	2	1/3	1/3	1/4	1/5
D	1	1/2	1/2	1	1/3	1/4	1/5	1/6
E	5	3	3	3	1	4	2	1/2
F	1/3	1/4	3	4	1/4	1	1/3	1/4
G	4	1/3	4	5	1/2	3	1	1/2
H	7	3	5	6	2	4	2	1

Table A.8.37 Comparison matrix for Lift, Novice 7 (Incon: 0.21)

Support	A	B	C	D	E	F	G	H
A	1	1/2	4	6	1/2	1/2	2	1/4
B	2	1	8	9	1	4	6	1/2
C	1/4	1/8	1	1/3	1/4	1/5	1/3	1/8
D	1/6	1/9	3	1	1/7	1/3	1/2	1/8
E	2	1	4	7	1	3	4	1/3
F	2	1/4	5	3	1/3	1	1	1/5
G	1/2	1/6	3	2	1/4	1	1	1/4
H	4	2	8	8	3	5	4	1

Table A.8.38 Comparison matrix for Support, Novice 7 (Incon: 0.06)

React	A	B	C	D	E	F	G	H
A	1	1/2	4	3	1	2	3	1
B	2	1	3	5	1	2	3	1
C	1/4	1/3	1	1	1/2	1/3	1/3	1/3
D	1/3	1/5	1	1	1/3	1/4	1/4	1/3
E	1	1	2	3	1	2	2	1
F	1/2	1/2	3	4	1/2	1	1	1/2
G	1/3	1/3	3	4	1/2	1	1	1/2
H	1	1	3	3	1	2	2	1

Table A.8.39 Comparison matrix for React, Novice 7 (Incon: 0.03)

	A	B	C	D	E	F	G	H	w_p
Lift	0.048	0.134	0.103	0.036	0.196	0.074	0.142	0.269	0.50
Support	0.094	0.220	0.024	0.031	0.172	0.084	0.056	0.320	0.25
React	0.171	0.209	0.049	0.042	0.161	0.105	0.097	0.166	0.25
Score	0.090	0.174	0.069	0.036	0.181	0.084	0.109	0.256	
Rank	5	3	7	8	2	6	4	1	

Table A.8.40 Priorities, scores and ranks for direct weights w_p for Novice 7

	A	B	C	D	E	F	G	H	w_e
Lift	0.048	0.134	0.103	0.036	0.196	0.074	0.142	0.269	0.293
Support	0.094	0.220	0.024	0.031	0.172	0.084	0.056	0.320	0.506
React	0.171	0.209	0.049	0.042	0.161	0.105	0.097	0.166	0.199
Score	0.095	0.192	0.052	0.034	0.176	0.085	0.089	0.274	
Rank	4	2	7	8	3	6	5	1	

Table A.8.41 Priorities, R^3I scores and ranks for entropy weights w_e for Novice 7

Novice 7		A	B	C	D	E	F	G	H
Case 1	Score	0.100	0.040	0.040	0.040	0.040	0.040	0.200	0.500
Case 1	Rank	8	4	3	6	5	7	2	1
Case 2	Score	0.095	0.192	0.052	0.034	0.176	0.085	0.089	0.274
Case 2	Rank	4	2	7	8	3	6	5	1
Case 3	Score	0.078	0.183	0.035	0.034	0.175	0.084	0.075	0.257
Case 3	Rank	5	2	7	8	3	4	6	1
Case 4	Score	0.090	0.174	0.069	0.036	0.181	0.084	0.109	0.256
Case 4	Rank	5	3	7	8	2	6	4	1
Case 5	Score	0.026	0.059	0.013	0.011	0.058	0.028	0.028	0.077
Case 5	Rank	6	2	7	8	3	4	5	1
Case 6	Score	0.313	0.563	0.176	0.109	0.529	0.263	0.295	0.755
Case 6	Rank	4	2	7	8	3	6	5	1
Case 7	Score	0.068	0.164	0.049	0.035	0.179	0.082	0.094	0.241
Case 7	Rank	6	3	7	8	2	5	4	1
Case 8	Rank	6	3	8	7	2	4	5	1

Table A.8.42 Scores and ranks for various Cases for Novice 7

Novice 8

Lift	A	B	C	D	E	F	G	H
A	1	1/3	5	3	1/3	3	1/7	1/7
B	3	1	1/3	3	3	3	1/4	1/5
C	1/5	3	1	5	1/5	3	1/5	1/6
D	1/3	1/3	1/5	1	1/5	1/2	1/8	1/9
E	3	1/3	5	5	1	3	1/4	1/4
F	1/3	1/3	1/3	2	1/3	1	1/8	1/9
G	7	4	5	8	4	8	1	1/2
H	7	5	6	9	4	9	2	1

Table A.8.43 Comparison matrix for Lift, Novice 8 (Incon: 0.16)

Support	A	B	C	D	E	F	G	H
A	1	1/3	4	5	1/2	5	1/6	1/8
B	3	1	1/2	5	1	4	1/4	1/6
C	1/4	2	1	4	1/6	4	1/6	1/8
D	1/5	1/5	1/4	1	1/7	1	1/5	1/8
E	2	1	6	7	1	5	1/4	1/5
F	1/5	1/4	1/4	1	1/5	1	1/8	1/9
G	6	4	6	5	4	8	1	1/3
H	8	6	8	8	5	9	3	1

Table A.8.44 Comparison matrix for Support, Novice 8 (Incon: 0.13)

React	A	B	C	D	E	F	G	H
A	1	1/3	4	5	1/2	5	1/5	1/5
B	3	1	1/3	4	1/2	4	1/5	1/6
C	1/4	3	1	3	1/5	5	1/4	1/6
D	1/5	1/4	1/3	1	1/7	2	1/8	1/8
E	2	2	5	7	1	5	1	1/2
F	1/5	1/4	1/5	1/2	1/5	1	1/7	1/7
G	5	5	4	8	1	7	1	1/5
H	5	6	6	8	2	7	5	1

Table A.8.45 Comparison matrix for React, Novice 8 (Incon: 0.13)

	A	B	C	D	E	F	G	H	w_p
Lift	0.075	0.100	0.069	0.022	0.110	0.027	0.265	0.332	0.50
Support	0.074	0.083	0.056	0.022	0.116	0.020	0.240	0.388	0.30
React	0.087	0.078	0.069	0.024	0.160	0.021	0.201	0.360	0.20
Score	0.077	0.090	0.065	0.022	0.121	0.023	0.244	0.354	
Rank	5	4	6	8	3	7	2	1	

Table A.8.46 Priorities, scores and ranks for direct weights w_p for Novice 8

	A	B	C	D	E	F	G	H	w_e
Lift	0.075	0.1	0.069	0.022	0.11	0.027	0.265	0.332	0.31
Support	0.074	0.083	0.056	0.022	0.116	0.02	0.24	0.388	0.37
React	0.087	0.078	0.069	0.024	0.16	0.021	0.201	0.36	0.31
Score	0.078	0.086	0.064	0.022	0.127	0.022	0.235	0.361	
Rank	5	4	6	7	3	8	2	1	

Table A.8.47 Priorities, R^3I scores and ranks for entropy weights w_e for Novice 8

Novice 8		A	B	C	D	E	F	G	H
Case 1	Score	0.150	0.169	0.132	0.037	0.132	0.037	0.160	0.179
Case 1	Rank	4	3	6	8	5	7	2	1
Case 2	Score	0.078	0.086	0.064	0.022	0.127	0.022	0.235	0.361
Case 2	Rank	5	4	6	7	3	8	2	1
Case 3	Score	0.077	0.085	0.063	0.022	0.124	0.022	0.232	0.360
Case 3	Rank	5	4	6	7	3	8	2	1
Case 4	Score	0.077	0.090	0.065	0.022	0.121	0.023	0.244	0.354
Case 4	Rank	5	4	6	8	3	7	2	1
Case 5	Score	0.076	0.089	0.064	0.022	0.119	0.023	0.242	0.352
Case 5	Rank	5	4	6	8	3	7	2	1
Case 6	Score	0.236	0.261	0.194	0.068	0.386	0.068	0.706	1.08
Case 6	Rank	4	5	6	7	3	8	2	1
Case 7	Score	0.026	0.028	0.021	0.007	0.041	0.007	0.077	0.119
Case 7	Rank	5	4	6	7	3	8	2	1
Case 8	Rank	5	4	6	7	3	8	2	1

Table A.8.48 Scores and ranks for various Cases for Novice 8

Novice 9

Lift	A	B	C	D	E	F	G	H
A	1	1/3	1/2	2	1/7	1/4	1/4	1/8
B	3	1	3	4	1/2	2	2	1/2
C	2	1/3	1	2	1/3	2	1/2	1/3
D	1/2	1/4	1/2	1	1/5	1/2	1/3	1/5
E	7	2	3	5	1	5	3	1
F	4	1/2	1/2	2	1/5	1	1/2	1/5
G	4	1/2	2	3	1/3	2	1	1/3
H	8	2	3	5	1	5	3	1

Table A.8.49 Comparison matrix for Lift, Novice 9 (Incon: 0.03)

Support	A	B	C	D	E	F	G	H
A	1	1/5	1/3	1/2	1/5	1/3	1/4	1/6
B	5	1	3	5	2	5	4	2
C	3	1/3	1	3	1/3	1	1/2	1/4
D	2	1/5	1/3	1	1/5	1/3	1/2	1/5
E	5	1/2	3	5	1	4	3	1
F	3	1/5	1	3	1/4	1	1/2	1/4
G	4	1/4	2	2	1/3	2	1	1/2
H	6	1/2	4	5	1	4	2	1

Table A.8.50 Comparison matrix for Support, Novice 9 (Incon: 0.04)

React	A	B	C	D	E	F	G	H
A	1	1/4	1/2	1/2	1/4	1/2	1/6	1/6
B	4	1	2	2	1	2	1/2	1/2
C	2	1/2	1	1	1/2	1	1/4	1/4
D	2	1/2	1	1	1/2	1	1/4	1/4
E	4	1	2	2	1	2	1/2	1/2
F	2	1/2	1	1	1/2	1	1/4	1/4
G	6	2	4	4	2	4	1	1
H	6	2	4	4	2	4	1	1

Table A.8.51 Comparison matrix for React, Novice 9 (Incon: 0.00)

	A	B	C	D	E	F	G	H	w_p
Lift	0.038	0.150	0.077	0.037	0.259	0.068	0.109	0.264	0.60
Support	0.030	0.287	0.074	0.040	0.202	0.067	0.098	0.202	0.30
React	0.035	0.131	0.065	0.065	0.131	0.065	0.253	0.253	0.10
Score	0.035	0.189	0.074	0.040	0.229	0.067	0.120	0.244	
Rank	8	3	5	7	2	6	4	1	

Table A.8.52 Priorities, scores and ranks for direct weights w_p for Novice 9

	A	B	C	D	E	F	G	H	w_e
Lift	0.038	0.150	0.077	0.037	0.259	0.068	0.109	0.264	0.33
Support	0.030	0.287	0.074	0.040	0.202	0.067	0.098	0.202	0.36
React	0.035	0.131	0.065	0.065	0.131	0.065	0.253	0.253	0.30
Score	0.034	0.193	0.072	0.046	0.199	0.066	0.148	0.238	
Rank	8	2	5	7	3	6	4	1	

Table A.8.53 Priorities, R^3I scores and ranks for entropy weights w_e for Novice 9

Novice 9		A	B	C	D	E	F	G	H
Case 1	Score	0.062	0.125	0.125	0.093	0.156	0.083	0.166	0.187
Case 1	Rank	8	4	7	5	3	6	2	1
Case 2	Score	0.034	0.193	0.072	0.046	0.199	0.066	0.148	0.238
Case 2	Rank	8	2	5	7	3	6	4	1
Case 3	Score	0.033	0.172	0.071	0.043	0.185	0.066	0.125	0.234
Case 3	Rank	8	3	5	7	2	6	4	1
Case 4	Score	0.035	0.189	0.0749	0.040	0.229	0.067	0.120	0.244
Case 4	Rank	8	3	5	7	2	6	4	1
Case 5	Score	0.034	0.172	0.074	0.039	0.219	0.067	0.111	0.240
Case 5	Rank	8	3	5	7	2	6	4	1
Case 6	Score	0.103	0.568	0.216	0.142	0.592	0.2	0.46	0.719
Case 6	Rank	8	3	5	7	2	6	4	1
Case 7	Score	0.011	0.056	0.023	0.014	0.060	0.022	0.042	0.078
Case 7	Rank	8	3	5	7	2	6	4	1
Case 8	Rank	8	3	5	7	2	6	4	1

Table A.8.54 Scores and ranks for various Cases for Novice 9

A.8.2 Results from Inputs of Expert Designers

		A	B	C	D	E	F	G	H
Expert 1	Score	0.150	0.250	0.050	0.050	0.150	0.100	0.100	0.250
	Rank	4	1	7	8	3	5	6	2
Expert 2	Score	0.050	0.050	0.150	0.200	0.100	0.150	0.100	0.200
	Rank	6	3	5	2	4	3	4	2
Expert 3	Score	0.140	0.240	0.100	0.010	0.190	0.050	0.120	0.150
	Rank	4	1	6	8	2	7	5	3
Expert 4	Score	0.100	0.400	0.050	0.050	0.050	0.050	0.250	0.050
	Rank	3	1	6	8	4	7	2	5

Table A.8.55 Scores and ranks provided by the Experts

Appendix A.9 Experiment Results for Realizability

In this Appendix, the results obtained from the novices and experts with respect to realizability evaluation methodology are laid down. The description of notations used in the tables is as follows:

S^{dc}_{R2N} = Score obtained from novice for Cost criteria of physical realizability evaluation

R^{dc}_{R2N} = Rank for S^{dc}_{R2N}

S^{dt}_{R2N} = Score obtained from novice for Time criteria of physical realizability evaluation

R^{dt}_{R2N} = Rank for S^{dt}_{R2N}

S^{da}_{R2N} = Average of scores S^{dc}_{R2N} and S^{dt}_{R2N}

R^{dc}_{R2N} = Rank for S^{da}_{R2N}

$P(A_i \mid X_B)$ = Probability that the concept is physically realizable with the allocated Budget.

$P(E \mid \bar{A}_i X_B)$ = Probability that the technology implemented and tested in earlier stages (before the prototype is built) would have still passed the tests, given that the prototype failed.

A.9.1 Results from Inputs of Novice Designers

Novice 1

	A	B	C	D	E	F	G	H
S^{dc}_{R2N}	0.05	0.15	0.05	0.15	0.10	0.10	0.20	0.20
R^{dc}_{R2N}	7	3	8	4	6	5	2	1
S^{dt}_{R2N}	0.15	0.05	0.15	0.15	0.05	0.15	0.15	0.15
R^{dt}_{R2N}	6	8	5	4	7	3	2	1
S^{da}_{R2N}	0.10	0.10	0.10	0.15	0.07	0.12	0.17	0.17
R^{da}_{R2N}	5	5	5	3	6	4	2	1

Table A.9.1 Scores and ranks for realizability, Novice 1

Novice 2

	A	B	C	D	E	F	G	H
S^{dc}_{R2N}	0.05	0.10	0.05	0.10	0.10	0.15	0.25	0.20
R^{dc}_{R2N}	8	6	7	3	4	3	1	2
S^{dt}_{R2N}	0.05	0.05	0.15	0.15	0.15	0.15	0.15	0.15
R^{dt}_{R2N}	7	8	4	5	3	2	1	6
S^{da}_{R2N}	0.05	0.07	0.10	0.12	0.12	0.15	0.20	0.17
R^{da}_{R2N}	8	7	6	5	4	3	1	2

Table A.9.2 Scores and ranks for realizability, Novice 2

	A	B	C	D	E	F	G	H
$P(A_i \mid X_B)$	0.01	0.03	0.90	0.60	0.80	0.70	0.60	0.80
$P(E \mid \bar{A}_i X_B)$	0.50	0.70	0.90	0.90	1.00	0.70	0.60	0.80

Table A.9.3 Probability values obtained from Novice 2

Novice 3

	A	B	C	D	E	F	G	H
S^{dc}_{R2N}	0.05	0.12	0.10	0.10	0.08	0.10	0.08	0.15
R^{dc}_{R2N}	6	2	3	3	5	3	5	1
S^{dt}_{R2N}	0.05	0.10	0.15	0.08	0.10	0.15	0.05	0.20
R^{dt}_{R2N}	7	4	3	5	4	2	6	1
S^{da}_{R2N}	0.05	0.11	0.12	0.09	0.09	0.12	0.06	0.17
R^{da}_{R2N}	8	4	3	5	6	2	7	1

Table A.9.4 Scores and ranks for realizability, Novice 3

	A	B	C	D	E	F	G	H
$P(A_i \mid X_B)$	0.30	0.50	0.60	0.30	0.70	0.70	0.20	0.70
$P(E \mid \bar{A}_i X_B)$	0.30	0.80	0.90	0.90	0.50	0.60	0.70	0.60

Table A.9.5 Probability values obtained from Novice 3

Novice 4

	A	B	C	D	E	F	G	H
S_{R2N}^{dc}	---	---	---	---	---	---	---	---
R_{R2N}^{dc}	5	8	6	4	7	3	2	1
S_{R2N}^{dt}	---	---	---	---	---	---	---	---
R_{R2N}^{dt}	4	7	8	5	6	3	1	2
S_{R2N}^{da}	---	---	---	---	---	---	---	---
R_{R2N}^{da}	---	---	---	---	---	---	---	---

Table A.9.6 Ranks for realizability, Novice 4

Novice 5

	A	B	C	D	E	F	G	H
S_{R2N}^{dc}	0.10	0.10	0.15	0.20	0.10	0.15	0.15	0.20
R_{R2N}^{dc}	8	6	5	1	4	7	3	2
S_{R2N}^{dt}	0.15	0.10	0.15	0.10	0.20	0.05	0.05	0.15
R_{R2N}^{dt}	4	5	2	6	1	8	7	3
S_{R2N}^{da}	0.12	0.10	0.15	0.15	0.15	0.10	0.10	0.17
R_{R2N}^{da}	4	5	3	3	2	6	5	1

Table A.9.7 Scores and ranks for realizability, Novice 5

Novice 6

	A	B	C	D	E	F	G	H
S_{R2N}^{dc}	0.14	0.06	0.04	0.18	0.20	0.14	0.10	0.10
R_{R2N}^{dc}	3	8	7	2	1	4	5	6
S_{R2N}^{dt}	0.09	0.10	0.08	0.15	0.12	0.14	0.14	0.14
R_{R2N}^{dt}	7	6	8	1	5	2	3	4
S_{R2N}^{da}	0.11	0.08	0.06	0.17	0.16	0.14	0.12	0.12
R_{R2N}^{da}	6	7	8	1	2	3	4	5

Table A.9.8 Scores and ranks for realizability, Novice 6

	A	B	C	D	E	F	G	H
$P(A_i \mid X_B)$	0.30	0.20	0.10	0.50	0.30	0.70	0.70	0.60
$P(E \mid \bar{A}_i X_B)$	0.20	0.40	0.40	0.50	0.60	0.80	0.40	0.50

Table A.9.9 Probability values obtained from Novice 6

Novice 7

	A	B	C	D	E	F	G	H
S^{dc}_{R2N}	0.02	0.02	0.20	0.02	0.02	0.02	0.30	0.40
R^{dc}_{R2N}	8	6	3	5	7	4	2	1
S^{dt}_{R2N}	0.10	0.10	0.05	0.05	0.05	0.10	0.25	0.30
R^{dt}_{R2N}	8	7	3	5	6	4	2	1
S^{da}_{R2N}	0.06	0.06	0.12	0.03	0.03	0.06	0.27	0.35
R^{da}_{R2N}	6	5	3	7	8	4	2	1

Table A.9.10 Scores and ranks for realizability, Novice 7

Novice 8

	A	B	C	D	E	F	G	H
S^{dc}_{R2N}	0.04	0.07	0.17	0.04	0.17	0.061	0.19	0.22
R^{dc}_{R2N}	7	5	2	8	4	6	3	1
S^{dt}_{R2N}	0.04	0.13	0.11	0.04	0.17	0.08	0.20	0.20
R^{dt}_{R2N}	8	5	4	7	3	6	2	1
S^{da}_{R2N}	0.04	0.10	0.14	0.04	0.17	0.07	0.19	0.21
R^{da}_{R2N}	7	5	4	7	3	6	2	1

Table A.9.11 Scores and ranks for realizability, Novice 8

Novice 9

	A	B	C	D	E	F	G	H
S^{dc}_{R2N}	0.04	0.08	0.13	0.13	0.13	0.13	0.17	0.17
R^{dc}_{R2N}	8	6	7	4	3	5	2	1
S^{dt}_{R2N}	0.02	0.05	0.05	0.16	0.10	0.16	0.21	0.21
R^{dt}_{R2N}	8	7	6	3	5	4	2	1
S^{da}_{R2N}	0.03	0.06	0.10	0.14	0.12	0.14	0.19	0.19
R^{da}_{R2N}	8	7	6	3	5	4	2	1

Table A.9.12 Scores and ranks for realizability, Novice 9

A.8.2 Results from Inputs of Expert Designers

Expert 1

	A	B	C	D	E	F	G	H
S^{dc}_{R2N}	0.03	0.08	0.08	0.08	0.03	0.10	0.20	0.40
R^{dc}_{R2N}	8	4	5	6	7	3	2	1
S^{dt}_{R2N}	0.07	0.10	0.04	0.06	0.40	0.20	0.05	0.08
R^{dt}_{R2N}	5	3	8	6	1	2	7	4
S^{da}_{R2N}	0.05	0.09	0.06	0.07	0.21	0.15	0.12	0.24
R^{da}_{R2N}	8	5	7	6	2	3	4	1

Table A.9.13 Scores and ranks for realizability, Expert 1

Expert 2

	A	B	C	D	E	F	G	H
S^{dc}_{R2N}	0.05	0.05	0.10	0.25	0.05	0.20	0.10	0.20
R^{dc}_{R2N}	7	6	4	1	7	2	4	3
S^{dt}_{R2N}	0.20	0.10	0.10	0.10	0.15	0.10	0.05	0.10
R^{dt}_{R2N}	1	3	4	4	2	3	5	4
S^{da}_{R2N}	0.12	0.07	0.10	0.17	0.10	0.15	0.07	0.15
R^{da}_{R2N}	3	5	4	1	4	2	5	2

Table A.8.14 Scores and ranks for realizability, Expert 2

Expert 3

	A	B	C	D	E	F	G	H
S^{dc}_{R2N}	0.08	0.06	0.24	0.15	0.04	0.13	0.10	0.20
R^{dc}_{R2N}	6	7	1	3	8	4	5	2
S^{dt}_{R2N}	0.03	0.13	0.20	0.07	0.27	0.07	0.08	0.15
R^{dt}_{R2N}	8	4	2	6	1	7	5	3
S^{da}_{R2N}	0.05	0.09	0.22	0.11	0.15	0.10	0.09	0.17
R^{da}_{R2N}	7	6	1	4	3	5	6	2

Table A.8.15 Scores and ranks for realizability, Expert 3

Expert 4

	A	B	C	D	E	F	G	H
S^{dc}_{R2N}	0.25	0.30	0.05	0.05	0.10	0.05	0.15	0.05
R^{dc}_{R2N}	2	1	6	7	4	8	3	5
S^{dt}_{R2N}	0.20	0.25	0.10	0.05	0.10	0.05	0.15	0.10
R^{dt}_{R2N}	2	1	6	7	4	8	3	5
S^{da}_{R2N}	0.22	0.27	0.07	0.05	0.10	0.05	0.15	0.07
R^{da}_{R2N}	2	1	5	6	4	6	3	5

Table A.8.16 Scores and ranks for realizability, Expert 4

References

Antonsson, E. K. 1997. Imprecision in engineering design. In *Proceedings of Intelligent Design in Engineering Applications Symposium IDEA'97,* Aachen, Germany, 1997.

Asimov, M. 1962. *Introduction to Design.* N.J.: Prentice-Hall.

Barton, J. A., D. M. Love, and G. D. Taylor. 2001. Design determines 70% of cost? A review of implications for design evaluation. *Journal of Engineering Design* 12(1): 47-58.

Bjarnemo, R. 1991. Evaluation and decision techniques in the engineering design process – in practice. In *Proceedings of International Conference on Engineering Design ICED 1991,* Zurich, Switzerland, 1991, 373-383.

Bjarnemo, R. 1994. Towards a computer implementable evaluation procedure for the mechanical engineering design process. PhD thesis, University of Lund.

Blessing, L. 1994. A process-based approach to computer-supported engineering design. PhD thesis, University of Twente.

Blessing, L., A. Chakrabarti, and K. Wallace. 1998. An overview of descriptive studies in relation to a general design research methodology, In *Designers, the Key to Successful Product Development,* ed. P. Badke-Schaub and H. Birkhofer, 42-56. London: Springer-Verlag.

Blessing, L. 2002. What is this thing called design research?. In *Annals of Int'l CIRP Design Seminar,* Hong Kong, 2002.

Blessing, L., and A. Chakrabarti. 2002. DRM: A design research methodology. In *Proceedings of Les Sciences de la Conception,* Lyon, France, 2002.

Booker, J. D., M. Raines, and K. G. Swift. 2001. *Designing Capable and Reliable Products.* Oxford: Butterworth Heinemann.

Brintrup, A. M., A. Timari, and J. Gao. 2004. A framework for handling qualitative and quantitative data in an evolutionary multiple objective design space. *International Journal of Computational Intelligence* 1(4): 282-288.

Broadbent, J. E. A. 1993. Evaluating concept designs for reliability, In *Proceedings of International Conference on Engineering Design ICED 93,* The Hague, Netherlands, 1993, 1186-1188.

BS4778. 1990. *Glossary of Terms used in Quality Assurance.* London: British Standards Institution.

Buchanan, L., and A. O'Connell. 2006. A brief history of decision making. *Harvard Business Review* 84(1): 32-41.

Chen, J. L., and C. R. Lee. 1993. Qualitative programming method for qualitative design evaluation in the conceptual design stage. *Journal of Engineering Design* 4(3): 213-220.

Cooper, G., and G. Thompson. 2001. Concept design and reliability. In *Proceedings of Advanced Engineering Design AED 2001*, Glasgow, UK, 2001, 183-188.

Covino, M. M., P. A. Rodgers, J. S. Smith, and J. P. Clarkson. 2000. Assessing reliability in mechanical systems. *Journal of Integrated Design and Process Science* 4(2): 67-84.

Czuilik, C., and J. Driscoll. Conceptual design evaluation based on function metrics. In *Proceedings of International Conference on Engineering Design ICED 97*, Tampere, Finland, 1997, 411-416.

Denson, W. 1998. The history of reliability prediction. *IEEE Transactions on Reliability* 47(3): 321-328.

Dwarkanath, S., and K. M. Wallace. 1995. Decision-making in engineering design: observations from design experiments. *Journal of Engineering Design* 6(3): 191-206.

Dyer, J. S. 1990. Remarks on the analytic hierarchy process. *Management Science* 36(3): 249-258.

Dym, C. L., W. H. Wood, and M. J. Scott. 2002. Rank ordering engineering designs: pairwise comparison charts and borda counts. *Research in Engineering Design* 13: 236-242.

Eckenrode, R. T. 1965. Weighting multiple criteria. *Management Science* 12(3): 180-192.

Fernandez, M. G., C. C. Seepersad, D. W. Rosen, J. K. Allen, and F. Mistree. 2001. Utility-based decision support for selection in engineering design. In *Proceedings of ASME Design Engineering Technical Conference*, Pittsburgh, USA, 2001, DETC2001/DAC-21106.

Fowlkes, W. Y., and C. M. Creveling. 1995. *Engineering Methods for Robust Product Design*. Reading: Addison-Wesley.

French, M. J. 1998. *Conceptual Design for Engineers*. London: Springer-Verlag.

Frey, D. D., and K. Lewis. 2005. The deciding factor. *ASME Mechanical Engineering Design*, March 2005.

Gero, J. S., and Kannengiesser U. 2004. The situated function-behaviour-structure framework. *Design Studies* 25: 373-391.

Gibbons, J. D. 1993. *Nonparametric Measures of Association*, Newbury Park: Sage Publications.

Goel, H., J. Grievink, P. Herder, and M. Weijnen. 2003. Optimal reliability design of process systems at the conceptual stage of design. In *Proceedings of Annual Reliability and Maintainability Symposium*, Tampa, USA, 2003, 40-45.

Golomski, W. A. 1995. Reliability and quality in design. *IEEE Transactions on Reliability* 44(2): 321-328.

Green, G. 1997. Modelling concept design evaluation. *Artificial Intelligence for Engineering Design, Analysis and Manufacturing* 11: 211-217.

Green, G. 2000. Towards an integrated design evaluation (IDE) tool. *Acta Polytechnica* 4: 50-56.

Green, G. 2003. Design evaluation: decomposition and state-space analysis. *Acta Polytechnica* 43: 11-16.

Gregory, G. 1988. *Decision Analysis*. London: Pitman.

Hatchuel, A., and B. Weil. 2003. A new approach of innovative design: an introduction to c-k theory. In *Proceedings of International Conference on Engineering Design ICED037*, Stockholm, Sweden, 2003, paper 1794.

Hernandez, G., J. K. Allen, and F. Mistree. 2003. Platform design for customizable products as a problem of access in a geometric space. *Engineering Optimization* 35(3): 229-254.

Hicks, B. J., S. J. Culley, and G. Mullineux. 2002. Cost estimation for standard components and systems in the early phases of the design process. *Journal of Engineering Design* 13(4): 271-292.

Ho, C. H. 2001. Some phenomena of problem decomposition strategy for design thinking: differences between novices and experts. *Design Studies* 22(1): 27-45.

Hurst, K. 1991. Design concept selection using spreadsheet analysis. *Journal of Engineering Design* 2(4): 291-302.

Hwang, C. L., and K. Yoon. 1981. *Multiple Attribute Decision Making: Methods and Applications*. Berlin: Springer-Verlag.

Hwang, C. L., and K. Yoon. 1995. *Multiple Attribute Decision Making: An Introduction*. Thousand Oaks: Sage Publications.

Ishii, K., and P. Barkan. 1991. Design compatibility analysis – a framework for expert systems in mechanical system design. *ASME Computers in Engineering* 1: 95-102.

Joshi, S. P., J. R. Umaretiya, and S. B. Joshi. 1991. Decision-making in preliminary engineering design. *Artificial Intelligence in Engineering, Design and Manufacturing* 5(1): 21-30.

Kapur, K. C., and L. R. Lamberson. 1977. *Reliability in Engineering Design*. New York: John Wiley & Sons.

Kara-Zaitri, C., A. Z. Keller, I. Barody, and P. V. Fleming. 1991. An improved FMEA methodology. In *Proceedings of Annual Reliability and Maintainability Symposium*, Orlando, USA, 1991, 248-252.

Khoo, L. P., and N. C. Ho. 1996. Framework of a fuzzy quality function deployment system. *International Journal of Production Research* 34(2): 299-311.

King, A., and S. Sivaloganathan. 1999. Development of a methodology for concept selection in flexible design strategies. *Journal of Engineering Design* 10(4): 329-349.

Kirby, M. R. 2001. A methodology for technology identification, evaluation, and selection in conceptual and preliminary aircraft design. PhD thesis, Georgia Institute of Technology.

Kirschman, C., and G. Fadel. 1998. Classifying functions for mechanical design. *Journal of Mechanical Design* 120: 475-482.

Kuppuraju, N., P. Ittimakin, and F. Mistree. 1985. Design through selection – a method that works. *Design Studies* 6(2): 91-106.

Lindahl, M. 2005. Engineering designers' requirements on design for environment methods and tools. PhD thesis, Royal Institute of Technology.

Liu, Y. C., T. Bligh, and A. Chakrabarti. 2003. Towards an 'ideal' approach for concept generation. *Design Studies* 24: 341-355.

Mamtani, G. 2004. Strategic planning for mass customization of machine tools. *Report to MacRobertson's Scholarship Committee*, Glasgow University, 2004.

Mamtani, G., and G. Green. 2004. Evolution of a computer evaluation tool in context with Scottish industries. In *Proceedings of 8th International Design conference Design 2004*, Dubrovnik, Croatia, 2004, 1435-1440.

Mamtani, G. and G. Green. 2006a. Reliability risk evaluation during the conceptual design phase. *Acta Polytechnica* 46(1): 8-14.

Mamtani, G. and G, Green. 2006b. Relative reliability risk assessment applied to original designs during conceptual design phase. *Proceedings of Institution of Mechanical engineers Part B*: Accepted and to appear.

Marples, D. L. 1961. The decisions of engineering design. *IRE Transactions on Engineering Management* June: 55-70.

Matthiasen, B. 1997. Design for robustness and reliability. PhD thesis, Technical University of Denmark.

Mattson, C. A., and A. Messac. 2003. Concept selection using s-pareto frontiers. *AIAA Journal* 41(6): 1190-1198.

Meyer, M. H. 1997. Revitalize your product lines through continuous platform renewal. *Research Technology Management* 40(2): 17-28.

Meyer, M. H., and A. P. Lehnard. 1997. *The Power of Product Platforms: Building Value and Cost Leadership*. New York: The Free Press.

Mistree, F., and D. Muster. 1985. Design harmonisation A computer based approach for design in the systems age, In *Optimization in Computer aided design*, ed. J. S. Gero, 1-30. Amsterdam: Elsevier Science publishers.

Mistree, F., K. Lewis, and L. Stonis. 1994. Selection in the conceptual design of aircraft, In *AIAA/NASA/USAF/ISSMO Symposium on Multidisciplinary Analysis and Optimisation*, Florida, USA, 1994, 1153-1166.

Mistree, F., J. K. Allen, H. Karandikar, H. Shupe, and E. Bascaran. 1995. *Learning How to Design:A Minds-On,Hands-On, Decision-Based Approach*. Atlanta, 1995. Online reference. http://www.srl.gatech.edu/vprs

Muster, D., and F. Mistree. 1988. The decision-support problem technique in engineering design. *The International Journal of Applied.Engineering Education* 4(1): 23-33.

Nachmias, C. F., and D. Nachmias. 1992. *Research Methods in the Social Sciences*. New York: St. Martin's Press.

Nachtmann, H., and J. Chimka. 2003. Fuzzy reliability in conceptual design. In *Proceedings of Annual Reliability and Maintainability Symposium*, Tampa, USA, 2003, 360-364.

Negnevitsky, M. 2001. *Artificial Intelligence- A Guide to Intelligent System*. Harlow: Addison Wesley.

NUREG-0492. 1981. *Fault Tree Handbook*. Washington: US Nuclear Regulatory Commission.

O'Connor, P. D. T., 1995. *Practical Reliability Engineering*. Chichester: John Wiley & Sons.

Ormon, S., C. Cassady, and A. Greenwood. 2001. A simulation-based reliability prediction model for conceptual design. In *Proceedings of Annual Reliability and Maintainability Symposium*, Washington, USA, 2001, 433-436.

Ormon, S., C. Cassady, and A. Greenwood. 2002. Reliability prediction models to support conceptual design. *IEEE Transactions on Reliability* 51(2): 151-157.

Otto, K., and K. Wood. 2000. *Product Design Techniques in Reverse Engineering and New Product Development*. New Jersey: Prentice Hall.

Pahl, G., and W. Beitz. 1996. *Engineering Design – A Systematic Approach*. London: Springer Verlag.

Park, J-H., and K-K. Seo. 2004. Incorporating life-cycle cost into early product development. *Proceedings of Institution of Mechanical engineers Part B* 218: 1059-1066.

Pederson, K., J. Emblemsvag, R. Bailey, J. Allen, and F. Mistree. 2000. Validating design methods and research: the validation square. In *Proceedings of ASME Design Engineering Technical Conference*, Baltimore, USA, 2000, DETC2000/DTM-14579.

Pugh, S. 1981. Concept selection – a method that works. In *Proceedings of International Conference on Engineering Design ICED81*, Rome, Italy, 1981, 497-506.

Pugh, S. 1991. *Total Design: Integrated Methods for Successful Product Engineering*. Workingham: Addison Wesley.

Radu, M. 2003. Applications of stress derating and thermal analysis to improve the reliability of electronic modules. In *Proceedings of 26^{th} International Spring Seminar on Electronics Technology*, Stara Lesna, Slovak Republic, 2003, 26-30.

Robson, C. 1993. *Real World Research*. Oxford: Blackwell publishers.

Roy, R. 1990. *A Primer on Taguchi Method*. New York: Van Nostrand Reinhold.

Roy, R., S. Kelvesjo, S. Forsberg and C. Rush. 2001. Quantitative and qualitative cost estimating for engineering design. *Journal of Engineering Design* 12(2): 147-162.

Saari, D. G., and K. K. Sieberg. 2004. Are partwise comparisons reliable?. *Research in Engineering Design* 15: 62-71.

Saaty, T. L. 1990. How to make a decision: the analytic hierarchy process. *European Journal of Operational Research* 48: 9-26.

Saaty, T. L. 2000. *Fundamentals of Decision Making*. Pittsburgh: RWS Publications.

Saaty, T. L. 2001. *Decision Making for Leaders*. Pittsburgh: RWS Publications.

Salo, A. A., and R. P. Hamalainen. 1997. On the measurement of preferences in the analytic hierarchy process. *Journal of Multi-Criteria Decision Analysis* 3: 309-319.

Sen, P., and J. Yang. 1998. *Multiple Criteria Decision Support in Engineering Design*. London: Springer-Verlag.

Shannon, C. E. 1948. A mathematical theory of communication. *The Bell System Technical Journal* 27: 379-423.

Siddall, J. N. 1982. *Optimal Engineering Design: Principles and Applications*. New York: M. Dekker.

Simon, H. A. 1990. Invariants of human behaviour. *Annual Review Psychology* 41: 1-19.

Sloane, E. B., M. J. Liberatore, and R. L. Nydick. 2002. Medical decision support using the analytic hierarchy process. *Journal of Healthcare Information Management* 16(4): 38-43.

Smith, J., and P. J. Clarkson. 2001. Improving reliability during conceptual design. In *Proceedings of International Conference on Engineering Design ICED 01*, Glasgow, UK, 2001, 83-90.

Smith, J. 2002. Design for reliability during concept development. PhD thesis, University of Cambridge.

Smithers, T. 1996. On knowledge level theories of design process. In *Artificial Intelligence in Design '96*, ed. J. S. Gero and F. Sudweeks, 561-579. The Netherlands: Kluwer Academic Publishers.

Sridharan, P., and M. I. Campbell. 2005. A study on the grammatical construction of function structure. *Artificial Intelligence for Engineering Design, Analysis and Manufacturing* 19: 139-160.

Stephenson, J. 1995. Design for reliability in mechanical systems. PhD thesis, University of Cambridge.

Stutsker, G. E. 1998. Decision making in vascular surgery. In *Proceedings of IEEE ISIC/CIRA/ISAS Joint Conference*, Gaithersburg, USA, 1998, 489-492.

Tam, M. C. Y., and V. M. R. Tummala. 2001. An application of the AHP in vendor selection of a telecommunications system. *Omega* 29: 171-182.

Taylor, A., and T. Ben. 1993. Enhancement of design evaluation during concept development. In *Proceedings of International Conference on Engineering Design ICED93*, The Hague, Netherlands, 1993, 481-484.

Thompson, G. 1999. *Improving Maintainability and Reliability through Design*. London: Professional Engineering Publications.

Thompson, G., and C. Nilsson. 2001. A multiobjective approach to design for reliability. *Proceedings of Institution of Mechanical engineers Part E* 215: 197-205.

Thurston, D. 1990. Subjective design evaluation with multiple attributes. In *Proceedings of ASME Design Theory & Methodology Conference*, Chicago, USA, 1990, 355-361.

Thurston, D. 1991. A formal method for subjective design evaluation with multiple attributes. *Research in Engineering Design* 3: 105-122.

Triantaphyllou, E. 2000. *Multi-Criteria Decision Making Methods: A Comparative study*. Dordrecht: Kluwer Academic Publishers.

Ullman, D. G.2001. Robust decision-making for engineering design. *Journal of Engineering Design* 12(1): 3-13.

Ulrich, K. 1995. The role of product architecture in the manufacturing firm. *Research policy* 24(3): 419-440.

Ulrich, K., and S. Eppinger. 2000. *Product Design and Development*. Boston: McGraw-Hill.

Vadde, S., J. K. Allen, and F. Mistree. 1995. Catalog design: selection using available assets. *Engineering Optimization* 25: 45-64.

Venegas, L., and A. Labib. 2001. Application of new fuzzy-weighted average (NFWA) method to engineering design evaluation. *International Journal of Production Research* 39(6): 1147-1162.

Verma, D., and J. Knezevic. 1996. A fuzzy wedge mechanism for feasibility assessment of system reliability during conceptual design. *Fuzzy Sets and Systems* 83: 179-187.

Verma, D., C. Smith, and W. Fabrycky. 1999. Fuzzy set based multi-attribute conceptual design evaluation. *Systems Engineering* 2(4): 187-197.

Wang, J. 1997. A fuzzy outranking method for conceptual design evaluation. *International Journal of Production Research* 35(4): 995-1010.

Wang, J. 2002. Improved engineering design concept selection using fuzzy sets. *International Journal of Computer Integrated Manufacturing* 15(1): 18-27.

White, S. A. 1996. A design metalanguage for design language creation. In *Proceedings of ASME and API Energy Information Management – Incorporating ETCE*, Houston, USA, 1996, 135-144.

Whitney, D. E. 1988. Manufacturing by design. *Harvard Business Review* 66(4): 83-91.

Wu, H., F. Wang, X. Zhang, and N. He. 1996. A model of inexact reasoning in mechanical design evaluation. *Artificial Intelligence in Engineering* 10(4): 357-362.

Yadav, O., N. Singh, P. Goel, and R. Campbell. 2003. A framework for reliability prediction during product development process incorporating engineering judgements. *Quality Engineering* 15(4): 649-662.

Yeo, S. H., M. W. Mak, and A. P. Balon. 2004. Analysis of decision-making methodologies for desirability score of conceptual design. *Journal of Engineering Design* 15(2): 195-208.

Zadeh, L. A. 1965. Fuzzy sets. *Journal of Information and Control* 8: 338-353.

Zavbi, R., and J. Duhovnik. 1996. The analytic hierarchy process and functional appropriateness of components of technical systems. *Journal of Engineering Design* 7(3): 313-327.

Bibliography

Alexander, K., and P. J. Clarkson. 2002. A validation model for the medical devices industry. *Journal of Engineering Design* 13(3): 197-204.

Burdea, G. 1996. *Force and Touch Feedback for Virtual Reality.* New York: John Wiley & Sons.

Campanari, S. 2001. Thermodynamic model and parametric analysis of a tubular SOFC module. *Journal of Power Sources* 92: 26-34.

Cartmell, M. P., A. P. Fothergill, and J. K. W. Forster. 1993. Theoretical foundations for a design brief expansion system. *Journal of Engineering Design* 4(3): 221-248.

Dahl, D. W., A. Chattopadhyay, and J. G. Gerald. 2001. The importance of visualisation in concept design. *Design Studies* 22: 5-26.

Garro, O., and P. Martin. 1993. Towards new architectures of machine tools. *International Journal of Production Research* 31(10): 2403-2414.

Gero, J. S., and V. Kazakov. 2000. Adaptive enlargement of state spaces in evolutionary designing. *Artificial Intelligence for Engineering Design, Analysis and Manufacturing* 14: 31-38.

Gerson, P., S. Charles, B. Eynard, B. Ramond, and G. Green. 2003. Open dynamic design: the developments in the industrial world of the mechanical based products and some answers from educational institutions. In *Proceedings of 3rd International Conference on Integrated Design and Production CPI 2003*, Meknes, Morocco, 2003.

Grange, S., F. Conti, P. Rouiller, P. Helmer, and C. Baur. 2001. Overview of the delta haptic device. *In Proceedings of Eurohaptics 2001*, Birmingham, UK, 2001, 164-166.

Haynes, C. 2002. Simulating process settings for unslaved SOFC response to increases in load demand. *Journal of Power Sources* 109: 365-376.

Haynes, C., and W. J. Wepfer. 2000. 'Design for power' of a commercial grade tubular solid oxide fuel cell. *Energy conversion & Management* 41: 1123-1139.

Isaksson, O., K-S. Sven, and S. D. Eppinger. 2000. Evaluation of design process alternative using signal flow graphs. *Journal of Engineering Design* 11(3): 211-224.

Landers, R. G., B. K. Min, and Y. Yoren. 2002. Reconfigurable machine tools. In *Annals of CIRP*, 2002, 269-275.

Lopez-Mesa, B., G. Thompson, and M. Willander. 2002. Managing uncertainty in the design and development process by appropriate methods selection. In *Proceedings of 7th International Design conference Design 2002*, Dubrovnik, Croatia, 2002, 829-836.

Medland, A. J., and G. Mullineux. 2000. A decomposition strategy for conceptual design. *Journal of Engineering Design* 11(1): 3-16.

Meniru, K., H. Rivard, and C. Bedard. 2003. Specifications for computer-aided conceptual building design. *Design Studies* 24: 51-71.

Moon, Y-M., and S. Kota. 2002. Generalized kinematic modelling of reconfigurable machine tools. *Journal of Mechanical Design* 124: 47-51.

Ong, K. L., S. G. Lee, and L. P. Khoo. 2003. Homogenous state-space representation of concurrent design. *Journal of Engineering Design* 14(2): 221-245.

Padulles, J., G. W. Ault, and J. R. McDonald. 2000. An integrated SOFC plant dynamic model for power systems simulation. *Journal of Power Sources* 86: 495-500.

Parmee, I. C., and J. A. Abraham. 2004. User-centric evolutionary design. In *Proceedings of 8th International Design conference Design 2004*, Dubrovnik, Croatia, 2004, 1441-1446.

Rogers, G. G., and L. Bottaci. 1997. Modular production systems: a new manufacturing paradigm. *Journal of Intelligent Manufacturing* 8: 147-156.

Salustri, F. A. 1998. Function modeling for an integrated framework: a progress report. In *Proceedings of 11th International Flairs Conference FLAIRS-98, Florida, USA, 1998.*

Salustri, F. A., and J. Parmar. 2004. Product design schematics: structured diagramming for requirements engineering. In *Proceedings of 8th International Design conference Design 2004*, Dubrovnik, Croatia, 2004, 1453-1460.

Smith, J., and P. J. Clarkson. 2005. Design concept modelling to improve reliability. *Journal of Engineering Design* 16(5): 473-492.

Smith, R. P., and S. D. Eppinger. 1997. Identifying controlling features of engineering design iteration. *Management Science* 43(3): 276-293.

Stillwell, W. G., D. A. Seaver, and W. Edwards. 1981. A comparison of weight approximation techniques in multiattribute utility decision making. *Organizational Behaviour and Human Performance* 28: 62-77.

Sutcliffe, A. 2003. *Multimedia and Virtual Reality: Designing Multisensory User Interfaces*. London: Lawrence Erlbaum Associates.

Tovey, M. 2002. Concept design CAD for the automotive industry. *Journal of Engineering Design* 13(1): 5-18.

Van Dijk, C. G. C. 1995. New insights in computer-aided conceptual design. *Design Studies* 16: 62-80.

Zavbi, R., and J. Duhovnik. 2000. Conceptual design of technical systems using functions and physical laws. *Artificial Intelligence for Engineering Design, Analysis and Manufacturing* 14: 69-83.

Zavbi, R., and J. Duhovnik. 2001. Conceptual design chains with basic schematics based on an algorithm of conceptual design. *Journal of Engineering Design* 12(2): 131-145.

Zhang, W. Y., S. B. Tor, and G. A. Britton. 2002. A heuristic state-space approach to the functional design of mechanical systems. *International Journal of Advanced Manufacturing Technology* 19: 235-244.

Zheng, J. M., K. W. Chan, and I. Gibson. 2001. Desktop virtual reality interface for computer aided conceptual design using geometric techniques. *Journal of Engineering Design* 12(4): 309-329.