Evaluation activity in the conceptual phase of the engineering design process.

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"Wisdom denotes the pursuing of the best ends by the best means"
-- Francis Hutcheson

This thesis is dedicated to:

my mother and the memory of my father

my wife , Christine, and my children , Stephanie and Christopher

Acknowledgement

I would like to thank Professor Brian F Scott for all his encouragement and guidance throughout the past five years.

Summary

This thesis reports the results of a five year, part-time research project investigating the evaluation activity within the conceptual design phase of the engineering design process. In parallel, the research addresses the issue of design research methodology employed in support of the investigation and in particular the necessity of validating a theory via experimentation.

The investigation commences with a literature review (Chapter 2) of engineering design process models which has as its main deliverable the identification of the requirements expected of the conceptual design evaluation activity.

This review is followed by an extensive consideration of current evaluation methods (Chapter 3) spanning a range of design related domains. These methods are compared against the identified conceptual design evaluation activity requirements and their strengths and weaknesses, in this regard, identified. This comparison highlights the lack of any single method capable of meeting the requirements expected while also identifying a range of methods providing scope for development. The most influential of these methods are shown to be:

- Initial Design Selection (IDS) — Esterline and Kota
- Design Compatibility Analysis (DCA) — Ishii et al
- Probabilistic Design Option — Siddall
- Design for Reliability — Carter et al

Chapter 4, therefore, describes the synthesis and development of a Conceptual Design Evaluation Method (CDEM) that is an amalgam of a number of methods and approaches taken principally from the probability, reliability, and quality domains. Decomposition of design is employed to enable evaluation at design characteristic level with the total design evaluation being achieved via recomposition by means of Conceptual Design Factor Ratings (CDFR) and Conceptual Design Solution Ratings (CDSR).

This methodology is next tested, within a controlled design environment, in order that its validity can be assessed.The experimental approach used is described in Chapter 5. The results of this experiment, which uses students along with technical and academic staff from the Department of Mechanical Engineering at the University of Glasgow as subjects, indicate that the developed Conceptual Design Evaluation Methodology does exhibit validity within the limits of the experimental environment. It is shown that the CDEM can match expert selection of preferred concept options thus offering the potential of enhancing novice capability and of providing advisory support to experienced designers. The experiment also exposes the problem of objectivity in design evaluation however it is also shown that the CDEM approach acts to mitigate against this tendency by effectively reminding the designer of the benefits of a range of conceptual options. In parallel, the experiment also exposes the limits of human objective evaluation in terms of the complexity of criteria addressed as well as the number of conceptual options considered. Once again CDEM is shown to enable evaluative objectivity to be maintained with increasing complexity.

It is also suggested that the CDEM approach is appropriate for a concurrent engineering environment since it displays a capacity to enhance traceability of design decision making. Finally, conclusions are provided regarding the specific outcomes of the described research along with implications for the wider issues of coherent design research strategy and professional engineering design practice.

Contents

List of Symbols

Symbol	***Meaning***
S	Mean value of a Strength Distribution
L	Mean value of a Load Distribution
σ_L	Standard deviation of the load distribution
σ_s	Standard deviation of the strength distribution
S(s)	Strength Distribution
L(s)	Load Distribution
d*m*	Decision from *m* exclusive and exhaustive decisions
e*n*	Event from *n* exclusive and exhaustive events
p(e*n*)	Probability of event e occurring
C*ij*	Consequence of decision d*i* and event e*j*
u	Utility
uC*ij*	Utility of consequence of decision d*i* and event e*j*
u(d*i*)	Utility of decision d*i*
y	Design characteristic
U(y)	Value curve function
f(y)	Probability density function for design characteristic
oV*j*	Overall value of design option *j*
w*i*	Weighting factor for criteria *i*
V*ij*	Value of parameter *i* associated with design option
n	Total number of criteria
V*ij* (max)	Maximum value of parameter
U(x)	Utility of a set of attributes x
k*i*	Single attribute scaling constant
U*i*(x*i*)	Single attribute utility function
K	Scaling constant
K*j*	Scaling constant for a single attribute value function

Symbol	*Meaning*
T*i*	Total value of alternative *i*
W*j*	Weighting factor for criteria *j*
nV*ij*	Normalised value for alternative *i* under criteria *j*
V*ij*	Value of alternative *i* under criteria *j*
nf*j*	Normalised factor for criteria *j*
nd*j*	Non-dimensionalising factor for criteria *j*
MI*i*	Match Index for a design value V*i*
M(s)	Match coefficient
U(s)	Weight of evaluation elements
K*i*	Set of design elements for the design value V*i*
nc	Number of characteristics, dimensions of design space
ncc	Critical characteristic
m*i*	Model retrieved from knowledge base
gm*i*	Goodness of match of retrieved model
th	threshold value of gm*i*
CD*i*	Characteristic description
Ch*i*	Characteristic *i*
Val*i*	Value of characteristic *i*
Int*i*	Acceptable interval of value *i*
W*i*	Weighting for characteristic *i*
Vs	Value specified for a characteristic
Vm	Value supplied by a retrieved model
Ls	Lower value of Vs
Hs	Higher value of Vs
Lm	Lower value of Vm
Hm	Higher value of Vm
Ch*ij*	*i*th characteristic antecedent of factor *j*

Symbol	*Meaning*
gom	Goodness of match
Ds	Design specification as a variable
Dch	Design characteristic
DchV	Design characteristic value
Df	Design factor
Dcch	Critical design characteristic
DchT	Design characteristic target value
DchE	Design characteristic estimate value
μDchT	Mean of target value distribution
μDchE	Mean of estimate value distribution
minT	Minimum target value
maxT	Maximum target value
minE	Minimum estimate value
maxE	Maximum estimate value
DchT(v)	Distribution of target values
DchE(v)	Distribution of estimate values

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List of Abbreviations

CDEM	Conceptual Design Evaluation Methodology
CDFR	Conceptual Design Factor Rating
CDSR	Conceptual Design Solution Rating
GDT	General Design Theory
DSD	Design by Scientific Discovery
MSD	Multi-Level Selection Development
QFD	Quality Function Deployment
GMI	General Manufacturability Indices
DFA	Design for Assembly
AEM	Assemblability Evaluation Method
DMED	Decision Making in Preliminary Engineering Design
UVA	Use-Value Analysis
MEDA	Methodology for the Evaluation of Design Alternatives.
DCA	Design Compatibility Analysis
IDS	Initial Design Selection
DFR	Design for Reliability
Dch	Design Characteristic
Dcch	Design Characteristic, Critical
DchT	Design Characteristic Target
DchE	Design Characteristic Estimate
Df	Design Factor
DM	Design Margin
LR	Loading Roughness
SM	Safety Margin

Chapter 1 *Introduction*

The past three decades have seen an increasing interest in researching the engineering design process. The main interrelated reasons generally cited for this interest are as follows:

- Increasing international competition
- Increasing demand for higher quality products and services.
- Technological advance
- Product Liability Legislation

These reasons are deemed to demand the following responses:

- Exploit emerging technologies more rapidly.
- Reduce design timescales.
- Provide 'Right first time' design.
- Innovate more frequently and produce more innovative products.
- Increase the reliability of products and systems.

These responses, in turn, require the following developments:

- Increased automation of the design process.
- Improved quality control of the design process.
- Improved quality control of the output of the design process.
- Increased understanding of the mechanisms enabling innovation.

The ever growing international competition, in every industrial sector, and the ever developing demand form consumers for higher quality products and services, coupled with the accelerating pace of technological development, act to increases the pressure

on companies trying to maintain their competitive position and forcing them to either innovate more frequently or introduce more innovative products [Cheese 1990].
Rapid product development and innovation, through the exploitation of enabling technologies, is seen as a principal way to stay ahead of the competition [Dickson 1990]. Developments of advanced manufacturing technologies and the equally significant expansion of advanced materials have added to an atmosphere of innovation and opportunity in the manufacturing sphere which has not been wholly reflected in the design field. The main exception to this has been the exploitation of computer technology in the form of Computer Aided Design (CAD) systems. However, the desire to achieve the full potential of CAD, by increasingly automating the design process, has succeeded in highlighting a fundamental lack of understanding of many aspects of the engineering design process.
Further, the recent advent of Product Liability legislation, first in the USA and now the EEC, has focused the thinking of manufacturers on the importance of design to their well being as well as the nations. In particular this legislation emphasises the importance of being able to bring a consistent, objective, traceable and defensible decision making to the design process since in the event of litigation it would be the manufacturer/designer who would need to show that he had taken all reasonable measures to ensure the safety of their product.

At no point within the design process are the above challenges more crucial than within the conceptual design phase. Conceptual design is considered to involve the development of a Functional Description of a device or system, gleaned from its Product Design Specification, and its transformation into a number of Structural Descriptions. It is at this point that many of the most important decisions about a design are taken and the seeds of innovation sown. In short, the potential for commercial success of a product is largely established at this time even though conceptual design receives the least attention in terms of resource allocation. And yet, the Conceptual Design phase involves decisions which have, perhaps, the greatest influence on eventual project success [Ulrich and Seering 1988]. The types of decision taken at this stage in the design process include:

- comparison between options
- comparison between an option and a specification

These comparative assessment activities are usually brought under the umbrella of 'evaluation' and, as will be shown, can be considered to combine, interactively, with synthesis and analysis activities to drive a design through the various phases of the design process.

Although there exists published work regarding the computer aided generation of conceptual designs [Ulrich and Seering 1988] little evidence of work into providing the fundamental basis for the interactive evaluation of conceptual engineering designs is evident.

It was therefore the purpose of this research to investigate the evaluation activity within the conceptual design phase of the engineering design process with a view to determining how the evaluation activity may be made more interactive with the quality of both the activity and its output improved.

Research Hypothesis

The purpose of this thesis is to report the results of the above investigation that used the following working hypothesis as a guide:

'A conceptual design evaluation method can be proposed that will enable the automatic evaluation of technologically innovative conceptual design options. In turn this will enable the mechanisms of innovation, assist in the reduction of design timescales, permit traceability of design decisions, and provide commercial success with the minimum of development time.'

Research Programme and Methodology:

In order to meet the challenges described above it has, for some time, been seen as necessary to provide a better understanding of the design process through programmes of design research [Rabins 1986]. Such programmes have recently been instigated in both the USA (Carnegie Mellon) and the UK (Engineering Design Centres) and published material is now flowing from both sources A significant body of design research literature also exists in Germany centred, most recently, on the work of Hubka, Pahl, Beitz, Eder et al. Japan and Australia are also, currently, very active in the design field with the principal contributions provided by Yoshikawa [Tomiyama 1990] and Gero et al [1991] respectively. It is to this growing body of research that reference will be made throughout this thesis. However, it is also widely recognised that design research is immature with little agreement, between researchers, on the specific areas worthy of research activity [Pugh 1990] or indeed of the research methods to be employed. In parallel, one of the principal criticisms of design research, to date, has been the lack of experimental evidence to support the adoption of theoretically based models of the design process or of some of the activities within the process [Stauffer et al 1991].

It was with these points in mind that the following research programme and methodology (Fig. No. 1.1) was devised and followed:

Phase 1

The design research literature was reviewed with a view to identifying current models of the design process and in particular to assess the perceived role of the evaluation activity within these models. It was important to identify the needs of any conceptual design evaluation methodology prior to reviewing the methods currently available and certainly before proposing any new methodology.

The deliverable from this phase was an interim report based on an extensive literature review which provides the basis for chapter 2 of this thesis.

Phase 2

The research literature was reviewed to identify the state of the art of conceptual design evaluation methods in parallel with developments in decision theory as well as technological and product forecasting. These methods were then assessed against the criteria established in phase 1

A deliverable from this phase was a second interim report which forms the basis for chapter 3 of this thesis.

Phase 3

As a result of deficiencies in existing methods being identified in phase 2, a new methodology was developed, via a process of morphological synthesis of existing methods and techniques, to meet the identified needs. The deliverable from this phase was a third interim report which forms the basis of chapter 4 of this thesis.

Phase 4

A design experiment was devised which sought to determine the validity and reliability of the proposed new methodology. The details of the design of the experiment and the results are recorded in chapter 5.

Phase 5

This phase of the research comprised the writing up of this thesis and in particular recording the conclusions about the research. This is contained in chapter 6

Contribution to Knowledge

In addition to the provision of a Conceptual Design Evaluation Methodology for use within the engineering design process this research project has contributed to knowledge within the design domain in the following ways:

- an improved understanding of the relationship between design phase and evaluation activity.
- an improved understanding of the appropriateness of specific design research methods.
- an improved understanding of the limitations of novice and expert evaluation capability during the conceptual design phase.
- an improved understanding of the interaction between prediction, decision making and evaluation.

The research, described in the following chapters, is considered novel in the following respects:

- The developed conceptual design evaluation methodology utilises methods and techniques from related domains which have never before been used in this area. Their validity has been demonstrated through experimentation.
- The lack of established research methods has demanded that a novel approach be used to test the proposed evaluation methodology within a controlled design experiment

Project Management

At the start of the project, a work plan was constructed detailing all the individual tasks required to complete the project. This is displayed in the form of a Gantt chart (Fig.No.1.2). Since, by necessity, this project was undertaken on a part time basis project management control was essential to ensure the completion of the work within the prescribed timescale.

RESEARCH METHODOLOGY

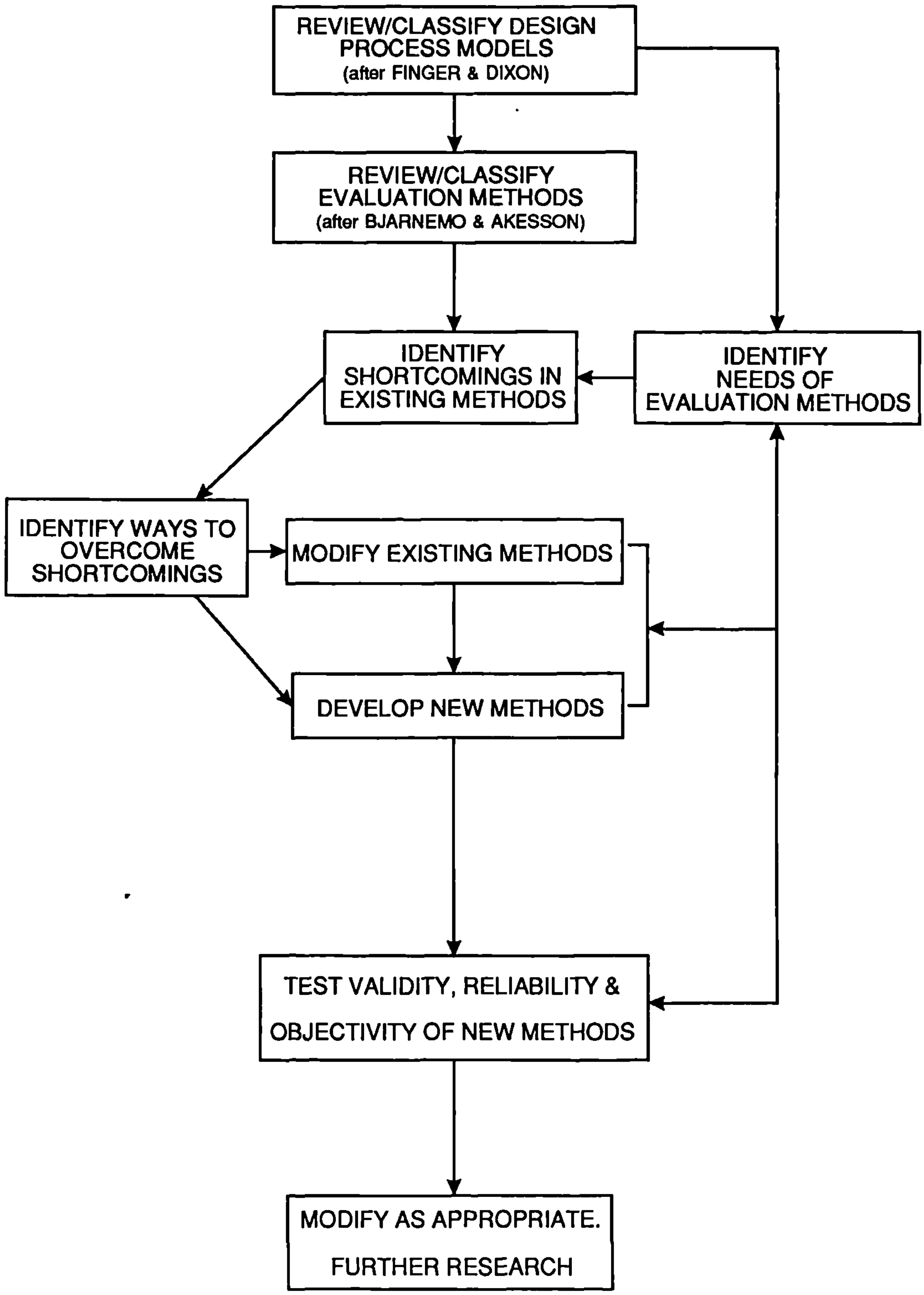


Fig. No. 1.1

PROJECT MANAGEMENT CHART

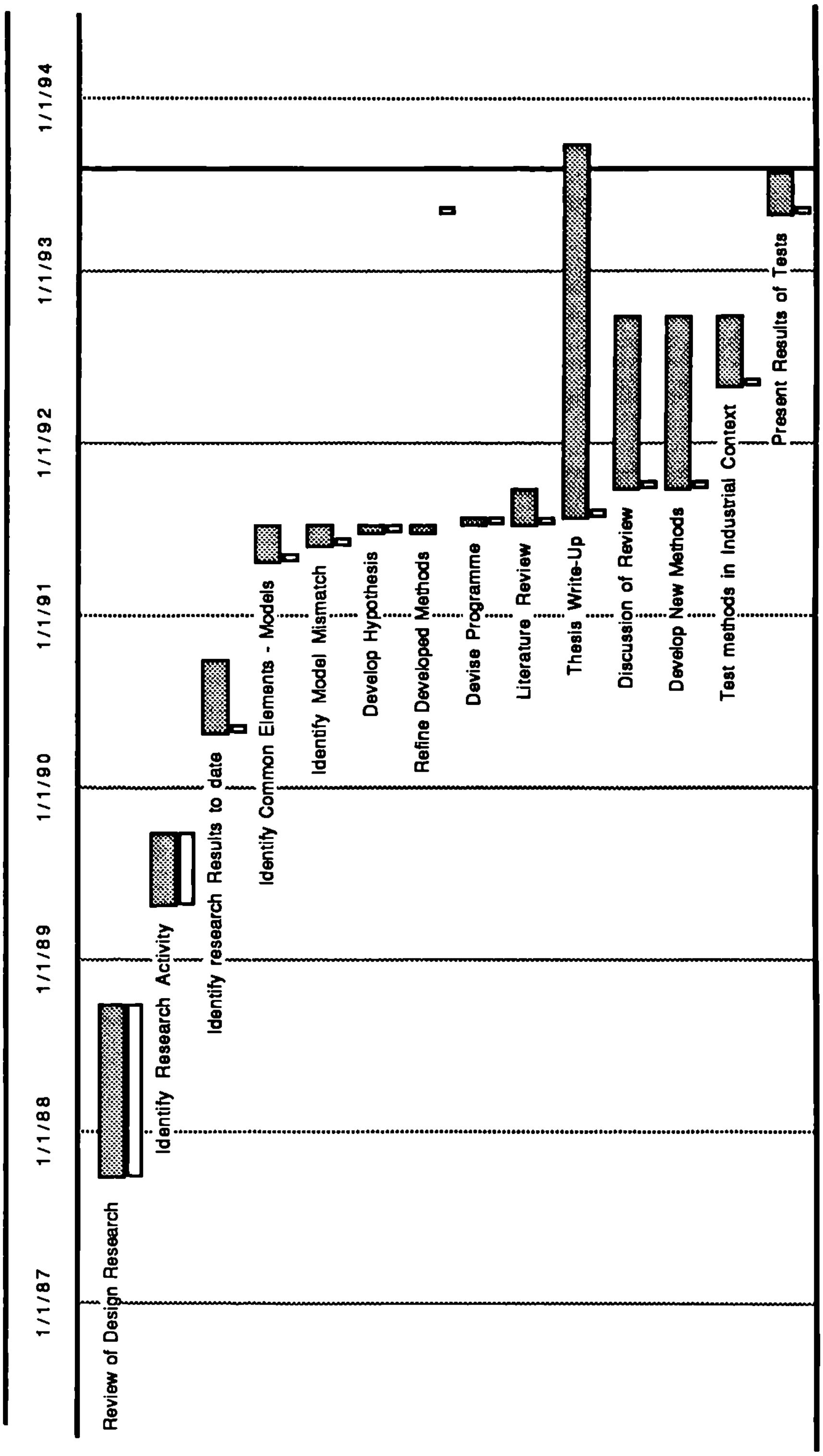


Fig. No. 1.2

Chapter 2 *Engineering Design Process Models*

Introduction

A principal result of design research effort , to date, has been the proposal of a number of models of the design process which may be classified under the following inter-related headings, [Finger and Dixon 1989]:

- Descriptive Models
    - Research
    - Case Studies
- Prescriptive Models
    - Organisational
- Normative Models
- Computer-Based Models
    - Cognitive

The result of this classification has been recorded in Table 2.1

The purpose of this phase of the research project was to identify the various needs for design evaluation activity within the conceptual design phase of the engineering design process. The above classification enabled this process in that it provided a framework for model comparison and the identification of the common evaluation activity requirements between the models. This process would have been more straightforward had an agreed generic model of the design process been identified. The lack of this agreed model required that a search be made for the links between these models.

Classification of Design Process Models

Model's	Descriptive	Prescriptive	Computer-Based	Cognitive	Normative	Case Studies	Research	Organisational	Generic	Domain Spec.
Gen. Design Theory	Δ		Δ	Δ						
Gen. Procedure Model		Δ						Δ		
Axiomatic Design		Δ								
Robust Design		Δ								Δ
Total Design		Δ						Δ	Δ	
EDRC Framework	Δ			Δ			Δ			Δ
VDI 2221		Δ			Δ					
Ullman's Model			Δ	Δ					Δ	
Pahl & Beitz Model		Δ								
March's Model		Δ		Δ						
Archer's Model		Δ								
DSD Model		Δ	Δ							
B.S. 7000		Δ			Δ			Δ	Δ	
M.S.D Model			Δ					Δ		Δ
Hubka's Model		Δ							Δ	
Wallace & Hales	Δ					Δ				Δ
Marples Model	Δ					Δ				Δ
French's Model		Δ							Δ	

Table 2.1 Classification of Design Process Models to Assist Literature Review

Descriptive Models:

Descriptive models of the design process are gleaned from observation of designers engaged in design work or from the personal experience of the researchers. Descriptive models, therefore, describe how the design process has been undertaken.

The research methods employed to develop descriptive models include the following:

- **Protocol Analysis**, borrowed from Artificial Intelligence research, is used to record the actions of individual designers during the design activity. The record of their actions is supplemented by a record of the designer 'thinking aloud' and his answers to questions posed by the researcher. A common criticism of this approach is that the designers verbal description of his actions is inadequate for actions that are inherently non-verbal. e.g. spatial reasoning.

An understanding of the mental processes in action during the design activity can lead to the development of Cognitive models which attempt to describe the processes that underlie a set of behaviours that are deemed to constitute a design skill.

- **Case Study methods** relate to the observation [Marples 1960] , often participatory in order to more effectively study and collect data [Wallace and Hales 1985], of design projects.

More traditionally, intuitive methods drawing on the personal experiences of researchers has led to a significant number of Intuitive models, that may result in both descriptive and prescriptive models, being proposed over the years. The validity of the models are tested either within academic settings or increasingly within an industrial context.

The following state of the art models, considered as falling within the descriptive classification, are now briefly reviewed:

- General Design Theory (GDT)
- EDRC Framework

General Design Theory (GDT) is a descriptive model of the design process, developed by Yoshikawa et al, which attempts to explain how design is conceptually performed in terms of knowledge manipulation. In GDT, the design process is considered to be a mapping from function space to the attribute space.

A descriptive model of the design process has been derived from GDT [Takeda 1990] in which design is viewed as the stepwise refinement of a design from a functional specification to a design solution. Takeda also describes a cognitive design process model obtained by observing design processes and using protocol analysis. Finally a computer model is discussed which seeks to explain most parts of the cognitive model and to interpret the descriptive model. That is, 'the computable model uses the framework of the descriptive model, and the reasoning in the computable model is an interpretation of the cognitive model.'

The Engineering Design Research Centre (EDRC) model, attributable to Scott, was developed in order to provide an initial framework or reference model to describe the design process and to guide the first directed research programmes, of the Engineering Design Research Centre (EDRC), into the following areas:

- Design Methods
- Design Tools
- Design Infrastructure

The framework is deemed to serve three important purposes:

- It depicts a 'process' which contains the main influential factors of design necessary for an effective design method.
- It indicates where 'tools' should be sought.
- It links resources, people and knowledge in a distributed infrastructure.

Prescriptive Models

Prescriptive models of the design process attempt to state how the design process should be undertaken. The underlying assumption of all the models within this category is that if these models were employed by designers then 'better' designs and or reduced design timescales will result. However, there is little evidence presented in the literature to fully support these claims.

Among the most prominent state of the art prescriptive models are:

- General Procedural Model
    - Theory of Technical Systems [Hubka, Eder]
    - Systematic Design [Pahl and Beitz]
    - VDI 2221: 1986
- Axiomatic Design
- Robust Design Methods
- Total Design Model

These models will now be briefly reviewed.

The General Procedural Model of the design process is essentially an umbrella term for a number of similar models which are based on a large body of design research work undertaken throughout the last three decades and centred on Germany. In more recent years important sections of the work have been translated into English and have become more accessible to a much wider audience. On the basis that design methodology aims to provide the designer with a model, procedure or strategy for design activity that will increase the likelihood of reaching a successful solution, the above models combine to provide a General Procedural Model of the Design Process. This model forms the basis for creating a procedural plan, or systematic design approach, suitable for specific design demands. The steps in the model were derived by Hubka and are justified in his book 'Theory of Technical Systems'. It was intended to make the model as comprehensive and as general as possible in order to accommodate as many design situations as possible. Although highly structured, the systematic approach is not intended to restrict creativity but rather to enhance it by providing a framework to allow original thought to emerge.

By contrast, Suh's 'Axiomatic Design' approach is based on the following hypothesis - ' '*There exists a small set of global principles, or axioms, which can be applied to decisions made throughout the synthesis of a manufacturing system. These axioms constitute guidelines or decision rules which lead to 'correct decisions, i.e., those which maximise the productivity of the total manufacturing system, in all cases.'* [Suh 1978,1990]

The set of axioms are developed via an heuristic approach. This involves proposing a set of 'hypothetical' axioms which are subjected to trial and evaluation in case studies and then refined until a comprehensive set of axioms is converged upon.

The Axiomatic approach has as a first step the determination of Functional Requirements which are defined as ' a minimum set of independent specifications that completely define the problem.'

The second step is to specify Constraints which are defined as' those factors which establish the boundaries on acceptable solutions'. The difference between Functional requirements and Constraints is that Functional requirements are 'negotiable' final characteristics of a product, while Constraints are not.

The third step, after the functional requirements and constraints have been defined, is to undertake Conceptual design and proceed to further stages of product realisation using axioms to aid decision making.

It is claimed that a product designed by following the axioms should be more readily manufactured than would be case using traditional design approaches. Therefore the axiomatic approach is based on the belief that ' fundamental principles or axioms of good design practice exist' [Rinderle and Suh 1982]. Further, a set of design axioms act as criterion for the evaluation of design decisions. Two principle axioms have been proposed:

- Maintain the independence of functional requirements. i.e. each functional requirement of a product should be satisfied independently by some aspect, feature or component within the design.
- Minimise the information content. i.e. that good designs are minimally complex

On the other hand, Taguchi's 'Robust Design' methods are concerned with producing designs that are less sensitive to uncontrollable factors (Noise factors) which can cause functional criteria to deviate from target values. Designs which attain this reduced sensitivity are termed 'Robust' To achieve robust designs, Taguchi divides the design process into three areas:

- System design: where the fundamental design and engineering concepts are established.
- Parameter design: where the target values for the design are set and where the sensitivity of the design to variation is determined.
- Tolerance design: where design tolerances are established

Design experiments are devised with the aim of identifying the settings of the design parameters at which the effect of changes in Noise factors is a minimum. The experiment is undertaken in two parts:

- Design Parameter matrix
- Noise Factor matrix

The combination of these matrices produces a Performance Characteristic for each test run. Continuous performance results are used to provide Performance Statistics which are used to predict better settings of the design parameters. The Performance Statistic takes the form of a 'signal to noise ratio' which combine both the mean of measurements and their variations around this mean as a single statistic. In its simplest form the signal to noise ratio is the ratio of mean to standard deviation.

Pugh [1981] has based his 'Total Design' model of the design process around a 'core' of design activities. Emphasis is placed upon the creation of a Product Design Specification that is defined as a dynamic document that describes all the requirements for product success both in terms of manufacture and the market place. The model seeks to be all embracing of the issues impinging on design, Pugh terms this Total Design . The core activities are supplemented and supported by methods aimed towards assisting in the divergent and convergent thought processes required at various phases of the design activity. At the conceptual phase, controlled convergence methods are used to employ divergent and convergent activities as required which ultimately assist convergence upon the most appropriate conceptual solution.

Normative Models

These are models of the design process that have been developed experientially for application in specific domains and are usually enshrined in Standards and Codes of Practice. By their very nature they tend to concentrate on the design needs within specific well established domains and concentrate on analysis activities within the domain.

Computer-based Models

These are models of the design process, often based on descriptive. prescriptive or normative models but modified to make effective use of the characteristics of the computational environment, which describe a method by which a computer may achieve a specific design task. Generally, computer models are concerned with how the computer can design or assist in designing.

Nevill [1988] states that computer models can play two distinct roles:

- Development of Computer Aided Design (CAD) tools in various fields.
- Support research into design theory and methodology

Finger and Dixon [1989] report on the development of computer-based models within the following classification:

- Conceptual design
- Configurational design
- Parametric design

They consider parametric design models to be the most mature though they accept that no single theoretical approach has yet emerged. Optimisation and Simulation approaches offer specific problem solving techniques aimed at producing the 'best' design.

In an earlier paper Dixon and Simmons [1985] introduced a number of general areas of research:

- Iterative redesign
- Decomposition
- Rule-based systems
- Geometry and CAD environments.

A model of the design process based on decomposition and iterative redesign models is presented leading to the creation of expert systems in both areas.

Dixon and Simmons also cite the most likely methods for representing knowledge in expert systems for mechanical design as being:

- Rule-based systems, consisting primarily of knowledge-based rules, short term or working memory and an interpreter to decide on which rule to apply next.
- Frames, are defined as generic data structures containing any desired number of categories (slots, which may also be frames themselves) of information attached to the subject of the frame.

Dixon and Simmons further characterise the engineering design process as involving iterative decision making with the decisions falling into two main categories:

- Process decisions, (Meta-decisions) that determine the course of the design process
- Technical decisions, (Domain decisions) that determine the actual design solutions.

They conclude that it is likely that different design solutions develop more as a result of the application of different design processes rather than the technical decisions made.

Knowledge-based approaches to design are considered [Coyne 1990] to be based on three basic design models:

- Logic, where design is seen as something about which one makes deductions.
- Linguistic, where design is regarded as sentences for which there are syntax and a semantics. The generation of design is seen as analogous to that of sentences in natural language.
- Typology, where design is seen as a process of instantiating from an understanding of the properties of a class of designs.

By contrast, Maher [1990] presents three models of the process of design synthesis:

- **Decomposition**, considered to be the most widely used computer based model and shown to be particularly applicable in Knowledge-based systems. The model simply describes the idea of dividing large complex problems into smaller more manageable problems where the type of design knowledge required can be more readily identified. The problem with this approach is seen as being the assumption that solutions to the decomposed problems can be recomposed to provide a valid solution to the complex problem.
- **Case-based reasoning**, directly employs design experience in the form of considering the solutions to previous design problems and transforming them so as to

provide solutions to new problems. The difficulties with this approach are centred on the appropriateness of the transformation.

- **Transformation**, is described as an holistic approach to design. Similar to case-based reasoning but uses generalisations rather than specific solutions. The design knowledge is expressed as a set of transformation rules. The difficulties associated with this model are cited as being controlling the selection and the applicability of the transformation rules.

Ullman's Model of Mechanical Design [Ullman 1991], unlike the previously described models, considers the needs of the evaluation activity in depth and identifies the following techniques for use within his model:

- Absolute Comparison
  - Feasibility Judgement
  - Technology readiness assessment
  - Go/No-go screening
- Relative Comparison
  - Decision matrix method

However, Ullman does not expand on these approaches or describe how they might be enshrined within a computer-based model or indeed whether they are applicable as such. Rather he settles for describing the information sources and interfaces within such a computer-based design environment.

The Design by Scientific Discovery (DSD) Model of the design process [Dasgupta 1991], on the other hand, is a novel and fresh thesis on the structure of the engineering design process. In his book, Dasgupta presents a well argued case as to how design may be considered as a form of scientific discovery and that therefore the methods employed should be the same for both. However, once again the thesis is not tested by experiment and one is left questioning the validity and reliability of such an approach.

More conventionally, the Multi-level Selection-Development (MSD) model of the design process [Sause and Powell 1991] is a computer model developed specifically for the structural engineering domain. The model is entirely intended for routine design, as opposed to creative or innovative design. MSD is also described as an organisational model for the design process since it aims to organise a problem into well defined selection and development sub-problems. Thus the design problem is successively decomposed into sub-problems for sub-systems and ultimately into components. The decomposition process proceeds ,through several levels, via two main steps:

- Each sub-problem is replaced by a Selection sub-problem which involves selection from a number of alternatives.
- Each sub-problem is replaced by a number of Development sub-problems each of which involve the design and evaluation of an alternative.

The effectiveness of each design alternative is assessed via heuristic evaluation which is considered to involve reasoning about:

- the situation, as given by the problem formulation
- the capabilities of the alternatives.

The types of reasoning used are given as:

- reasoning about geometry (spatial reasoning)
- reasoning about compatibility
- reasoning about suitability

The above process is said to result in the assignment of 'qualitative measures of merit' that are used to rank the alternatives.

The evaluation approaches are again domain oriented and are thus analysis focused in that they do not necessarily involve comparison between options nor do they encourage such activity.

Discussion

Although all the models developed to date have their individual characteristics it is now generally accepted , within the literature, that they all exhibit a core of basic engineering design phases that are undertaken recursively within the design process.[Konda et al 1992]

- **Functional requirements**, transforms identified needs into functional descriptions often encapsulated within a product design specification
- **Conceptual design**, transforms a functional description into a number of structural descriptions.
- **Configurational design**, transforms a structural description into a configuration with a defined set of attributes or characteristics, but with no particular values assigned.
- **Parametric design**, assigns specific values to attributes. These values may be numeric or may also be a type or class designation (e.g. material choice)

This was checked, and confirmed, by undertaking a classification of each of the identified models against phases of the design process. This is shown in Table 2.2.

This core of engineering design phases may be extended for consideration of product design [Bertoncelj 1987] with the addition of the following phases:

- Recognition of need
- Engineering design phases
- Product Realisation

It is accepted, within all the models reviewed, that the conceptual design phase of the design process is by far the most important of all in that the inherent reliability, cost, manufacturability and potential for commercial success of the product are largely established at this time. It can also be seen to be the most critical phase in that it is the initial point of the transformation of the design requirements into a physical description of a system possessing these requirements. Subsequent phases of the design process act

Classification of Design Process Models

Model's	Functional Requiremets	Design Characteristics	Conceptual Design	System Design	Configurational Design	Embodiment Design	Parameter Design	Tolerance Design	Detail Design	Design Realisation
	Increasing Definition of Design State within Design Process Phases									
Gen. Design Theory	Δ		Δ		Δ		Δ			
Gen. Procedure Model	Δ		Δ			Δ			Δ	
Axiomatic Design	Δ	Δ	Δ							Δ
Robust Design				Δ			Δ	Δ		
Total Design		Δ	Δ			Δ			Δ	Δ
EDRC Framework										
VDI 2221	Δ		Δ		Δ	Δ			Δ	Δ
Ullman's Model										
Pahl & Beitz Model	Δ		Δ			Δ			Δ	
March's Model		Δ								
Archer's Model		Δ								
Dasgupta's Model	Δ		Δ							
B.S. 7000		Δ	Δ			Δ			Δ	
M.S.D Model						Δ			Δ	Δ
Hubka's Model	Δ		Δ			Δ			Δ	
Wallace & Hales			Δ							

Table 2.2, Classification of Process Models and Design Phases

iteratively with each other, as well as with the conceptual phases, to refine, develop and evaluate the initial concept against the original design specification. To fundamentally alter or pursue a new concept it is necessary to restart the whole design process. In order to minimise design timescales it is essential that the initially selected concept offers the maximum chance of success.

Reviewing the design process models also revealed an interesting divergence in the strategies inherent in the descriptive and prescriptive models.

Prescriptive models of the design process tended to promote the strategy of generating as many conceptual ideas as possible in order to maximise the chance of identifying the 'best' concept for development. Much research has been undertaken within this area principally with a view to identifying methods to enhance the conceptual generation process [Cross 1989].

However, this strategy was clearly at odds with descriptive models which tend to record a tendency for designers to quickly identify and develop a single concept.

One tentative explanation for this dichotomy is that traditionally the difficulties of evaluating conceptual designs has meant that designers have been reluctant to generate large numbers of concepts, especially those with technologically innovative features, since this would require the designer to spend a substantial amount of time in the decision making process. Innovative concepts also represent high risk and designers tend to reflect management attitudes to risk [Tebay et al 1984]. Due to the lack of an established conceptual evaluation methodology and time the risks involved may be viewed as unacceptable. Inevitably the designer is forced to rely on personal experience and intuition in order to evaluate and select suitable conceptual designs and therefore elected to generate what they perceived to be low risk concepts. The growing complexity of modern products and processes and the parallel demands for ever reducing product design and development timescales act together to make the over reliance on intuition and experience an unacceptable approach. It may be true, given enough time, that a designer can acquire enough experience and an intuitive ability to make comparative assessments between designs but he will not necessarily be able to say with any degree of accuracy whether a design will meet the required design specifications. The accuracy of any such assessments will depend to a large extent upon the degree of definition of the design. If the definition is complete, hence all information regarding the design is available, the assessment will have a greater likelihood of being accurate. If the definition is incomplete then a degree of forecasting or prediction is required and hence a less accurate assessment may be expected. Equally, the designer's ability to make justifiable and traceable trade-offs between requirements, based on experience and intuition alone, must be in question as is the consistency of intuitive assessments between individuals. Further, the increasingly recognised need to utilise flexible multi-disciplinary teams during a concurrent design process gives emphasis to the requirement for decision making methods that can be coherently applied within such teams. Such methods are essential if team members are to participate fully in the evaluation of emerging design options [Wallace and Hales 1989].

Concluding Observations

The above literature review and discussion, complemented by classification of the models, has revealed a number of specific requirements expected of an evaluation method employed within the conceptual phase of the engineering design process. These are:

- It must be specific as to the point in product life to which the evaluation is projected.
- Forecasting methods need to be integral with evaluation and decision making methods available for use by the design team and be applicable to the short, medium and long term.
- Each conceptual option must be defined in terms of known components and sub-assemblies, with either known or assumed characteristics.

- The evaluator should take the viewpoint that he is evaluating the potential of the concept to meet the specifications at some defined point in the future when the concept will be subject to defined conditions.
- Technologically innovative components and sub-assemblies must be assigned characteristics, previously forecast, within the product model.

It was next necessary to review the research literature on conceptual design evaluation methods, in light of the above, and to determine whether any of the current methods met the demands or whether a new methodology had to be developed.

Chapter 3 *Engineering Design Evaluation Models and Methods*

Introduction

It was generally accepted, within the literature reviewed in chapter 2, that any design that is being offered for sale in the market place had to be designed such that the resulting design satisfied a range of requirements. These requirements were classified under the following general headings:

- Technical
- Economic
- Human factors
- Legal
- Environmental

Each general heading can, in turn, be sub-divided into an extensive list of specific product design requirements [Pugh 1981]. These requirements act as constraints defining the design space where an acceptable solution may be found. The constraints are highly interactive requiring the values assigned to each constraint to be constantly under review throughout the design process. These constraints also form the reference base for evaluation. It is clear that evaluation of any proposed design solution requires to be evaluated at various levels of abstraction. If more than one solution is proposed then the evaluation needs to be extended to enable a selection between competing alternatives. The literature review was therefore sub-divided into the following areas:

- Identification of Evaluation Criteria
- Evaluation of Concept Design Characteristics
- Design Forecasting and Decision Making
- Evaluation of Concept Design Alternatives

The identified evaluation methods were subsequently classified against these headings. (Table 3.1)

Classification of Design Evaluation Methods

Design Evaluation Methods	Select Criteria	Initiate Analysis	Comparison Phase	Prediction Phase	Decision Phase	Initiate Synthesis
	Conceptual Design Evaluation Activities					
DFR	Δ		Δ	Δ	Δ	
DCA		Δ	Δ		Δ	Δ
GMI's		Δ	Δ			
QFD	Δ					
Systematic	Δ	Δ	Δ		Δ	
Technical Systems	Δ	Δ	Δ		Δ	
Cont. Convergence	Δ		Δ		Δ	
Design Methodics	Δ		Δ		Δ	
MEDA						
Prob. Design. Option			Δ		Δ	
Taguchi		Δ	Δ		Δ	Δ
Roozenburg			Δ		Δ	
IDS	Δ		Δ			
EDESYN			Δ		Δ	
DMED						
DFA	Δ		Δ		Δ	Δ

Table 3.1, Classification of Evaluation Methods to Assist Literature Review

Identification of Evaluation Criteria

In all the design process models reviewed in chapter 2 it was assumed that the criteria used in any evaluation would be generated by the designers themselves. How they were to do this was not addressed. Over the past decade, however, the need to take more careful account of user and customer needs has become more widely recognised and implemented with most vigour in Japan.

Quality function deployment (QFD) originally developed in Japan but is now gaining acceptance in the USA.[Sullivan 1986]. It is a product development tool which provides a methodology directly to relate the customers needs with engineering characteristics to ensure that what is eventually produced matches the original requirements. This approach has been recently described in an application for software development [Thackeray and Van Treeck 1990]. Sullivan states the QFD system concept is based on four key documents:

- Overall Customer Requirement Planning Matrix-translates customer requirements into specific product control characteristics.
- Final Product Characteristic Deployment Matrix-translates product control characteristics into critical component characteristics.
- Process Plan and Quality Control Charts - identifies critical product and process parameters.
- Operating Instructions - identifies operations to be performed to ensure that the identified critical product and process parameters are achieved.

The purpose of these documents is to assist in providing a continuous flow of information from customer requirements to plant operating instructions. According to Sullivan, it is therefore a customer driven system for evaluating the relationships between:

- Customer requirements and characteristics to be used to develop and control the product.
- Customer and company evaluations of competitive products.

More recently, research has been conducted into the need to transform initial specification information into well-defined design objectives [Umaretiya and Joshi 1990]. The approach, termed 'Specification Extraction Interface for Structural Design' (SEISD), is implemented within an expert system .

Evaluation of Concept Design Characteristics

As previously indicated, the design requirements are assumed to have been defined before any design activity begins. At regular intervals within the design activity it is necessary for the state of the design solution to be evaluated. Analysis provides information, regarding the state of the design, to allow an evaluation to be made. The current state of the design is compared with the desired state and a decision is made on how to proceed. We can see that evaluation is closely related to both analysis, forecasting and decision making.

Design evaluation may be summarised 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 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 state to the next identifiable state or to the final desired state, within defined timescales, given knowledge of resources and abilities .

A difficulty facing designers involved in evaluation is that, in a complex product, the number of constraints defining the state of the design can be large. The points of reference may also change making it easy to get lost. In the design of a simple component, the constraints may be few and hence more manageable. The points of reference may also be more secure.

Given the appropriate level of security there are a number of well known quantitative analytical methods and approaches available to the designer that can assist in providing the necessary information on the state of the design being considered:-

Technical Evaluation

It is generally accepted that at whatever level technical analysis is undertaken it follows the same procedure:

- Objective formulation
- Model formulation
- Mathematical, or experimental, analysis

It is clear that the objective of the analysis must be both well defined and quantifiable. In turn the model must be gradually increased in complexity as the design process progresses and more information becomes available. The degree of match between the model and the real world must be tempered with the constraints of time and resources in its provision of meaningful solutions. Exercising the above approach provides information on the following:

- Confirmation of satisfaction of fundamental principles inherent in concept.
- Prediction of future performance given present assumptions and information.

In light of the information obtained the conceptual design may be rejected or modified and re-modelled as appropriate to allow further analysis.

An implicit, if not explicit, requirement of design is to identify the 'best' design possible. This implies the existence of an optimum solution. Achieving the best possible performance at the least possible cost is the designers dream.

Techniques for the functional analysis of designs are well advanced particularly in the areas of stress analysis, mathematical modelling and simulation. A great deal of information, regarding the proposed design, is required prior to these techniques being applied and are thus more appropriate for the later stages of the design process. Recent work [Suri 1988] promotes the idea of taking a 'Design for Analysis' approach which recognises that a product should be designed to enable effective analysis just as other techniques attempt to ensure that products are designed to enable effective and economic manufacture.

Design for Manufacture

There is an increasing awareness of the need for the design process to match the advances occurring in manufacture to ensure that the maximum benefits are realised [Shah et al 1990]. It is also accepted that there has to be a right first time approach adopted within design in order to minimise the number of deficiencies discovered at the fabrication stage.

Generalised Manufacturability Indices (GMI)

Jansson et al [1990] present the development of a framework for the evaluation of design concepts early in the design process through the use of a set of Generalised Manufacturability Indices (GMI's). It is argued that GMI's are aimed at providing designers with a deeper insight into design issues which affect manufacturability than would be available from a cost estimate or indeed the use of design guidelines. It is further claimed that GMI's enables application to very dissimilar designs and be applicable at the early stages of the design process.

The recent literature is well represented with work which is directed towards improving and understanding the link between design and manufacture and particularly in providing techniques that enable the rapid identification of features within a proposed design that do not lend themselves to effective manufacture.[Dargie et al 1980, Stoll 1986, Miles 1990, Allen et al 1991]

Design for Assembly (DFA)

Design for assembly is now a mature technique due principally to the work of Boothroyd and Dewhurst who claim that DFA not only provides a reduction in assembly costs but may also result in significant reductions in overall manufacturing costs since it encourages product simplification.

DFA involves two important steps:

- Minimisation of the number of separate items
- Improve assemblability of remaining parts.

Although they address both manual and automatic assembly techniques it is significant that one of the results seems to be that which ever one is emphasised it has beneficial effects on the other simply because the thought given to the problem provides a general improvement in the design. Boothroyd and Dewhurst have developed a computer based version of their previously developed handbook based techniques which allows more rapid assessment of designs in terms of their assemblability. it has not yet reached the stage whereby computer based models of the design are automatically interrogated and suggestions for improving the design given.

Other significant developments in this area includes Knowledge-based DFA Evaluation [Allen and Swift 1990] which has been developed and employed, apparently successfully ,in conjunction with Lucas Ltd.

A similar approach has been developed in parallel by Hitachi Ltd, termed simply the 'Assemblability Evaluation Method' (AEM) [Shimada et al 1992].

Design for Reliability

The literature on Design for Reliability identifies a number of techniques or tools used to assist in the assessment and prediction of mechanical reliability:

1. Generic Parts Count Reliability Prediction
2. Failure Modes and Effects Analysis.

3. Fault Tree Analysis.
4. Design Review
5. Physical Reliability and Probabilistic Design Methods
6. Systems Modelling Methods
7. Markov Analysis
8. Reliability Growth Modelling
9. Prototype Testing

Those having most relevance to this research project are now briefly reviewed.

Physical Reliability and Probabilistic Design Methods

The consideration of Physical Reliability and the application of Probabilistic Design Methods try to take account of the stochastic nature of both load and strength. Proceeding on the premise that failure occurs when applied load exceeds inherent strength, the aim of the above methods is to separate the statistical distributions of applied load and inherent strength to a point where an acceptable level of interaction is achieved. This approach [Carter 1984] highlights the shortcomings of the use of Factors of Safety (FOS) in design and suggests that they should perhaps be more accurately described as Factors of Ignorance. The application of probabilistic design methods proposes the use of the Safety Margin as the parameter defining reliability.

Assuming both applied load and inherent strength to be normally distributed then the Safety Margin (SM) can be shown to be:

$$SM = \frac{S - L}{\sqrt{(\sigma_L + \sigma_S)}} \qquad (3.1)$$

Where, S = mean value of the strength distribution

L = mean value of the loading distribution

σ_L and σ_s are the standard deviation of the loading and strength distributions respectively.

Carter further develops the above theme by evaluating the reliability of an item subject to repeated loading from arbitrary distributions. It accounts for the combined probability of a component having a particular strength and the probability that the applied load will be in excess of the strength. The reliability (R) can be evaluated once the nature of the applied load and inherent strength distributions are known.

$$R = \int_0^{\infty} \left[S(s) \int_0^{s} L(s) ds \right] ds$$

(3.2)

where, S(s) is the strength distribution

L(s) is the loading distribution

However, [Spoormaker 1987] it has been suggested that it is an illusion to expect that the reliability of a product can be predicted exactly but by means of this theory the effect of changing design parameters can be evaluated. That is that the application of Probabilistic Design methods allows the designer to compare his design alternatives, in terms of their reliability, in a rational manner. At the conceptual design stage it may be appropriate to make initial assumptions as to the nature of the load and strength distributions simply to allow the designer to make initial comparative measures of his conceptual designs. The danger is that these assumptions become 'cast in stone'. To avoid this it would be necessary to emphasise the iterative nature of this comparison by ensuring regular re-evaluation of the concepts as knowledge of the loading conditions increases and as the component strengths are gradually optimised in light of this growing information.

Carter argues that designers should accept the impossibility of evaluating an accurate failure rate at the design stage since the failure rate is very sensitive to changes in 'Safety Margin.' Consequently failure rates can only be determined practically by testing during the development process. The designer should make more use of qualitative aids to his own experience and expertise. Carter accepts that reliability is largely determined by design but argues that designers should not be lulled into believing the quantitative predictions of reliability gained from current system modelling theory which he shows as being flawed particularly when applied to mechanical systems since the classic Product Rule is shown to be invalid in 'Rough Loading ' conditions.

Carter defines Loading Roughness (LR) as:

$$LR = \frac{\sigma_L}{\sqrt{(\sigma_L + \sigma_s)}} \tag{3.3}$$

where, σ_L and σ_s are the standard deviation of the loading and strength distribution respectively.

He does however emphasise the need for traditional deterministic design to give way to stochastic design. That is, he encourages the implementation of Probabilistic Design Methods which applies much of his thinking regarding physical reliability at component level.

Cost Evaluation

The need to provide manufacturing cost estimating methods for application during preliminary design has been recognised [Bradford 1989] and discussed in the literature for many years. Design to cost is a term often used to describe the approach taken to consider cost within the design process.

Work concerning the consideration of costs during the design process is evident in the recent literature [French 1990] and in relation to design for economic manufacture the consideration of costs are even enshrined within British Standards.[P.D. 6470: 1981]

The record for the application of these techniques particularly within the earlier phases of the design process is not good and there is little evidence of them being widely adopted by industry. The need however still remains [Allen et al 1991, Allen and Swift 1990].

Recent work [Dewhurst and Boothroyd 1990] describes product costing procedures which are intended to form the basis for a design analysis method for product design for efficient manufacture (DFM). It is argued that efficient manufacture should consist of two steps:

- Identification of appropriate materials and manufacturing processes for the component parts of a new design.
- Detail design of the individual components consistent with the capabilities and limitations of the material-process combinations.

A prerequisite to the above is the availability of manufacturing cost information, at the conceptual design stage,.that is based on assumed optimum manufacturing methods irrespective of the processes and equipment ultimately used.

Parametric analysis [Mileham et al 1993] is a tool applicable to both marketing and design. It enables a products place in the market, relative to its competitors, to be identified and allows a greater understanding of the inter relationships between the product parameters to be gained by the designer.

The technique involves the cross-plotting of product parameters in order to identify any relationships. To be of any value, a large number of plots have to be made. A number of rules for the application of the technique are listed by Hollins and Pugh and they stress that parametric analysis is particularly appropriate in providing information for inclusion within the product design specification. For example, the technique can help to identify the target cost of a design if it is to compete in present and projected markets.

Design Forecasting and Decision Making

Design Decision Making

'Designers tend to reflect management's, or the corporate, attitude to risk in their own decision making.' [Tebay et al 1984]

It has long been accepted that designing consists essentially of a sequence of critical decisions [Marples 1960] leading from the initial problem statement to the final realisation of the product, system or service. Most decisions involve a choice between at least two options coupled with a prediction of the outcomes. More recent research [Wales et al 1987] has shown that successful decision makers use an iterative process of five basic operations:

- Define the situation
- State the goal
- Generate ideas
- Prepare the plan
- Take action

Each operation incorporates an analysis, synthesis and evaluation sequence

The selection made in each operation is important as it determines the path to be followed in future work.

Tebay et al confirm the idea that design is in essence a sequence of decisions and go on to claim that systematic planning of these decisions can form a basis for controlling the design work itself.

Lindley [1985], in his book 'Making Decisions', presents a normative model of decision making with the following elements:

- Decision making is a choice between actions.
- Produce an exhaustive list of decision options.
- The decision options must be exclusive.

- Produce an exhaustive and exclusive list of uncertain events.
- The uncertainty is described as a probability.
- Assign Utilities to the consequences.
- Combine the two numerical concepts of probability and utility to form an Expected Utility.
- Make a decision based on the Maximum Expected Utility.

Therefore, there is a list d1, d2, d3.............d*m* of *m* exclusive and exhaustive decisions; and a second list of e1, e2, e3.........e*n* of *n* exclusive and exhaustive events which in turn have an associated probability of p(e1), p(e2), p(e3).......p(e*n*). As Lindley points out, the problem is to select a single item from the first list without knowing which member of the second list will be true. It also requires that measures of probability and utility can be made in every case.

Now the combination of a decision d*i* with event e*j* will result in a predictable consequence C*ij*. Now since each event has an associated probability this will have an influence on the desirability of the consequence. The degree of desirability is termed the Utility (u), with a value between 0 and 1, of the Consequence (u(C*ij*)). The final step is to associate numbers with the decisions such that the decision with the resulting highest number is deemed to be the 'best' decision. Lindley shows that both the probabilities and the utilities obey probability laws and that they must therefore be combined in a way prescribed by these same laws.

Without proof:

$$u(d_i) = \sum_{i=1}^{n} u(C_{ij})p(e_j) \tag{3.4}$$

where, u (d*i*) is the Utility of decision d*i*.

The 'best' decision is the decision with the Maximum Utility

However, Siddall [1982], in his book 'Optimal Engineering Design', asserts that the concept of Utility is too vague and unclassified for use in design decision making. The concept of Value is used instead. He defines Design Characteristics as those characteristics that directly generate desirability or value in a design. e.g. cost, weight, speed, noise levels etc. Therefore every design is seen to posses a set of design characteristics with associated, subjectively assigned, values (U) resulting in a Value Profile for the design.

When faced with the choice between two or more competing designs, Siddall states that the criterion for choice is that design having the highest total value. He considers two approaches:

- The deterministic design option problem
- The probabilistic design option problem

Having produced a subjectively drawn value curve for each measurable design characteristic the designer next analyses the design option to ascertain the current status of the characteristic and plots this on the value curve. A current value for the characteristic is then read from the curve. The summation of the individual values for each characteristic provides a measure of the overall value of the design option under consideration.

$$U = U1 + U2 + \ldots\ldots\ldots\ldots\ldots Un \quad (3.5)$$

The design option problem becomes more difficult when the design characteristics become random variables. A probabilistic approach, or stochastic approach [Simmons 1993], is then required. In this case a hypothetical probability density function is drawn for the current measure of the design characteristic under review and compared with the associated value curve.

Without proof;

The expected value for each design characteristic is given as:-

$$U_l = \int U(y) f(y) dy$$

(3.6)

Where, y = design characteristic

U(y) = Value curve function

f(y)= density function for the design characteristic

Again, the total expected value for the design option is the summation of the expected values of the individual design characteristics.

i.e.

$$U = \sum_{i=1}^{n} \int U_i(y_i) f_i(y_i) dy_i$$

(3.7)

Decision Making in Preliminary Engineering Design (DMED)

A designer often has to deal with complex and ill-structured situations during specification development and conceptual engineering design. To assist in the development of computer-aided design systems, it is necessary to capture the designers decision making process during these design activities. To this end, two postulates are presented [Joshi et al 1991]:

- Design decisions are neither optimum or just satisfying but retain characteristics of both.
- the design is driven by the critical objectives among all the specified objectives, during conceptual design, although the remaining objectives continue to exercise a weak influence.

Decision making models are developed, with the aid of Fuzzy Set Theory, which explicitly or implicitly follow the above two postulates. It is claimed that the models are suitable for discrete decision situations where the given postulates apply.

Design Forecasting

Forecasting the future and profitability of new product is one of the most difficult management functions [Makridakis and Wheelwright 1989] since the actual performance in the market place is dependant on many factors. The need still exists for such a forecast to take place regardless of the difficulties.

The various aspects of the forecasting process for new products may be summarised [Mahajan and Wind 1988] as follows:

- Forecasting the feasibility of the new product.
- Forecasting acceptability to customers.
- Forecasting usage of the new product.
- Forecasting revenues based on test-market information.
- Sales forecasting

They also state that the forecasting process requires information that may be found from one or other of the following sources and used as appropriate at various stages of the new product development process:

- Expert judgements
- Analogous products
- Consumers

The above approaches refer to established classes of products and not to technologically innovative products. In the latter case Makridakis and Wheelwright suggest that management simply have to rely, at the present time, upon judgement. They also recognise that rapid technological advances and strong market competition demand a more focused approach towards the identification and development of new products.

Forecasting methods concerned with business forecasting [Thomas 1987] tend to focus on the short and medium terms. In the case of technological innovative products [Thamhain 1990] it is necessary that methods are used which can cope with the long term. Makridakis and Wheelwright describe a range of applicable methods used in the following situations:

- Forecasting when a new process or product will become widely adopted.
- Predicting what new developments will be made in a specific area.
- Forecasting relationships that may emerge from an area about to be subject to major changes.

Technological forecasting approaches are classified into four main areas:

- Exploratory methods; seek to predict the future from knowledge of present trends
- Normative methods; assess future goals and then work back to identify the technological changes that would most likely provide achievement of these goals.
- Analogy methods; future prediction based on known trends from analogous areas.

Evaluation of Conceptual Alternatives

Design Methodics

A useful classification of evaluation methods has been suggested [Bjarnemo and Akesson 1983, Bjarnemo 1991] along with a proposal for an integrated evaluation procedure. Initially they suggest a model of formalised approaches to design which they term 'Design Methodics' and which can be seen as the addition of Design Method (How) to the Design Process (What and When). The evaluation procedure is seen to consist of the integration of a number of methods applied at various phases of the design process. Their integrated evaluation procedure is defined as consisting of the following phases:

- Generation and revision of criteria

- Analysis of candidates to determine their properties corresponding to the criteria.
- Value determination of the results of the analysis.
- Selection and recommendation of a solution.
- Decision

In their classification of evaluation methods recognition is given to the evaluation procedures being partly dependent upon the design phase within which it is to be applied. The design phases are given as:

- Planning
- Conceptualisation
- Embodiment
- Detailing

Therefore in their classification system, Bjarnemo and Akesson relate the identified evaluation methods to both the above design and evaluation phases as well as to their perceived limitations. They conclude that none of the identified evaluation methods extend to all the evaluation phases though some are considered to span all the design phases e.g. Value Analysis. This inability to cover all the evaluation phases in one method is considered to be detrimental to the development of future computer aided integration of the functions of companies.

Controlled Convergence

Attempts have been made in the recent past to establish an approach or method to allow a systematic and controlled evaluation and selection of concepts. [Pugh 1981] Here Pugh describes a Method of Controlled Convergence towards the selection of the most appropriate concept for a given design situation. The method involves the formal and disciplined evaluation of designs one against the other, in terms of criteria derived from the product design specification and within a group context, which has the effect of highlighting conceptual weaknesses and strengths. In the process of trying to eliminate weaknesses other conceptual variations emerge and are subject to a series of divergent and convergent phases which are ultimately convergent. It is also argued that the Controlled Convergence method is applicable at any level in design, that is, system, sub-system and component.

The application of this approach has been most recently [Khan and Smith 1989] referred to as the 'Datum Method', and is addressed as part of an overall structured design strategy used in the design of a Dynamically Tuned Gyroscope (DTG).

The Concept selection approach is further expanded by [Kuppuraju 1985] providing a combination of methods based on the work of Pugh, Mistree and Muster. Kuppuraju concludes that three types of decision problem commonly occur in engineering design synthesis:

- **selection**; choosing from several alternatives without modification
- **compromise**; improving an alternative through modification
- **conditional**; design decisions taking risk and uncertainty into account.

Kuppuraju's work centres on the selection but he cites work in the other two areas.

The methods employed within the design selection approach have been implemented in a spreadsheet [Hurst 1990] incorporating a modified form of the weighted criteria versus concept matrix. It is claimed that the spreadsheet based system accelerates the selection procedure and allows rapid sensitivity analysis of individual choices.

Systematic Evaluation

Pahl and Beitz equate the conceptual form as having low embodiment and hence low state of information. They claim that the most useful methods are 'Use - Value Analysis' (UVA) , also known more generally as 'Cost-Benefit Analysis,' based on the systems approach and the combined technical - economic evaluation technique in Guideline VDI 2225 which is linked to original work by Kesselring.

Evaluation Methods are seen as being aids, not automatic decision mechanisms [Beitz and Pahl 1981]

The evaluation process is sub-divided into several steps as follows:

- **Identify evaluation criteria:** Usually derived from the set of objectives enshrined in the requirements of the specification and applicable check-lists. UVA systematises this process through the application of an objectives tree in which the individual objectives are arranged hierarchically. It is stressed that the objectives should be as independent of one another as possible.

- **Weighting of evaluation criteria:** A measure of the relative importance of each criteria to the overall value of the design. Again the objective tree approach is utilised with the weighting factors being subjectively applied though preferably on a group basis.

- **Assignment of known parameters to criteria:** The parameters should ideally be quantifiable, though not exclusively, and represent the focus during evaluation of the criteria. e.g. a criteria ...'simple production' may have a parameter of........' number of components'. etc.

- **Assessment of values:** Initially a Value Function, which plots value (Scale-0 to 1) against an acceptable range of parameter magnitude, must be available. The shape of the function is determined by known mathematical relationships or estimated from experience. Assuming that the parameter can be assessed from the current status of the design, then a value point may be selected.

- **Determination of overall value:** The overall value of the design option is deemed to be the summation of the individual parameter values.

$$oV_j = \sum_{i=1}^{n} W_i \, . \, V_{ij} \qquad (3.8)$$

oV_j = overall value of design option j

W_i = weighting factor for criteria i

V_{ij} = value of parameter i associated with design option j

n = total number of criteria

- **Comparison of concept options (variants):** The design option with the maximum overall value is deemed the 'best' design. If this comparative rating is considered insufficient then a comparison with an imaginary ideal is suggested.

i.e.

$$R_j = \frac{oV_j}{\sum_{i=1}^{n} W_i . V_{ij} \quad (max)}$$

(3.9)

- **Estimation of evaluation uncertainties and weak spots:** The inherent shortcomings of the above procedure are the result of the 'prognostic uncertainty' arising from the fact that the parameter magnitudes and the values are not precise but subject to uncertainty and random variation. Estimates of the mean error is suggested as a means of reducing the mistakes.

Technical System Evaluation

An evaluation can be performed in two basic ways [Hubka and Eder 1988]:

- subjective
- objective

and in order to evaluate systems they suggest that one needs to:

- Select Criteria - Properties
- Measure the Properties

- Compare Measures with targets
- Combine measures into a Characteristic Value (Synthesising Characteristic)
- Compare Characteristic Values between competing systems
  (Select the larger value)

It is recognised that the Selection of Criteria is influenced by the aims of the evaluation and the phase of life of the design to be evaluated.

Combining the criteria, with differing associated units, into a Synthesising Characteristic presents a difficulty that may be overcome as follows:

- Express all criteria in terms of money.
- Use a form of Point-Rating
- Search for a combination of criteria that provides a trend or insight.
- Compare options one against the other, on a better, worse, equal basis.

Combining the characteristic values to obtain a value for the total system can be achieved via a number of mathematical techniques and algorithms.

e.g.

- Arithmetic mean
- Geometric mean
- Vector sum

Hubka and Eder also make a distinction between Technical and Economic Evaluations and try to treat each criteria as being independent of the others. 'Relative strength' graphs of Technical & Economic Evaluations are made to clarify assessment. Thus Technical Rating (Rt) is plotted against Economic Rating (Re). Since each rating number lies between 0 and 1 then the ideal situation has co-ordinates (1,1). The position of the concept relative to the ideal can be seen and its development recorded. This is also reflected in the work of Pahl and Beitz and VDI 2225 described above.

Interestingly, Hubka refers to the following measures:

- Technical value

- Economic value
- Aesthetic value
- Usage value
- Esteem value

The Total Value is regarded as the vector resultant of all the individual values.

The individual value can be contrasted relative to one another by means of two dimensional 'relative strength diagrams.'

Qualitative Evaluation

Some researchers have attempted to propose methods for the evaluation of design concepts, which incorporate qualitative attributes [Roozenburg 1982, Thurston 1991], drawing principally on established decision theory. Most recently, [Maher 1989], considers evaluation using multi-criteria during the synthesis and evaluation of preliminary designs and its implementation within an expert system.

Others [Hyde and Stauffer 1990] have looked at the reliability of measures used to evaluate qualitative attributes such as quality.

Methodology for the Evaluation of Design Alternatives (MEDA)

Thurston [1991] presents a formal methodology, entitled 'Methodology for the Evaluation of Design Alternatives (MEDA), employing deterministic multi-attribute utility analysis to compare the overall utility of an alternative design as a function of selected performance characteristics. The evaluation function is supposed to reflect the designers subjective preferences. Sensitivity analysis is incorporated to provide information as to how the design may be modified to increase its utility in the eyes of the designer.

Initially the range of the design attribute (or characteristic) is determined followed by the creation of the associated Utility function (Single Attribute Utility Function) and a Scaling

Constant. A Multi-attribute Utility Function is derived from the single attribute utility functions as follows:

Without Proof :-

$$U(x) = [[\Pi(Kk_i . U_i .(x_i) + 1)] - 1] / K$$

(3.10)

U(x) = Overall utility of set of attributes X

k_i = single attribute scaling constant

$U_i(x_i)$ = single attribute utility function

i = 1,2,3.....n attributes

K = scaling constant, derived from:

$$1 + K = \prod_{i=1}^{n}(1 + Kk_i)$$

(3.11)

Two-Stage Method (EDESYN)

Maher [1989] considers that preliminary design evaluation of feasible options is based on multiple criteria and incomplete or partial information. A two stage evaluation process is presented:

- Reduce the number of alternatives by removing the dominated alternatives.
- Subjective information about preferences is used to rank the remaining alternatives.

The concept of Pareto Optimality is introduced and defined as, '*A feasible solution to a multi-criteria problem is Pareto Optimal if no other feasible solution exists that will yield an improvement in one criterion without causing degradation in at least one other criterion*' and is used by Maher to find a set of non-dominated solutions given a set of feasible alternatives. The Pareto set is determined by pairwise comparison of the alternatives for each criterion.

The ranking of the non-dominated set of feasible alternatives is achieved by assigning weights to each criterion as a measure of preference.

i.e.

$$T_i = \sum_{j=1}^{k} W_j \cdot nV_{ij} \qquad (3.12)$$

where,

$$nV_{ij} = \frac{V_{ij}}{nf_j \cdot nd_j} \qquad (3.13)$$

T_i = total value of alternative *i*

W_j = weighting factor for criterion *j*

nV_{ij} = normalised value for alternative *i* under criterion *j*

V_{ij} = value of alternative *i* under criterion *j*

nf_j = normalised factor for criterion *j*

nd_j = non-dimensionalising factor for criterion *j*

The methods described are implemented by Maher within an expert system (EDESYN) that is intended to facilitate the development and use of a knowledge base for design.

Measurement of Design Quality

Hyde and Stauffer [1990], describe the testing and comparison of three subjective scales, developed for judging the quality of a solution to a design problem, in order to ascertain their reliability over time. The scales are drawn from the area of Psychometrics, which seeks to aid a person's cognitive effort so that judgements can be reliable, valid and sensitive.

The three scales tested were as follows:

- Global (Likart) Scale
- Global -Guided (Cooper-Harper)Scale
- Multidimensional Global (Task Load Index (TLX))Scale

Their test concluded that only the Global-Guided scale was unsuitable for measuring design quality. The other two scales were shown to be suitable but required further testing to determine fully their sensitivity and validity.

Design Compatibility Analysis (DCA)

Recent research has attempted to provide a means of unifying design life cycle issues [Ishii et al 1988, 1989]. DCA is claimed to focus on the compatibility between the design specification and the proposed design and allows evaluation of the design based on the compatibility knowledge of experts. It draws from the field of Artificial Intelligence through knowledge based tools which are seen to promote the aims of simultaneous engineering. DCA uses the theory of fuzzy measure to quantify the compatibility evaluation , termed the Match Index (MI), of the design with the requirements within the design specification. In essence DCA provides a model of evaluation within a simultaneous engineering framework. The DCA model aims to simulate the design review process in which a group of experts evaluate a proposed design and suggest improvements. To evaluate the compatibility of a proposed design with respect to a set of requirements it is seen as necessary to have a sound definition of an evaluation measure and a methodology which allows identification of reasons for an evaluation as well as improvements to design.

The Match Index MI_i for a design value V_i is:

$$MI_i = \sum_{Ki} U(s) \cdot M(s) \tag{3.14}$$

Where, K_i = the set of design elements for the design value Vi.

U(s) = the weight of evaluation elements

M(s) = match coefficient for design elements

Initial Design Selection (IDS)

Esterline and Kota [1992] use the concept of discretisation of design space to make initial selection of prior designs using specification matching to direct redesign with evaluation and iteration. The approach may be summarised as follows:

- Discretisation of Design Space
- Design Characteristics provide dimensions to space
- Models (or known designs) occupy the design space

Note: *Characteristics have a domain to which its values are restricted.*

e.g. 1. Interval of Values (Interval equipped domains)

2. Single value (Point Domains)

These domains are defined via User Analysis etc.

Now, let nc = No of characteristics

nc - dimensional design space

Each point in the design space is represented by an nc -tuple.

To allow progress, the dimensionality of the space is reduced via:

1. Classify certain characteristics as 'Critical' - ncc

(i.e. they must be met or the model rejected)

2. The design space is further reduced by partitioning the nc-ncc into sub-sets, referred to as 'Factors.' e.g. Cost, Manufacture, Performance, Aesthetics etc.

Thus, if there are nf factors where nf < nc-ncc then a model is located in not only the simpler (nc-ncc) dimensional space but also a coarser nf-dimensional space.

It is claimed that this approach matches the heuristic methods used by humans.

The IDS system treats specifications as constraints on the design. For each specification, the IDS searches the knowledge base for known models and returns a list of pairs (m*i*, gm*i*)

where, m*i* = a model

gm*i* = goodness of match, 0< gm*i* < 1

Generally there is some threshold, th, such that if gmi < th then the associated pair would not be output on the list.

Therefore a ranking is achieved between models based on the output goodness of match.

A simple specification is characterised as a set of ordered pairs (CD*i*, w*i*), where w*i*, 0< w*i* < 10 is a real number called a 'weight' and CD*i* = Characteristic Description which is itself an ordered pair or tuple. If the domain of the characteristic is a point domain, then CD*i* is an ordered pair (Ch*i*, Val*i*), where Ch*i* is the characteristic in question and Val*i* is the value of this characteristic.

If the domain is an Interval equipped domain then CD*i* is an ordered tuple (CH*i*, Val*i*, Int*i*) where Int*i* is the acceptable interval of the value and Val*i* is the preferred value.

Weight, w*i*, indicates the importance of the Ch*i* for the problem at hand.

To summarise:

- Simple spec. => (CD*i*, w*i*)
- Point Domain => ((Ch*i*, Val*i*) w*i*)
- Interval Equipped Domain => ((Ch*i*, Val*i*, Int*i*) w*i*)

Now, some characteristic values are 'Maximising', i.e. any value greater or equal to that specified is acceptable, the higher the better.

Also, some may be 'Minimising', i.e. any value less or equal to that specified is acceptable, the lower the better.

Finally, some are 'Equating', i.e. acceptable values are bounded above and below the value specified.

For a Point Domain Characteristic, Ch, the matching function is straight forward.

e.g. let Vs = value specified for Ch

Vm = value supplied by the model

=> match (Vs, Vm)

if Vs (R) Vm then 1 else 0

where (R) is

< if Ch is Maximising

> if Ch is Minimising

= if Ch is Equating

For an Interval equipped Domain the situation is more complex,

Now, define a function, 'Match with range' which detects simple cases where goodness of match should = 1 or 0

Also, function 'Range-Match' covers < 1>0

Let Ls = lower value of the Vs

Hs = higher value of the Vs

therefore [Ls, Hs] is the acceptable interval for Ch as per the spec.

equally, [Lm, Hm] is the achievable interval for Ch as per the model

=> Match-with-Range (Vs, Vm [Ls, Hs], [Lm, Hm])

if Vs (R) Vm

then 1

then 0

else Range-Factor x Range-match (Vs, Vm, [Ls, Hs], [Lm, Hm])

Where Range-factor is a constant C if Ch is equating and Vs is not in the interval [Lm, Hm]; otherwise, Range-factor = 1

Now, R, -> ([Ls, Hs], [Lm, Hm]) is Hm < Ls, Ch is Maximising

R, -> ([Ls, Hs], [Lm, Hm] is Lm > Hs, Ch is Minimising

R, -> ([Ls, Hs], [Lm, Hm]) is Hm < Ls or Lm > Hs, Ch is Equating

To compute goodness of match given come specification - model pair

Therefore, define factor; gom

The argument list Ch1*j* - pair, Ch2*j*-pair..........

Where Chij - pair, 1< i < n*j*, is the pair

(Utility -functionij (Ch*ij* -gom), Ch*ij*- weight)

Where Ch*ij* is the *i*th Characteristic antecedent of factor *j*

Ch*ij* - gom is the goodness of match value for Ch*ij* for the pair S-M in question (computed by match or match-with-range) and Ch*ij*-weight is the weighting assigned by the specification.

The definition of factor *j* - gom

$$\Rightarrow \frac{\Sigma[\text{Ch}_{ij} - \text{weight}\ ].\ \text{Utility} - \text{function}\ (\text{Ch}_{ij} - \text{gom})}{\Sigma\text{Ch}_{ij} - \text{weight}} \tag{3.15}$$

Now, let factor*j*-weight = Σ Ch*ij*-weight

The definition of solution is:

$$\frac{\Sigma \text{ factor}_j\text{ -weight } \times \text{ Utility - function}_j \text{ (factor - gom)}}{\Sigma \text{ factor}_j \text{ - weight}}$$

(3.16)

Discussion

In chapter 2, of this thesis, the various requirements of an effective conceptual design evaluation methodology were identified through a literature review and classification process. These requirements are reproduced here in list format.

1. Need for computer based evaluation within a concurrent engineering environment.
2. Need to clarify the state of the design at each point of evaluation within every phase of the design process.
3. Need to have identifiable common links between the evaluation methods employed within each phase of the design process.
4. Need for forecasting of embodiment projections within a defined design and development resource environment.
5. Need to link analysis, synthesis, evaluation, forecasting and decision making within a team context.
6. Need to communicate the design state in appropriate form within these interdisciplinary teams.
7. Need to include a reliable measure of the effectiveness of the evaluation method being employed and thus enable traceability of decision making.

Each of the above criteria are now reviewed in turn, and in light of increased knowledge of currently available evaluation methods outlined in first section of this chapter, with a view to placing each in context and setting out a framework within which an evaluation methodology can be developed and assessed.

1. It is clear, from the above review, that the prime motivation behind the interest in trying to better understand design evaluation is the development of computer aided design tools which are well developed in terms of representing the design and its analysis, in certain areas, but lack decision making ability regarding the appropriateness of the design [Arai and Iwata 1992]. It still left to the design team to view the design, determine its deficiencies with respect to the product design specification and either review the specification in light of this new information about the design or modify the design in an attempt to more nearly meet the specification. The evaluation process needs to be better understood and modelled if it is to be successfully implemented within a computer environment.

2. If one relates the above to the conceptual design process; then the results of prior decisions may be alternative conceptual proposals, these proposals are then required to be assessed to determine the extent to which they are likely to satisfy the design objectives given that they successfully progress through the rest of the design process and are placed in the market place, purchased and used, this demands the ability to forecast the future, this may be classed as Total Design Evaluation. Equally we may only wish to evaluate the concept in terms of its potential to be successful within the next phase of the design process, therefore this suggests that the evaluation is time dependant, this may be classed as Partial Design Evaluation. However, it would appear clear that it is important that the any Partial Design Evaluation is undertaken in light of the Total Design requirements. The idea of partial design evaluation is clearly used to assess potential reliability, cost, manufacturability [Thurston 1990, Shah et al 1990, Jansson et al 1990] etc. at the completion of each of the main phases of the design process. (i.e. Conceptual, Embodiment and Detail) [Aguirre and Wallace 1990]

'In order to compare technical systems with its requirements or with other competing systems, the properties of the technical system must be determined. The methods of determining the properties will change according to the life phase in which the determination is to be made.' [Hubka and Eder 1988]

e.g. is the system to be evaluated in a conceptual form or a realised form.?

The following available techniques have been identified by Hubka and Eder:

Measuring, Estimating, Modelling, Calculation, Comparing, Determining optimal measures (values)

In current evaluation methods [Pugh 1990,91], and in the recent work to automate the method [Hurst 1990], it is not clear what it is that is being evaluated! The criteria are stated all right but they are not related to the product life cycle and the criteria selection method is not stated. For example, when evaluating cost is one evaluating what the concept would cost as it stands, i.e. without tolerances, material spec. etc. or is one costing what the cost is likely to be if the concept were fully detailed etc.? If this is the case, then appropriately presented information regarding the cost of past similar products is required. Of course, in the case of technologically innovative concepts this would not be possible! Further, if one is evaluating the reliability or manufacturability then both criteria have to be related to an image of a developed form of the proposed concept at some point in the future. In the case of reliability it may be some months during prototype test or some years hence when being used. In the case of manufacturability, it may be months hence as well as for many years to come. Explicit statements of time and design state are therefore missing from current methods.

Further, one may argue, with some justification, that what one is evaluating is the potential, intrinsic within the concept, for it to be developed to a point where its manufacturability can be expected to be some measurable figure then we again require a method of forecasting to supplement intuition particularly for technologically innovative products.

3. Taking the example of reliability prediction, where the aim is to provide an early indication of a systems potential to meet the design reliability requirements, we can see that this prediction is based on the known or assumed failure rates of components or sub-assemblies used in the proposed design. This presupposes that the conceptual idea can be defined in terms of known sub-assemblies or components, therefore the concept is defined to a specific degree. Therefore evaluation can only take place when the concept is defined to this degree. If this is the case then each assumed component or sub-assembly can have an assumed cost, manufacturability and maintainability etc. given that this information is available. This supports the idea that a new configuration of sub-assemblies is one form of innovation [Navinchandra 1991]. However the incorporation of new technology in conjunction with new configuration represents an even higher degree of innovation.

There needs to be a consistent approach applied at all phases of the design process. This is not to say that the same methodology should be used but rather that the methodologies applied in each phase should employ a consistent underlying philosophy that develops in a clear and traceable way throughout the design process. The methodology needs to develop with the design.

e.g.

Manufacturability: the ease with which the component, sub-assembly or product and be produced (manufactured) given specified resources. The manufacturability will vary with time since experience will act to make it easier to produce. Detail design changes will also presumably help manufacturability as indeed will developments in manufacturing technology. So any subjective conceptual evaluation of ease of manufacture must be made in light of a forecast of future resources, experience - learning curves, design changes etc.

4. If one accepts the premise that in order for evaluation to take place within the conceptual phase then a degree of forecasting of the likely embodiment providing the

desired design characteristic has to take place. This forecasting must be based on prior knowledge of those undertaking the evaluation. Therefore the characteristic under evaluation is physically realised to a small extent within the concept phase. A future projection of the physical embodiment of the characteristic has to be made and compared with known acceptable embodiments. The main difficulty with this is when the evaluators are faced with a concept incorporating new technology. There is likely to be no known embodiments of characteristics with which to compare the new design. The forecasting and projection methods then become even more important if a realistic evaluation is to be undertaken. The mechanisms involved in allowing this to take place probably require to be the subject of parallel research as indeed does the identification of the criteria for evaluation.

However, to test the developing methodology within a computer environment demands that an initial model of how the projection facility might be provided is required. One approach that may be fruitful is to develop a system of design classification that relates design architecture, functionality, interfaces, cultural environment, design resources, investment policy and working environment. If a knowledge base of known designs can be created along these lines then developing designs can be more readily compared and potentially achievable design characteristic values output.

5. One is therefore evaluating the results of prior decision making in order to enable further decision making. Implicit in this evaluation process is the ability to predict future consequences as a result of a prior decision. This implies the need for decision-making and forecasting methods to be incorporated within any effective methodology. Equally the evaluation process requires a knowledge of the past, which needs to be available in a usable format, in order that previous errors are not repeated.

By having this combination of knowledge and methods one will be in the best position to both evaluate our existing ideas as well as allow us to propose further perhaps more innovative ideas in light of the initial evaluation and the forecast results. To this extent it would build upon the ideas of the Controlled Convergence Method.

6. Design teams may consist of many experts who will inevitably view the design concept from their own point of view and interest e.g. manufacturability, cost, serviceability, reliability, analysability, marketability etc. The way the concept is communicated to the team becomes increasingly important. Is there a universal method of communicating an idea such that each expert can predict / forecast future states of the idea given the base start or should we enable the rapid translation of product definition between the preferred evaluation languages of the evaluators? This raises the possibility of another research area, where computer based translation between design definition 'languages' is made possible. For example, would it be possible for a manufacturing expert to have the product design specification translated into terms that he can readily relate to. Equally it is possible to translate a physically realised concept sketch into a design definition language that a reliability expert can relate to. Or is there a universal language?

Designers use many techniques to assist or aid their subjective evaluation and in the case of 3D modelling this may be one of the most effective in terms of ergonomic and aesthetic properties.

7. It is important that designers are able to learn from the results of their design activity. Traditionally this learning process has been ad hoc with no formal traceability of design decision making and certainly no means of measuring the quality of the decisions. This is usually left to the end of the design process when the consequences of change are most expensive. This realisation has led researchers, notably Scott, to suggest that a design audit needs to be established and applied throughout the design process and throughout the life cycle of the output of the design process. Not only should there be a measure of the quality of the decision making between design phases but also within and

between the design activities driving the design through each phase. Most notable is the need to trace decisions which invoke analysis and synthesis activities as a result of evaluation.

Assessment of Evaluation Methods

The approach or method adopted to permit analysis of existing evaluation methods was as follows:

Firstly,

- To perform a cross comparison between the methods and the needs in order to identify those needs that were not being addressed by current methods. (Table 3.2)

- To identify and record the mathematical foundation upon which each method was based.(Table 3.3)

- To identify and record the method of reasoning used within each of the evaluation methods or techniques (Table 3.4).

Consequently,

- To identify the current methods that could be most easily modified to meet the identified needs.

- To indicate possible merging of methods to meet the identified needs.

This first point to be highlighted, in Table 3.2, is that none of the identified methods appear to meet all of the requirements desired of an evaluation methodology as identified within the current models of the engineering design process. This observation is not unexpected since little linking is evident, within the design research literature, between design process models and design activity methods and techniques. This reflects a tendency for researches to ignore the hierarchical nature of the design process. Fortunately, this attitude is showing some encouraging signs of changing [Yerramareddy and Lu 1993].An initial attempt to suggest the linking between method, activity and phase is summarised in Table 3.5.

However, Table 3.2 does show that selective interaction of methods does span the range of identified requirements. In particular the customer focused approach of QFD is largely unique in its capability of having a structure able to identifying those criteria dominating the acceptability of the design. Since the needs of the manufacturer and supplier are also considered in parallel with the ultimate needs of the user, there emerges an opportunity for clearly identifying the state of the design at any evaluation point in its life-cycle.

In turn, DFR techniques provide mechanisms that permit projection ability and traceability of decisions. By employing the ideas of Safety Margin there appears the possibility of being able to assess in a very clear way the degree to which an idea, or some characteristic of an idea, matches with the design specification. Interestingly, this may also permit a more effective and justifiable assessment and measure of the relative importance of individual criteria, as opposed to the rather crude method of subjective application of weighting factors as advocated by the Systematic and Technical Systems evaluation methods. It may be achieved by placing limits on the acceptable degree of overlap of target value, established within the specification via the application of QFD, and the estimated values for a particular characteristic as judged by observers. This judgement will clearly vary with time as the design moves from a information poor state to an information rich state. As this occurs, the notion of simple rectangular distributions overlapping can give way to the ideas of value curves as proposed by Siddall in his Probabilistic Design Option approach and to the application of Loss Factors, as advocated by Taguchi, whereby an increasingly refined evaluation of the acceptability of a design starts to emerge. This notion is further supported and extended by utilising the strengths of the IDS method where the idea of establishing upper and lower limits of both targets and estimates can enable quantifiable assessment of the criticality of meeting certain characteristic target values.

Conclusion

The initial review and classification of evaluations methods, from a number of related domains, has revealed that no one method can by itself meet the requirements expected by the current models of the design process. It was highlighted that a number of methods may offer the potential to be combined to provide a well founded basis for evaluation which, it was suggested, could grow and develop with the design. These methods were as follows:

- Quality Function Deployment
- Design For Reliability
- Probabilistic Design Option
- Taguchi Methods
- Initial Design Selection
- Design Compatibility Analysis

The next Chapter describes the attempt to combine the above methods in a unified evaluation methodology

Classification of Design Evaluation Methods

Design Evaluation Methods	Computer Based	Clarity of Design State	Common Links	Projection Ability	Team Communication	Design Traceability	Select Criteria	Initiate Analysis	Comparison Phase	Prediction Phase	Decision Phase	Initiate Synthesis
	Conceptual Design Evaluation Activity Needs						Conceptual Design Evaluation Activities					
DFR	Δ	Δ		Δ	Δ	Δ	Δ		Δ	Δ	Δ	
DCA			Δ					Δ	Δ		Δ	Δ
GMI's								Δ	Δ			
QFD					Δ	Δ	Δ					
Systematic		Δ				Δ	Δ	Δ	Δ		Δ	
Technical Systems		Δ				Δ	Δ	Δ	Δ		Δ	
Cont. Convergence					Δ		Δ		Δ		Δ	
Design Methodics							Δ		Δ			
MEDA			Δ			Δ	Δ		Δ		Δ	
Prob. Design. Option			Δ			Δ			Δ		Δ	
Taguchi								Δ	Δ		Δ	
Roozenburg					Δ				Δ		Δ	
IDS			Δ			Δ	Δ		Δ		Δ	
EDESYN	Δ								Δ		Δ	
DMED								Δ	Δ			
DFA	Δ	Δ			Δ	Δ	Δ		Δ		Δ	Δ

Table 3.2, Classification of Evaluation Methods in terms of Needs and Activities

Classification of Design Evaluation Methods

Design Evaluation Methods	Fuzzy Measure	Probability Theory	Analysis of Variance	Utility Value	Pareto Optimality	Use-Value Analysis	Pairwise Comparison	Design Rules	Subjective	Heuristics
	Conceptual Design Evaluation - Mathematical Basis									
DFR		Δ								
DCA	Δ			Δ						
GMI's	Δ									
QFD							Δ	Δ		
Systematic				Δ		Δ				
Technical Systems				Δ		Δ				
Cont. Convergence							Δ		Δ	
Design Methodics							Δ		Δ	
MEDA				Δ						
Prob. Design. Option		Δ		Δ						
Taguchi			Δ							
Roozenburg				Δ					Δ	
IDS				Δ					Δ	
EDESYN					Δ					Δ
DMED	Δ									
DFA							Δ	Δ	Δ	

Table 3.3, Evaluation Methods and their Mathematical Basis

Classification of Design Evaluation Methods

Design Evaluation Methods	Fuzzy Measure	Probability Theory	Analysis of Variance	Utility Value	Pareto Optimality	Use-Value Analysis	Pairwise Comparison	Design Rules	Subjective	Heuristics
	Conceptual Design Evaluation - Mathematical Basis									
DFR		Δ								
DCA	Δ			Δ						
GMI's	Δ									
QFD							Δ	Δ		
Systematic				Δ		Δ				
Technical Systems				Δ		Δ				
Cont. Convergence							Δ		Δ	
Design Methodics							Δ		Δ	
MEDA				Δ						
Prob. Design. Option		Δ		Δ						
Taguchi			Δ							
Roozenburg				Δ					Δ	
IDS				Δ					Δ	
EDESYN					Δ					Δ
DMED	Δ									
DFA							Δ	Δ	Δ	

Table 3.3, Evaluation Methods and their Mathematical Basis

Classification of Design Evaluation Methods

Design Evaluation Methods	Axiom Based	Case Based	Model Based	Characteristic Based	Heuristic	Analogical	Domain Based	Intuitive	Holistic	Associative	Process Based	Resource Based	Technology Based
DFR			Δ			Δ	Δ						Δ
DCA		Δ		Δ									
GMI's				Δ			Δ				Δ		Δ
QFD		Δ				Δ							
Systematic			Δ	Δ									
Technical Systems			Δ	Δ									
Cont. Convergence				Δ		Δ		Δ					
Design Methodics				Δ									
MEDA			Δ	Δ									
Prob. Design. Option		Δ		Δ									
Taguchi			Δ										
Roozenburg				Δ				Δ					
IDS			Δ	Δ		Δ							
EDESYN				Δ			Δ						
DMED			Δ	Δ									
DFA						Δ	Δ				Δ	Δ	Δ

Table 3.4, Evaluation Methods and Reasoning Basis

Design Evaluation Methods	Recognise Need	Functional Requirements	Conceptual Design Phase						Configurational Design	Parametric Design	Product Realisation
	Phases of the Engineering Product Design Process										
			Select Criteria	Initiate Analysis	Comparison Activity	Prediction Activtity	Decision Activity	Initiate Synthesis			
			Activities of the Conceptual Design Phase								
DFR			Δ		Δ	Δ	Δ		Δ		
DCA				Δ	Δ		Δ	Δ	Δ		
GMI's				Δ	Δ				Δ		Δ
QFD	Δ		Δ						Δ		Δ
Systematic		Δ	Δ	Δ	Δ		Δ		Δ		
Technical Systems		Δ	Δ	Δ	Δ		Δ		Δ		
Cont. Convergence			Δ		Δ		Δ				
Design Methodics			Δ		Δ		Δ				
MEDA					Δ		Δ		Δ		
Prob. Design. Option				Δ	Δ		Δ		Δ	Δ	
Taguchi					Δ		Δ			Δ	
Roozenburg			Δ		Δ		Δ		Δ		
IDS					Δ		Δ				
EDESYN					Δ		Δ		Δ		
DMED							Δ				
DFA					Δ			Δ	Δ		Δ

Table 3.5, Summary Classification of Evaluation Methods

Chapter 4 *Conceptual Design Evaluation Methodology (C.D.E.M)*

Synthesis and Development

Introduction

Failure during the design process is determined by the lack of conformance, of the proposed design, to the design specification applying at each phase of the process. Taguchi has shown that, through his considerations of Robust design, satisfaction of specification alone is not sufficient and that the idea of Loss function should be adopted. This in essence provides a way to consider and quantify the variance of a value from a set target value. In many ways it is similar to the notion of providing a utility curve which seeks to describe the degree of desirability of the value of a variable as it deviates from its ideal or target value.

Also the relative importance of a particular design characteristic does not, as is often assumed, remain constant throughout the design process but rather it varies as information is gained regarding the design opportunity being addressed.

As information regarding a design is scarce during the conceptual stages of design, especially with respect to innovative concepts, there is a tendency for designers to favour the low risk option and perhaps to reject innovative ideas too quickly. Any formalised evaluation method must therefore provide mechanisms to ensure that innovative suggestions are given time to develop prior to final decisions being made.

The on-going moves towards concurrent engineering bring new exacting demands upon the evaluation activity. The drive towards reduced design timescales puts further pressure on the design decision makers which seems to have had two distinct results in terms of the design strategies adopted to cope with this pressure. One approach, as stated earlier, is to adopt a low risk policy and the other is to adopt a team driven medium risk policy with rapid incremental development of designs. The second approach appears to have been commercially more successful although it requires good communication of ideas as well as effective, visible and consistent team based decision making techniques.

It is also imperative that there is a mechanism available to enable traceability of the decision making process in order to permit a learning process to take place and to establish a knowledge base to support future design activity. There is also a clear need for a formal classification of past designs, and present concepts, to enable future projection of opportunities. This is particularly the case if emerging technologies are to be effectively acquired and implemented within a design environment.

Methodology Development

The above describes the consideration driving the synthesis of the Conceptual Design Evaluation Method (CDEM). The following describes the methodology that has been developed in accordance with these constraints whilst using existing methods as an appropriate knowledge base to enable synthesis of a more appropriate methodology.

The CDEM approach takes as fundamental the idea of a sub-division of design space. That is, for a given design domain, the associated design characteristics allow all associated specifications and models to be described in terms of the values of the characteristics. These characteristics can then be visualised as being the dimensions of the design space, which is sub-divided into a finite number of cells each containing a potential model of a design solution. Clearly the dimensionality of the design space can be extremely variable depending upon the complexity of the design task. In most engineering design domains the number of design characteristics is large which needs to be reduced to allow manageable searching through the design space for suitable models. One approach, as used by Esterline and Kota in their IDS system, is first to identify certain critical characteristics that must be satisfied if the model is to be acceptable. The critical characteristics can then be eliminated from further consideration. Another idea is to group the characteristics in to design factors. That is, a group of design characteristics which interact to determine the value of a design factor e.g. ease of manufacture, cost, reliability etc.

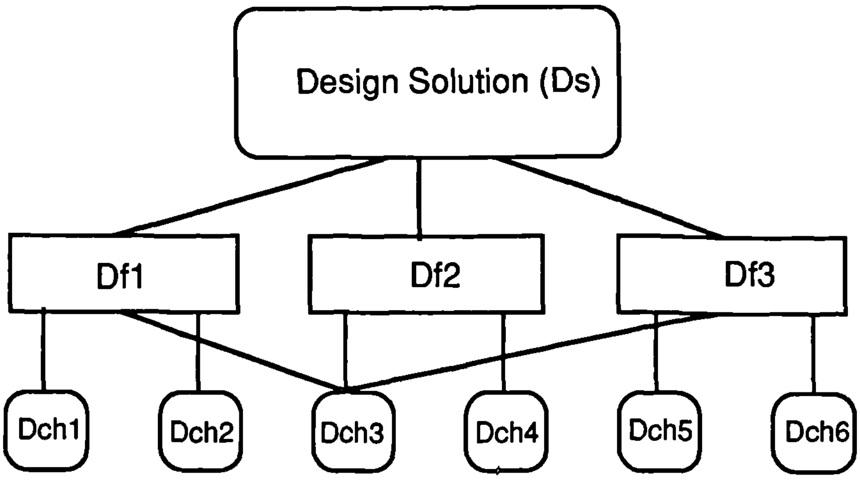


Fig. No. 4.1

Given the above, the design specification can be viewed as a written model of the desired design solution against which all developed models can be compared. The design specification thus contains the information regarding the desired values of design characteristics and design factors. It is left as part of the synthesis activity for the relationship between the characteristics and the factors to be defined and developed. It is useful to view the design factors as being user oriented measurements of the design solution and for the design characteristics to be viewed as designer oriented measurements of partial design solutions.

Let the design specification be a variable - Ds

Now, the Ds is comprised of a number of design characteristics and design factors,

let each characteristic be a member of the set Dch1, Dch2, Dch3,.........Dch*n*.

Let each factor be a member of the set Df1, Df2.................................Dfn

Ds [(Dch1, Dch2, Dch3...........Dch*n*), (Df1, Df2.............Df*n*)] (4.1)

As previously asserted, each design factor is determined by one or more design characteristic.

Df1 (Dch1, Dch2)...................Df*n* (Dch*n*-1, Dch*n*)

(4.2)

Further, each characteristic may be determined by or be dependant upon other characteristics. In the Taguchi methodology this would parallel the notion of design parameters and noise factors which contribute to the overall value of the performance characteristic.

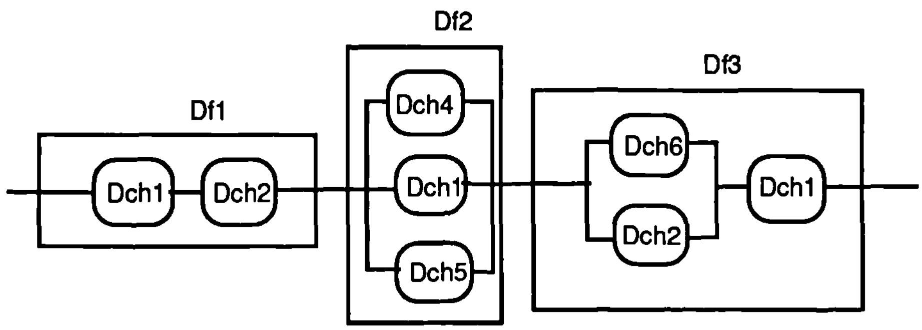


Fig. No. 4.2

As previously shown, an individual design characteristic may impinge upon one or more of the design factors. Further, a Design Characteristic may be considered to be a critical Design Characteristic (Dcch). A Dcch may defined as any Design Characteristic which must be fully satisfied if a design option is to progress further in the design process. Therefore, a Design Factor may be dependent upon two Dcch's allowing it to be modelled as shown in Df1 of Fig 4.2. That is, it is modelled as a series system implying that both characteristics must be satisfied or the design may be considered to be unacceptable. Equally, a Df may comprise a number of Dch's that are not considered critical. In this case the relationship between the characteristics may be modelled in parallel as shown in Df2 of Fig 4.2. In the reliability domain this would be considered as a 'minimal cut-set' but in this context is defined as: '*An identified group of characteristics that contribute to a* *design factor and allow the design option to progress in the design process as long as one of the characteristics is within specification or if the combined conformance to specification is above a defined threshold level.'*

This approach permits temporary out of specification situations to be both identified and tolerated within time limits. Further, the relative importance of each characteristic, traditionally defined by an individual weighting, can be seen to be inappropriate when the interaction of characteristics takes place. A more acceptable and logical approach is to define the importance or criticality of each characteristic in terms of the degree of match with the design specification target levels.

Clearly a combination of the two situations may also exist, as show in Df3 of Fig 4.2.

There is also a marked degree of uncertainty regarding the value of each characteristic at each stage in the process or rather there is uncertainty over the value that the characteristic would have given that the design is developed along certain assumed lines with assumed resources available.

Now, each design characteristic has a variable design characteristic target (DchT) value associated with it. For an acceptable design, the DchT can have minimum and maximum limits set for an allowable or desirable range of values. The Taguchi , and that suggested by the IDS system, approach would be to also provide a target or mean value from which the deviation of the estimated value could be assessed. This is perhaps more appropriate during the other phases of the design process when the design is more defined and moves towards more refinement and perhaps optimisation can confidently start to take place. During the conceptual phase it is difficult to conceive of an ideal target level for a particular characteristic but rather this should be identified as knowledge and information increase. However, there is also likely to be critical characteristics that are totally deterministic even at the earliest stages of design. This is more likely with routine design activities but should not be assumed to exclude innovative design situations. Equally, to reflect the varying utility of the value a curve may be drawn spanning the set limit values

(Fig. 4.3). As previously stated this may also take the form of a loss function depending upon the nature of the characteristic being addressed.

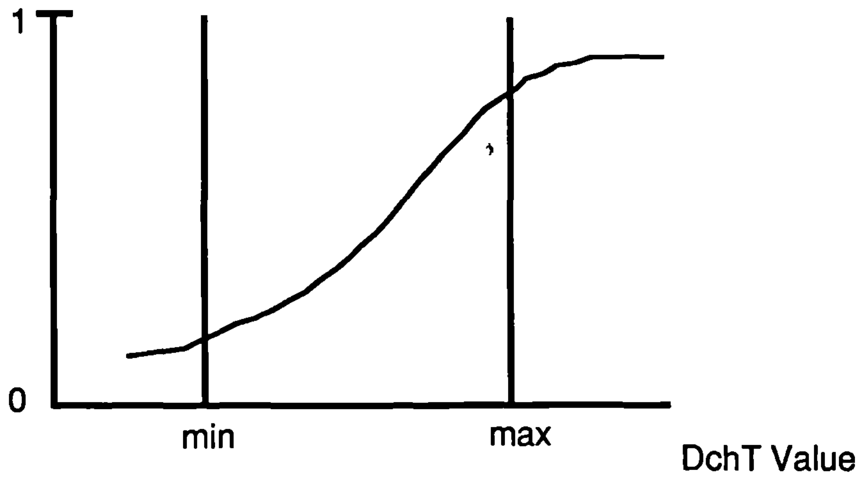


Fig. No. 4.3

Within the conceptual design evaluation activity it is necessary to judge the likelihood that a given conceptual design option will exhibit a particular design characteristic estimated (DchE) value that will fall within the DchT limits. Given the uncertainty of forecasting the ultimate value of a particular Dch, at the conceptual phase it can be best described in the form of a probability density function (pdf). We therefore have a number of ways of describing the DchT values and a pdf of DchE values. It is useful to simplify and illustrate this situation by assuming rectangular distributions for both DchE and DchT (Fig. No. 4.4).

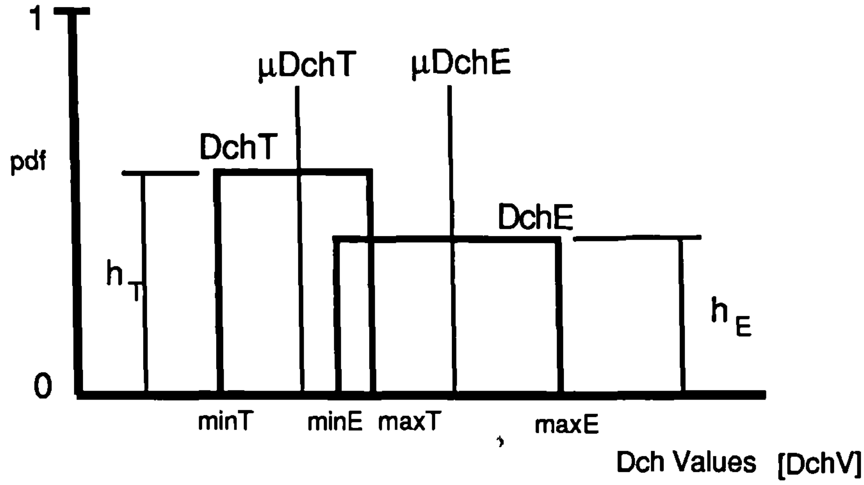


Fig. No. 4.4

The use of rectangular distributions is appropriate since they represent the spread of acceptable and estimated achievable values as well as indicate the level of uncertainty associated with the range of values identified.

With the use of the rectangular distribution, the limiting values of minT, minE, maxT and maxE will be given by:

$$\min E = \mu DchE - \sqrt{3}\sigma_E \qquad (4.3)$$

$$\min T = \mu DchT - \sqrt{3}\sigma_T \qquad (4.4)$$

$$\max T = \mu DchT + \sqrt{3}\sigma_T \qquad (4.5)$$

$$\max E = \mu DchE + \sqrt{3}\sigma_E \qquad (4.6)$$

The probability density functions, DchT and DchE, will be given by:

$$DchT = h_T = \frac{1}{2\sqrt{3}\sigma_T} \quad \text{for minT < DchV < maxT} \qquad (4.7)$$

$$DchE = h_E = \frac{1}{2\sqrt{3}\sigma_E} \quad \text{for minE < DchV < maxE} \qquad (4.8)$$

It is possible to develop this theme further by first of all focusing on a Target Value T. The probability that the Target Value will have a value lying between T and (T+dv) is DchT(v)dv. Also, the probability that the Estimated Value will be less than the desired Target Value is:

$$\int_{\min E}^{T} DchE(v)dv \tag{4.9}$$

Equally, the probability that the Estimated Value will be greater than the desired Target value is:

$$\int_{T}^{\max E} DchE(v)dv \tag{4.10}$$

If it is accepted that the process of creating the estimated and target values are independent then the Product Rule applies, thus the probability that the Estimated Value will be less than a Target Value ,T, is:

$$DchT(v)dv . \int_{\min E}^{T} DchE(v)dv \tag{4.11}$$

and the probability that the Estimated value will be greater than the Target Value, T, is:

$$DchT(v)dv . \int_{T}^{\max E} DchE(v)dv \tag{4.12}$$

If the Target Value is now allowed to take any value between minT and maxT, then the overall probability that the Estimated Value, E, will not exceed the Target value, T, is:

$$\int_{\min T}^{\max E} \left(DchT(v) \int_{\min E}^{T} DchE(v)dv \right) dv \tag{4.13}$$

This expression can be simplified [Carter 1986] to more clearly define the probability that the Target Value specified for a Design Characteristic will be met.

In general,

$$\int_{\max(\min T,\, \min E)}^{\min(\max T,\, \max E)} DchE(v)$$

(4.14)

and for the specific situation depicted in Fig. 4.4

$$h_E.[\max T - \min E]$$

(4.15)

which is the probability that matching of estimate and specification will occur.

Upon inspection, it is clear that the above relationship exhibits significant limitations upon its applicability, as follows:

- As separation of the two distribution increases then the result is an increasing negative value.
- When one or both of the distributions tend to a single value then the result also tends to zero giving the impression of no overlap when in reality single a value may be entirely encompassed by the other.

One may conclude that the above relationship is only effective when both the Target and the Estimated values are distributed and some overlap occurs. Although the negative values mentioned do signal a separation of the distributions it mitigates against the combination of values to represent design factors.

Similar difficulties manifest themselves when the matching situation is represented by the product of the probability that the estimated range of values will fall within the specification limits and the probability that the specification range of acceptable values will fall within the estimated range of values. In this case it is of course assumed that the two events are statistically independent.

Therefore, this may be expressed as follows:

$$\left[\int_{\min E}^{\max E} DchT(v)dv . \int_{\min T}^{\max T} DchE(v)\,dv\right]$$

(4.16)

It is prudent not to discard these models at this stage. Rather it is worth testing these models with those characteristics where overlap does occur and where deterministic values are not present

As indicated within the limitations cited above, as information and knowledge regarding the design situation increases so a single target value may begin to be identified and thus the rectangular distribution may change form to another continuous distribution or develop into a single deterministic value. Another approach, as encompassed within the IDS system, is to assume certainty in the selection of desirable and achievable ranges of values but this is applicable only with routine design within the embodiment design phase of the design process (Table 4.1).

The forecast, or predicted, distributed values of DchE can be obtained by using Delphi techniques to elicit expert views on the expected value of a particular Dch. It may be that the reasoning used by the experts providing this estimate is case-based or analogical and is usually assumed to be best undertaken within a team environment [Kolodner 1991]. It is important that this activity is consistent and repeatable and traceable given the same assumptions. One way of trying to achieve this consistency is to classify existing products and the environments within which they were created and functioned. If a controlled classification system is used then the proposed concepts can be classified in the same manner and a matching produced with the output being an estimated achievable range for a particular design characteristic along with a probability measure that the range is correct.

The exact nature of this classification needs to be the subject of future research which could be enabled, at least in terms of the classification of the environment in which the products were created, by the EDRC Framework for Design Model (Fig.4.4.1).

In the meantime, human expert assessment is relied upon.

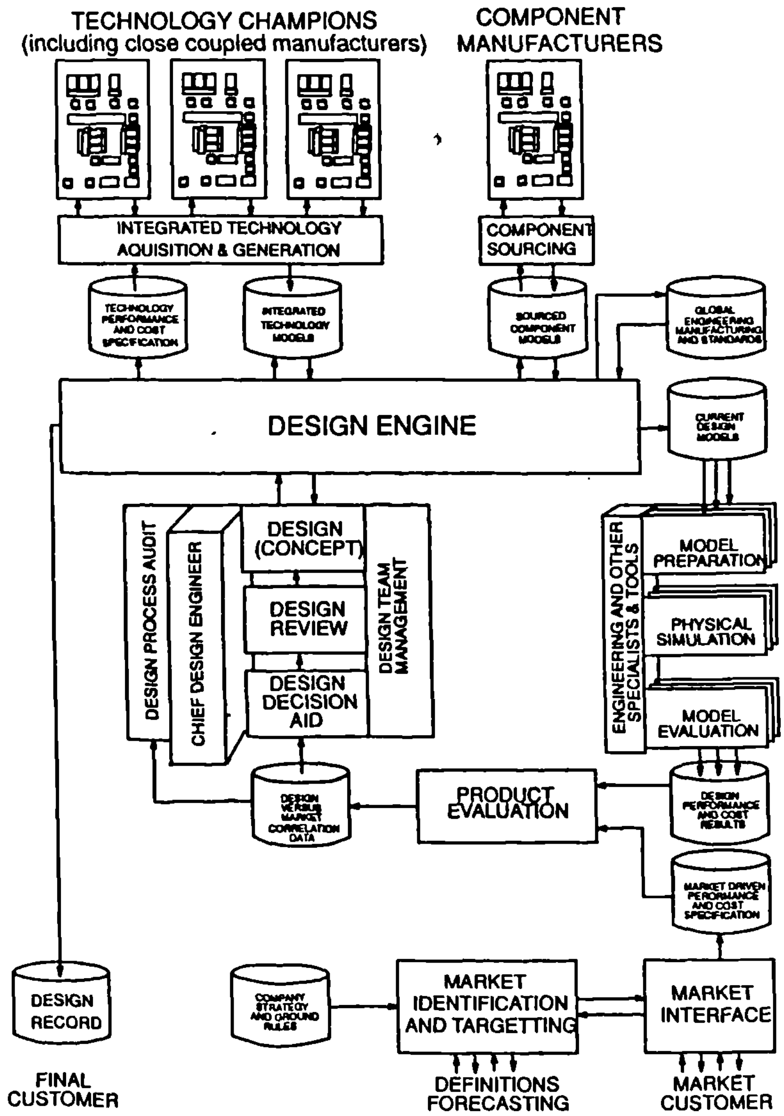


Fig. No. 4.4.1

Classification of Design Evaluation Methods

Evaluation Methods	Functional Requiremets	Design Characteristics	Conceptual Design	System Design	Configurational Design	Embodiment Design	Parameter Design	Tolerance Design	Detail Design	Design Realisation
	Increasing Definition of Design State within Design Process Phases									
DFR				Δ	Δ	Δ			Δ	
DCA		Δ			Δ	Δ				
GMI's	Δ					Δ				
QFD	Δ	Δ								
Systematic			Δ		Δ	Δ			Δ	
Technical Systems			Δ		Δ	Δ			Δ	
Cont. Convergence		Δ	Δ		Δ					
Design Methodics		Δ	Δ		Δ					
MEDA					Δ	Δ				
Prob. Design. Option			Δ		Δ					
Taguchi							Δ	Δ		
Roozenburg			Δ		Δ					
IDS						Δ				
EDESYN					Δ	Δ				
DMED				Δ	Δ					
DFA					Δ	Δ			Δ	
CDEM:-										
Model 1			• • • • • • • •	• • •						
Model 2			• • • • •	• • • • • •	• •					
Model 3			• •	• • • • •	• • • • • • • • • •	• •				

Table 4.1, Overlay of Evaluation Method and Design Phase

If the two distributions do not interact, to any extent, then the design can be considered to have failed 100% at this phase of the design process. This approach therefore provides an interim measure of the quality of a conceptual design characteristic via consideration of the degree of conformance with the target values and limits of the design specification. In the above case, the designer has to decide whether to invoke analysis in order to increase the information available regarding the Dch and thus to alter the spread of the DchE distribution or to invoke synthesis with the same result to the DchE distribution. A third option is to reconsider the DchT distribution with a view to forcing the distribution to overlap. i.e. change the specification. If the two distributions overlap completely then there is 100% success in terms of the characteristic under consideration. For 100% overlap we require that both the mean values of the distribution coincide and that the variances are equal.

The limitations of the previously discussed models remain and as the design proceeds and the associated information levels increase then the degree of match may also begin to be measured in terms of the degree of separation of the mean values of the two distributions as well as the variance of the two distributions. This also allows for the presence or emergence of deterministic assessments of value.

The degree of separation of the distributions can be described by the following relationship, taken from the reliability domain.

$$\frac{\mu DchT - \mu DchE}{\sqrt{(\sigma_T^2 + \sigma_E^2)}} = D.M \tag{4.17}$$

This can be termed the Design Margin and be designated as DM, as the degree of matching increases the value of DM will tend to zero. This expression effectively represents the inverse of the coef.. of variance with the resultant mean and standard deviation from the subtraction of the DchT and the DchE distributions. It thus allows for deterministic values in combination with distributed values and provides a measure of the separation of both. Thus a traceable method is made available which both indicates the current state of a design and yet can provide data regarding how the state of the design or a characteristic was judged to have changed throughout the design process.

As previously stated, a design is considered to be defined by a number of design characteristics and that the values of these characteristics combine and interact in a complex way to determine the value of design factors and ultimately the design solution. A model of how these characteristics interact is required.
One way of investigating this is to first of all obtain expert opinion as to the likelihood of a design meeting its combined design targets as enshrined in the design specification. This will result in another pdf which represents the considered subjective probability of the design option being successful. It does not however explain how the experts have undertaken the evaluation and apparently overcome the complexity of the interaction of the design characteristics. This issue can be examined further by proposing both new models of the interaction, as well as examining previously proposed models, and testing these against the performance of experts.

Conceptual Design Factor Rating (CDFR)

It is assumed in the CDEM model that each of the design characteristics has to be taken into consideration. The identified design critical characteristics (Dcch) are considered to have a threshold overlap of 1 and that this is fixed. To account for the relative importance of each Dch, and to allow for the variability of its relative importance as the design process proceeds, the Dch threshold value can be varied by the designer. (See further remarks, regarding the above, in the conclusions to this chapter)
This flexibility is important in that it allows innovative ideas which might otherwise be rejected on the grounds of insufficient matching to be progressed further through the process and to permit information levels surrounding the innovative features to grow.

Some initial models, based upon previously described considerations, are now presented to describe the combination of design characteristic matching measures with design factor matching.

1.

$$\prod_{i=1}^{n}\left[\int_{\min T}^{\max E}\left(DchT(v).\int_{\min E}^{T}DchE(v)dv\right)dv\right]\rightarrow 0$$

(4.18)

as shown earlier, this expression can be simplified as follows:

$$\prod_{i=1}^{n}\left[\int_{\max(\min T,\min E)}^{\min(\max T,\max E)}DchE(v)dv\right]$$

(4.19)

This model represents the product of the joint probabilities of the design characteristics estimates (DchE) and the design characteristic targets (DchT) falling within each others target limits. The assumption here is that the probability of overlap of each design characteristic is statistically independent of the others and therefore effectively models the interaction as if it were a simple series system.

Further, for a collection of non-critical design characteristics, the above may be modified to accommodate modelling these characteristics in parallel thus allowing the application of the previous notion of considering 'minimal cut-sets' combining to form a design factor.

$$\prod_{i=1}^{n}\left[1-\int_{\max(\min T,\min E)}^{\min(\max T,\max E)}DchE(v)dv\right]\rightarrow 0$$

(4.20)

That is, the product of the probabilities that the Target Values specified for each Design Characteristic will not be met. If a number of minimal cut-sets are considered to exist when modelling a particular conceptual design option then, once more drawing on practice in the reliability domain, each minimal cut-set may be combined as follows:

$$\sum_{i=1}^{n}\left\{\prod_{i=1}^{n}\left[1-\int_{\max(\min T,\,\min E)}^{\min(\max T,\,\max E)} DchE(v)dv\right]\right\}\rightarrow 0$$

(4.21)

2. It may also be reasonable to consider that the estimates provided for characteristic values are the result of the application of an intuitive model the basis of which may be minimal cut-sets of sub-characteristics. Therefore the joint probability may be treated as the quantity associated with a minimal cut-set, allowing a simple summation of the joint probabilities to provide a C.D.F.R. as follows:

$$\sum_{i=1}^{n}\left[\int_{\max(\min T,\,\min E)}^{\min(\max T,\,\max E)} DchE(v)dv\right]$$

(4.22)

and as shown earlier, with reference to Fig. 4.4, this may be simplified to:

$$\sum_{i=1}^{n}[h_E.(\max T-\min E)]$$

(4.23)

3. As outlined earlier, it is also possible to model the situation using the product of the probability of the estimated range of values falling within the limits of the specification and the probability of the specification range falling within the estimated range.

The summation of this product, for each characteristic, provides a model of the combination of characteristics to form a design factor or in some cases a design solution.

$$\sum_{i=1}^{n}\left[\int_{\min E}^{\max E} DchT(v)dv \, . \int_{\min T}^{\max T} DchE(v)\, dv\right]$$

(4.24)

The limitations of the basis of the above models requires that certain limits have to be placed on allowable values entered into the equation. These are as follows:

- A value of 1 will be entered in place of a negative value.
- A value of zero will be accepted in the case of an overlap of one or two deterministic values.

These arrangements permit the output of the model to indicate that the concept design with the highest extent of overlap is indicated by the smallest value. This allows direct comparison with the next model.

4. As the design process moves further through the conceptual phase and where information increases or where deterministic values emerge, the following model is more appropriate.

$$\sum_{i=1}^{n}(DM) \rightarrow 0$$

(4.25)

This model represents the summation of the individual Design Margins (DM) as previously defined. A simple summation model is appropriate for the same reasons cited for model (2).

Any test of these models requires that the expert generation of overall evaluation is done with the knowledge of the design characteristic target values whereas the expert group assessment of the individual design characteristic values be undertaken without knowledge of the design target values. By comparing the above models with actual expert evaluation it should be possible to begin a process of developing a more complex though valid and reliable computer based model that can match or improve upon [Levi 1989] human evaluation.

Conceptual Design Solution Rating (CDSR)

Assuming that we now have an initial estimate for the design factor quality rating, it is necessary to modify this measure in terms of the acceptability of this level of quality at this point within the design hierarchical structure. This has been tried using Utility measures though the idea of Loss function application is gaining ground in the quality domain. The notion of the Loss function is attributed to Taguchi who states that a simple quadratic loss function can be used in the absence of a more defined function. During the conceptual design phase it seems logical to test this initial approach prior to increasing the complexity. Therefore, a chart indicating a loss function rating between 0 and 1 on the vertical axis with the design factor estimate rating on the horizontal axis can be constructed. The quadratic loss function is drawn between the axis. By marking the design factor estimate and reading of the loss factor value the modification process is complete.

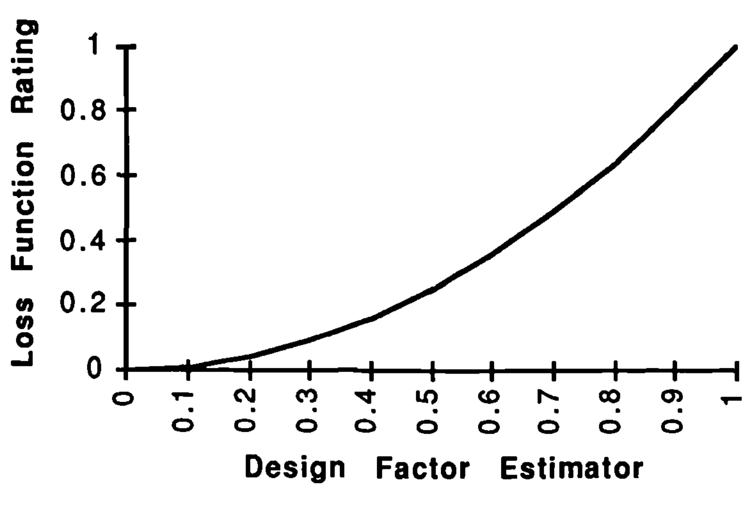


Fig. No. 4.5

If this process is repeated for each design factor then, according to Taguchi, they may be combined simply by taking the summation of the individual loss factors, as follows:

$$\sum_{i=1}^{n}(\text{Loss. factors})$$

(4.26)

The result is a Quality rating measure for the conceptual design solution being proposed. The maximum rating for any particular design solution will be a function of the number of design factors combining to produce a conceptual design solution rating.

i.e. No. of design factors x 1(max possible rating)

The relative quality ratings between the conceptual options can therefore be measured.

Mathematically, the Conceptual Design Solution Rating (CDSR) model options can be defined as follows:

Model 1

$$CDSR = \sum_{i=1.}^{n}\left\{\sum_{i=1}^{n}\left[\int_{\min T}^{\max E}\left(DchT(V).\int_{\min E}^{T}DchE(v)dv\right)dv\right].\text{Loss. function}\right\}$$

(4.27)

Model 2

$$CDSR = \sum_{i=1}^{n}\left\{\sum_{i=1}^{n}\left[\int_{\min E}^{\max E}DchT(v)dv.\int_{\min T}^{\max T}DchE(v)\,dv\right].\text{Loss. function}\right\}$$

(4.28)

Model 3

$$CDSR = \sum_{i=1}^{n}\left\{\left[\sum_{i=1}^{n}(D.\ M)\right].\text{Loss. function}\right\}$$

(4.29)

Conclusion

The Conceptual Design Evaluation Methodology (CDEM), described above and summarised in Fig No. 4.6, has been developed in line with the identified needs and is built upon established methods to provide the basis of a unified approach which exhibits the following potential advantages:

- Formalised classification of past designs to enable projection.
- Formalised new concept ideas to enable projection.
- Enables concurrent design development within teams.
- Allows traceability of design decisions and development via an on-going assessment of design quality at various levels within the design.
- Provides consistency through the idea of Loss Function.
- Allows dynamic threshold adjustment as design progresses.
  (This mechanism is in effect similar to the approach, advocated by Siddall in his probabilistic design option method, of applying a value or utility curve across the upper and lower limits of acceptable design characteristic values.)
- Encourages innovative designs to be retained and developed.
- Lends itself to linking to other phases within the design process.

For reference, the CDEM approach is shown classified in Table 4.2 along with the previously identified methods.

The next chapter seeks to test the CDEM approach in a controlled design experiment with a view to determining both its validity and reliability.

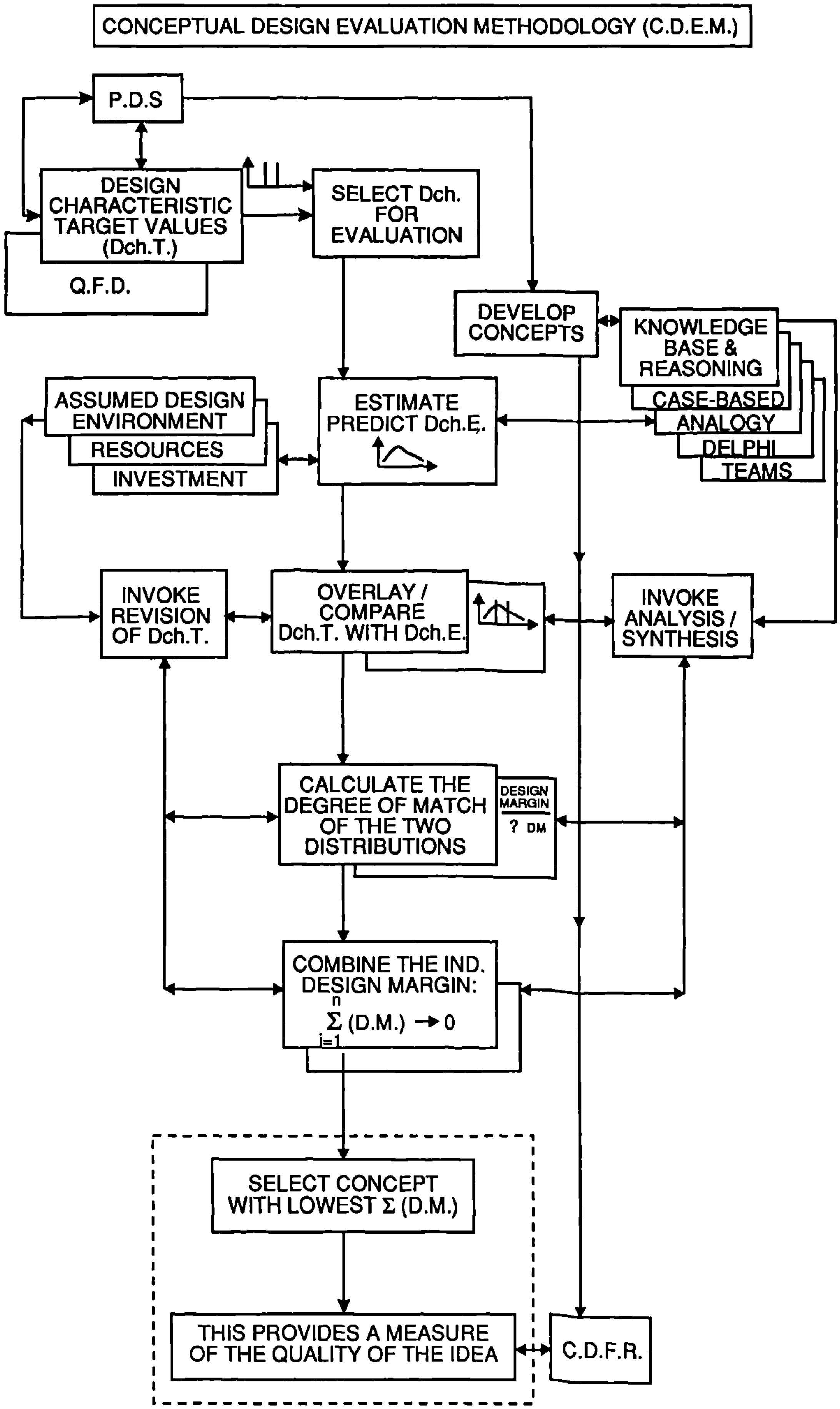

CONCEPTUAL DESIGN EVALUATION METHODOLOGY (C.D.E.M.)
P.D.S
DESIGN CHARACTERISTIC TARGET VALUES (Dch.T.)
Q.F.D.
SELECT Dch. FOR EVALUATION
DEVELOP CONCEPTS
KNOWLEDGE BASE & REASONING
CASE-BASED
ANALOGY
DELPHI
TEAMS
ASSUMED DESIGN ENVIRONMENT
RESOURCES
INVESTMENT
ESTIMATE PREDICT Dch.E.
INVOKE REVISION OF Dch.T.
OVERLAY / COMPARE Dch.T. WITH Dch.E.
INVOKE ANALYSIS / SYNTHESIS
CALCULATE THE DEGREE OF MATCH OF THE TWO DISTRIBUTIONS
DESIGN MARGIN
? DM
COMBINE THE IND. DESIGN MARGIN:
$\sum_{i=1}^{n}$ (D.M.) → 0
SELECT CONCEPT WITH LOWEST Σ (D.M.)
THIS PROVIDES A MEASURE OF THE QUALITY OF THE IDEA
C.D.F.R.

Fig. No. 4.6

Classification of Design Evaluation Methods

Design Evaluation Methods	Computer Based	Clarity of Design State	Common Links	Projection Ability	Team Communication	Design Traceability
	Conceptual Design Evaluation Activity Needs					
DFR	Δ	Δ		Δ	Δ	Δ
DCA			Δ			
GMI's		Δ				Δ
QFD					Δ	Δ
Systematic		Δ				Δ
Technical Systems		Δ				Δ
Cont. Convergence					Δ	
Design Methodics					Δ	
MEDA			Δ			Δ
Prob. Design. Option			Δ			Δ
Taguchi		Δ				Δ
Roozenburg					Δ	
IDS			Δ			Δ
EDESYN	Δ				Δ	Δ
DMED						Δ
DFA		Δ				Δ
CDEM						

Table 4.2, CDEM Comparison with Evaluation Methods

Chapter 5 *Experimental Method, Design and Results*

Introduction

As mentioned in the introduction to this thesis, one of the principal criticisms of design research has been the lack of experimental evidence to support the adoption of theoretically based prescriptive models of aspects of the design process. Much work has been done in terms of developing models intended to improve the quality of design output, or to maintain quality of output but with reduced timescales, but there is little empirical evidence that the application of any of the theoretical models actually has a measurable beneficial effect [Ehrlenspiel and Dylla 1989].

There has also been over recent years a move towards the automation of the design process via the development of computer aided tools. An important aspect of this work has been the development of understanding of the design process and the interactive mechanisms driving the design phases coupled with the degree of commonality of these issues within diverse domains [Stauffer 1989]. This has led in part to the development of computer-based models derived largely from technological and domain independent prescriptive and descriptive models.

Further, the proposal of a model of any aspect of the design process can only be justified, and indeed will only be adopted by the design community, if it can result in one or more of the following:

- reduce manpower required in the design process without loss of quality of design output and at an acceptable cost.
- reduce timescales without loss of quality of design output and at an acceptable cost.
- allow the resolution of problems that cannot be tackled intuitively with any degree of confidence.
- substantially increase confidence in decisions that could and would traditionally be addressed intuitively.
- the effect of application must be measurable.

The focus for the earlier phases of this design research project was the need for a methodology of conceptual design evaluation and the development of such an appropriate methodology. The next phase of the research will seek to test this methodology both under artificial experimental conditions and within a design project setting and provide a measure of the beneficial effects and thus attempt to demonstrate the degree of match with the above criteria.

The Experiment

The aim of the experiment was to examine existing conceptual evaluation methods in comparison with the developed methodology. The intention was to compare the effectiveness of formal and intuitive evaluation approaches via measurement of the quality of the decisions arising from the evaluation activity. These decisions will be of the following types:

- selection/rejection of a conceptual design option.
- decision to invoke synthesis with a view to altering and progressing the current state of a design option.
- decision to invoke analysis with a view to obtaining further information about the current state of a design option.
- decision to alter the design characteristic target setting.

The outcome from this experimental phase was to be an increased understanding of the nature of the evaluation activity during the conceptual phase of the design process. It sought to test the validity of a hypothesis relating to the nature of expert evaluation, encapsulated within a systematic methodology, by allowing non-experts to use the methodology and measure their performance when compared to an expert. Not only did this provide knowledge regarding the fundamental nature of the evaluation activity it also provided a possible approach to encompassing evaluation activities within computer based expert design systems.

The Design of the Experiment

Two complementary methods were used to test the validity, reliability and objectivity of the developed methodology:

- Controlled artificial experimentation
- Controlled application within a project setting.

In the first case the developed methodology was compared against current conceptual evaluation methods. This comparison process took the form of the selection of a conceptual option from a range of given options in terms of the quality of the selected option. The measurement of the quality was based upon the following:

- the degree to which non-expert judgement of the potential value of the individual conceptual design characteristics match the judgement of experts.

- the degree to which the non-expert selection of conceptual design option, when based on their previous judgements of design characteristic values, match the selection of experts.

If the CDEM could be shown to be repeatedly capable of selecting the same concept option preferred by experts then the methodology would be seen to be both valid and reliable. Therefore a group of experienced designers (experts) and ten groups taken from each of the four years of undergraduate engineering courses based in the department of

Mechanical Engineering at Glasgow University were used as subjects for the experiment. The students were familiar, to varying degrees, with current formal and intuitive evaluation approaches. Each group was presented with a number of equally detailed conceptual designs, [Appendix A] communicated in the same format, along with the associated design specification and the design characteristics to be used in the evaluation. The concepts had been generated independently of anyone within the subject groups and indeed was based upon an example previously described in the literature [Kuppuraju et al 1985]. Thus the problem of evaluation objectivity was at this stage avoided. It would however be addressed in the project based approach described below. Each group was then be asked to estimate values for each design characteristic and for each concept. This data was recorded within a spreadsheet format [Appendix B] to facilitate analysis of data in terms of a comparison between expert and non-expert judgements at this level. Each group was next asked to select one concept that they considered most clearly satisfied the requirements of the design specification and to explain why. If the results of the application of the methodology repeatedly matched with the expert view more often than would be expected through chance, and consistently out perform the novice groups, then the validity and reliability of the methodology is assured.

In the second case, all three identified decision outcomes from the evaluation activity were examined in a project based setting. That is, the quality of concept selection as well as the quality of the decision to invoke both synthesis and analysis activities. The quality of the latter two decisions were measured as follows:

- the degree to which the decision to invoke synthesis activity moves the concept closer to satisfying the design specification.
- the degree to which the decision to invoke analysis alters the distribution of the potential values of individual design characteristics or indeed alters the design specification distribution.

In this experiment each subject group generated their own conceptual design, and were provided with a further three new concepts, prior to the initial experimental procedure being repeated. This approach then allowed the objectivity question to be addressed and measured its effect upon consistency of the output from subjects applying the methodology. However, this approach also allowed the concept communication format to become variable between the subject groups creating uncertainty as to the amount, and consistency, of information contained within each concept description. This issue requires further research to identify how one might adequately measure the amount of information contained within a concept and to measure the relevance of its variability upon the consistency and quality of evaluation activities. Previous research has tended to side step this issue by simply saying that......*each concept should be taken to the same level of detail*... this is clearly inadequate if both the validity and the reliability of a methodology is to be assured. For the purposes of this research programme the approach taken was to restrict the nature of the problem being addressed and to place specific controls over the format and extent of concept communication techniques. This was also required because of the range of experience and skills present in the identified subject groups.

As previously indicated, each group was allowed to invoke synthesis activities intended to modify some aspect of the conceptual design which they felt would beneficially alter the perceived value of a particular design characteristic. Equally, each group was allowed to invoke analysis activities intended to elicit further information regarding one particular design characteristic. The evaluation activity was repeated to assess the effect of the increased information resulting from the design change and the information gained by analysis on the perceived quality of the conceptual design as well as on the value of the individual design characteristics. Once again the results were recorded within a spreadsheet format to enable analysis of the data.

Experimental Task

In the selection of the experimental task it was important that the given design specification described a design task that was neither insoluble for the non-expert subjects nor trivial for expert subjects. Equally, to ensure that conceptualisation took place, the design task did not have an immediate off the shelf solution. Further, the design characteristics used in the evaluation were of a nature that was understandable by all the subjects thus allowing at the very least the option of purely intuitive judgement. The task therefore did not require specific domain knowledge or excessive timescales.

The description or statement of the assumed resources and environment available for concept development was kept simple, clear and unambiguous to all the subjects whilst representing a realistic scenario as judged by the expert subjects.

Interpretation

It has become normal practice in recent times to observe the activities of designers using video recording which can often take considerably more time to analyse than the time spent in the design activity itself. This has resulted from a tendency to try to view the complete design process and has produced only more descriptive models which are never validated nor their reliability assessed. The research which forms the subject of this thesis took the approach of observing and recording the results of a definable and bounded activity within a specific phase of the design process and sought to test an hypothesis, contained within a systematic methodology, of how evaluation activities are undertaken by experts. Through comparison with how non-experts undertake evaluation, knowledge was gained as to how expert approaches to evaluation can be made available within computer based tools via an interface that effectively enhances and enables non-expert evaluation. Spreadsheet software was the main method used for recording and manipulating data. This approach had the added advantage that the application software will be familiar to all the subjects to an acceptable degree.

Implementation

Twenty-three volunteer novice subjects were arranged in either small groups or as individuals on a random basis. Each group consisting of students from the same year. In parallel, a small number of volunteer experienced engineers, drawn from the academic and technical support staff of the department, tackled the experiment on an individual basis. The subjects were given documents describing the tasks they were to undertake (Appendix A) which included details of the conceptual designs of a motor-car horn. This particular product was chosen for the experiment since it was judged to satisfy the criteria established within the planning phase of the experiment and that it was a well known example previously cited in the design research literature allowing some independent comparison with the results of previous work [Kuppuraju et al 1985]. A time limit of two hours was placed on the experiment in order to focus the thinking of the subjects and apply an element of realistic decision making under pressure of time. A standard format was used to record the views and judgements of all the subjects (Appendix B). The form was designed to allow the design evaluation process to take place in a controlled manner with an increasing number of conceptual options. It also permitted the question of objectivity in the evaluation process to be addressed by incorporating the possibility of the subjects generating their own design options.

Analysis of Results

The results of the design experiment were entered into a computer-based spreadsheet (Microsoft Excel 3.0) to enable analysis and presentation (Appendix C). Some judgement had to be exercised, by the author, over a small number of the terms used by the subject in relation to the evaluation criteria used and their classification headings within the spreadsheet. A distribution of the range of responses from the subjects for each criteria was created from the data and combined together to present a view of the overall feedback for each conceptual option (Fig. No. 5.1). These distributions were also formatted as rectangular distributions (Fig. No. 5.2) to permit the application of the

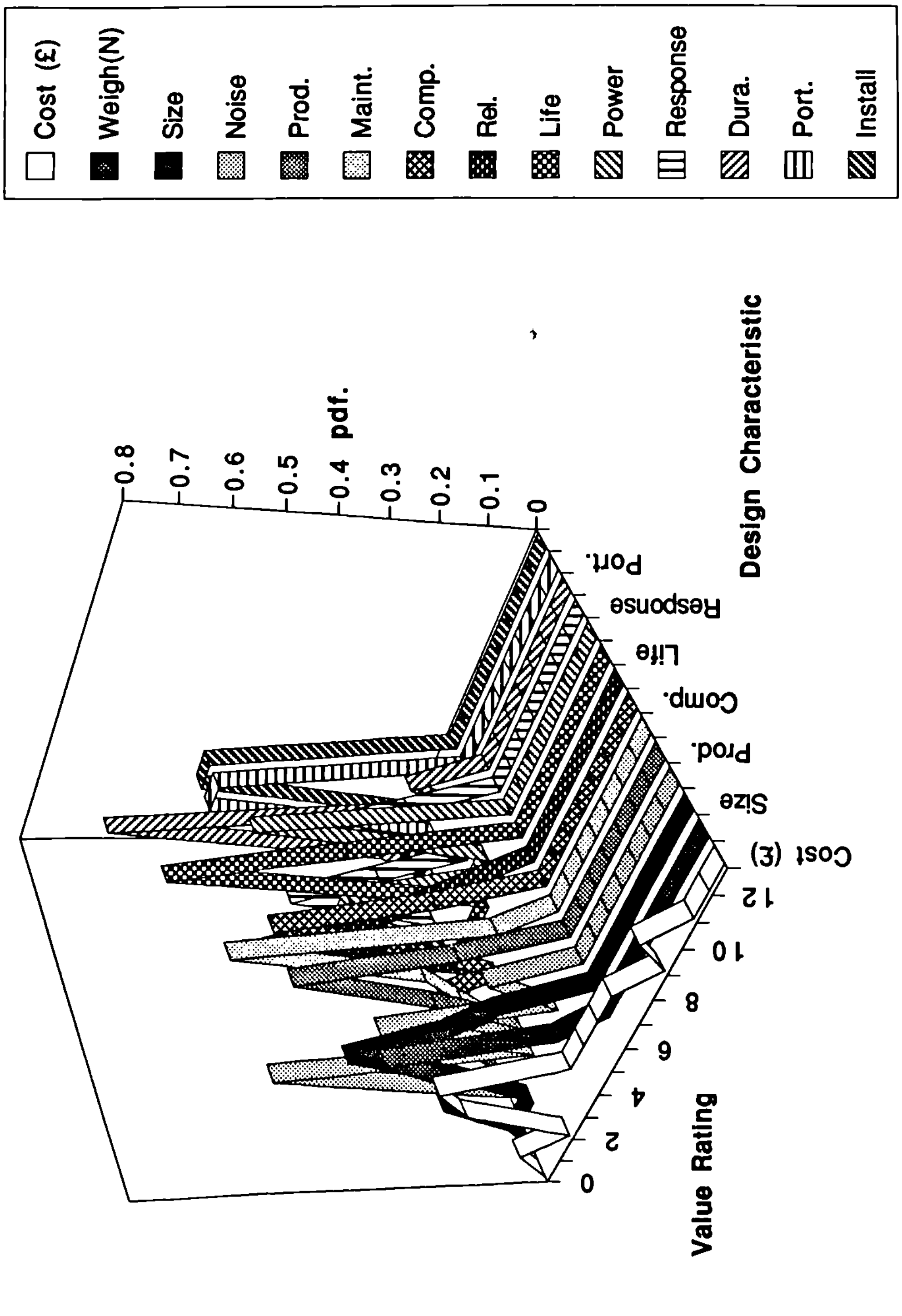


Fig. No. 5.1, Concept 4 Design Characteristic Profile

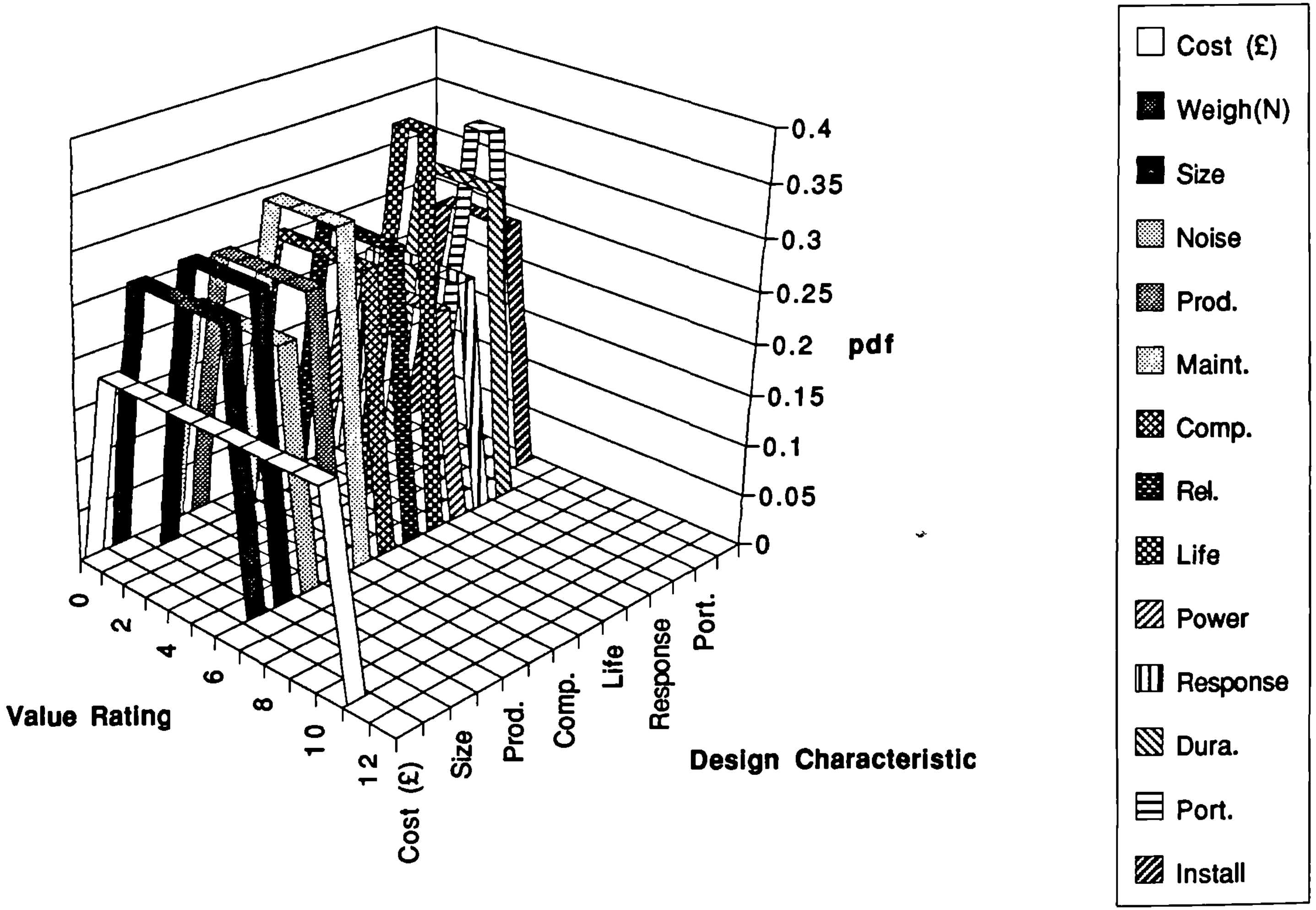


Fig. No. 5.2, Concept 4 Design Characteristic Profile, Rectangular Distribution proposed evaluation methodology and to simplify comparison. An identical procedure was used to format the data contained within the target design specification in order that the forecast values of the evaluation criteria could be readily overlaid with the target values set within the design specification. An example of this overlay (Fig. No. 5.3) shows the Design Characteristic Target 'Complexity', for concept 4, being overlaid with the forecast values. This procedure can be extended to cover a sub-set of all the design characteristics or indeed all the characteristics targeted within the design specification (Fig. No. 5.4).

This facility provides designers with a means of visualising the extent to which their ideas are matching with the specification set for it. It has the potential to enhance the designers ability to make decisions regarding undertaking analysis or synthesis activities. It will help in deciding which analysis tools to use and then show the effectiveness of their application in terms of improving the degree of match between the design and the specification. The opportunity for traceability of design decisions starts to emerge since a mechanism is provided which allows the effect of design decisions to be monitored and recorded as well as having the capability of measuring the effectiveness of the invocation of both synthesis and analysis activity. This is an important tool for designers since it permits an advance upon the reliance of anecdotal evidence as to the effectiveness of specific design methods by allowing designers to view and absorb past experience in a much more effective manner.

Application of Conceptual Design Factor Rating (CDFR) Models

The next step in the analysis of the experimental data was to separate the novice data from that of the experts and to incorporate both sets of data within the developed evaluation models permitting the results of this process to be compared against the declared preferences of the expert subjects. In this way the validity of the models may begin to be assessed.

As described earlier, three related models were used:

- Σ DM
- $\Sigma\int\int$
- $\Sigma\int(\int)$

The results of this comparison are summarised, for data from Experiment 1, in Table 5.1 and shown in Fig. Nos. 5.5 to 5.9. The data used to produce the graphs is given in Table 5.2.

	Novice	Expert
Declared Preferences	1 and 2	4,5 and 1
Individual Data		
ΣDM	2 and 4	4 and 2
$\Sigma\int\int$	5 and 4	4 and 1
$\Sigma\int(\int)$	5 and 4	2 and 4

Table 5.1, Summary of Results of CDFR Model Comparison (Concepts 1 to 5)

The above table indicates the the first two concepts identified, as having the greatest degree of overlap with the design specification and indicated with the lowest value rating, by the three related evaluation models.

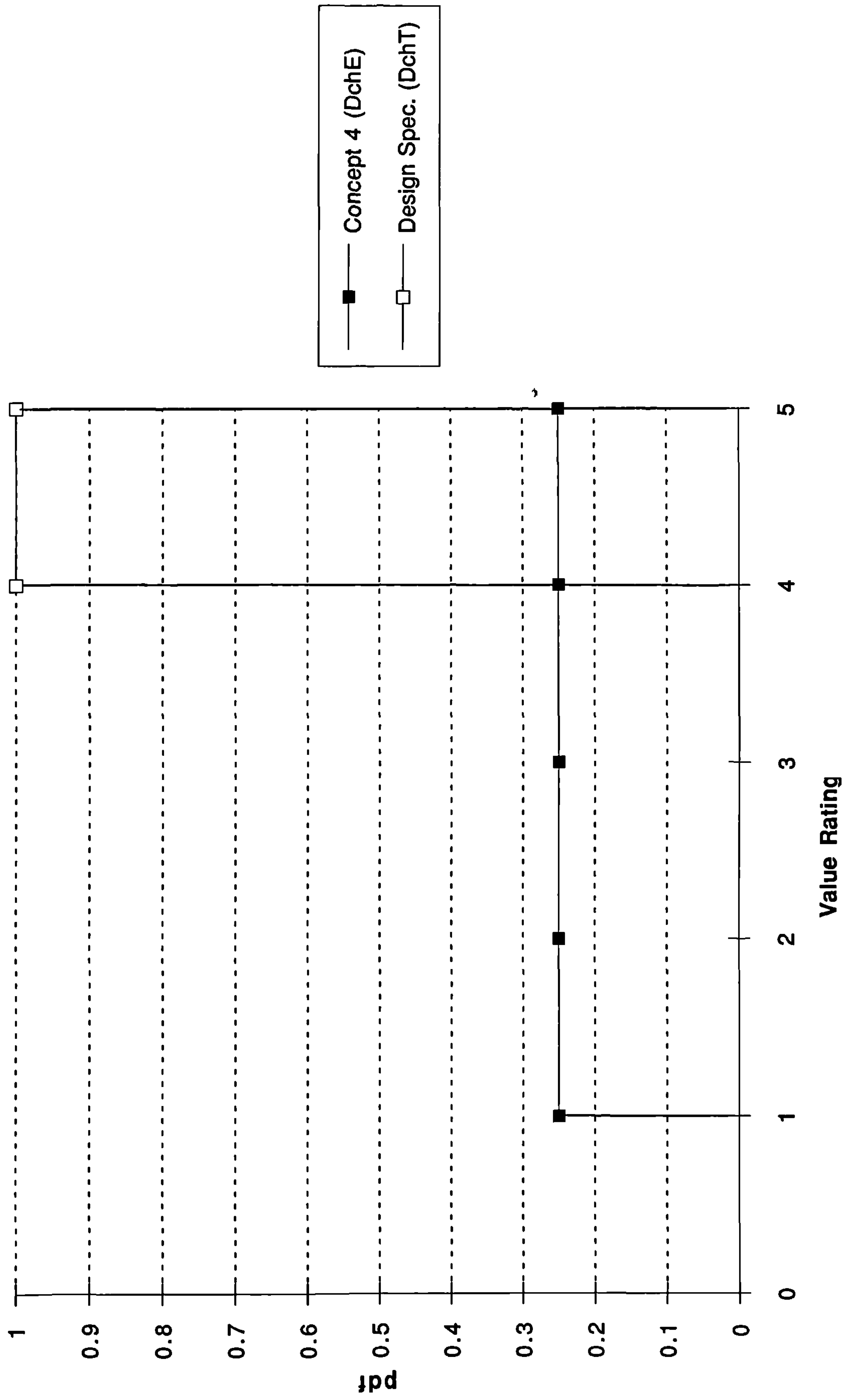


Fig. No. 5.3, DchT and DchE Overlay

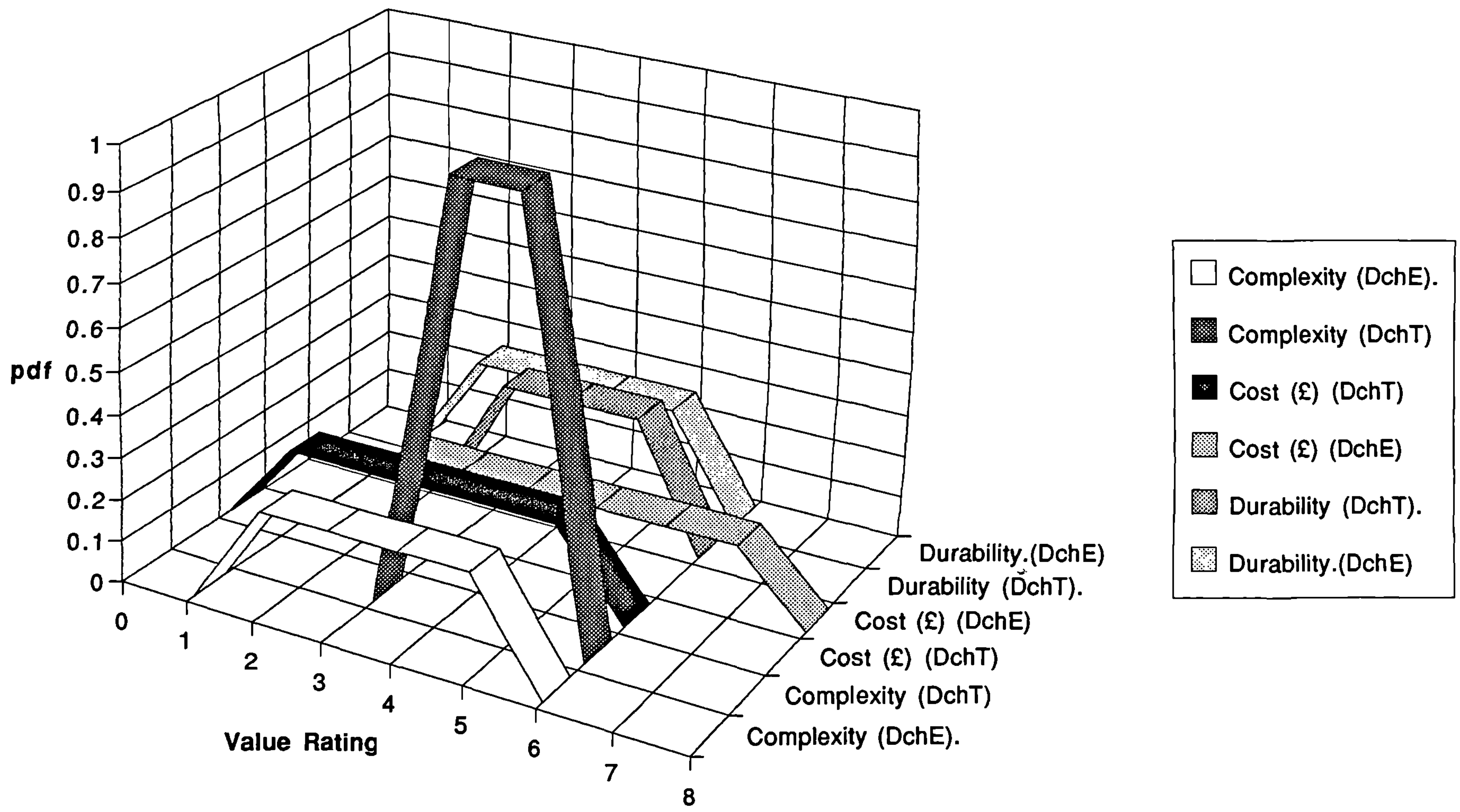


Fig. No. 5.4, Design Characteristic Sub-set Overlay

Conceptual Design Factor Rating (CDFR)
CDEM Model Comparisons

Concepts	ΣDM N&E	Novice ΣDM	Exp. ΣDM	Σ∫∫ N&E	Novice Σ∫∫	Exp Σ∫∫	Σ∫(∫) N&E	Novice Σ∫(∫)	Exp Σ∫(∫)
1	11.25	11.46	38	7.12	6.14	3.53		6.28	1.23
2	7.56	6.86	32	6.91	6.52	4.26		6.39	0.69
3	13.11	12.62	35	8.09	7.56	4.03		6.32	2.03
4	8.71	8.20	29	6.16	5.80	0.26		6.18	1.03
5	7.05	12.81	36	5.19	4.17	3.89		5.03	1.39
6	5.62	5.16	39	7.59	6.58	3.25		7.06	1.32
7	11.08	10.83	33	8.56	7.24	2.65		5.95	1.52
8	18.62	6.41	30	6.59	4.90	0.43		5.82	1.37
9									
10									

Table 5.2, CDFR Model Comparison (Data)

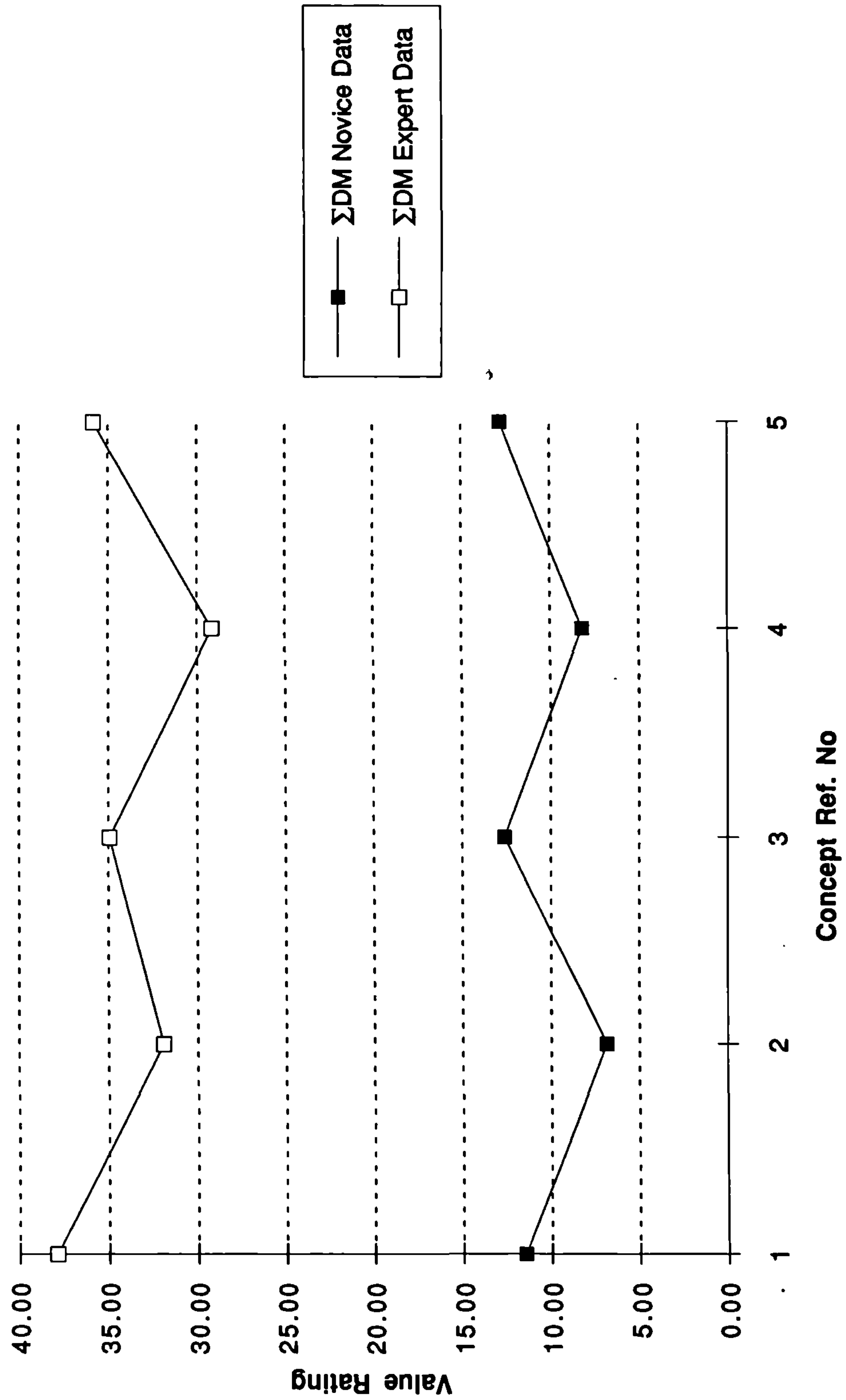


Fig. No. 5.5, CDEM Model Comparison (Experiment 1)

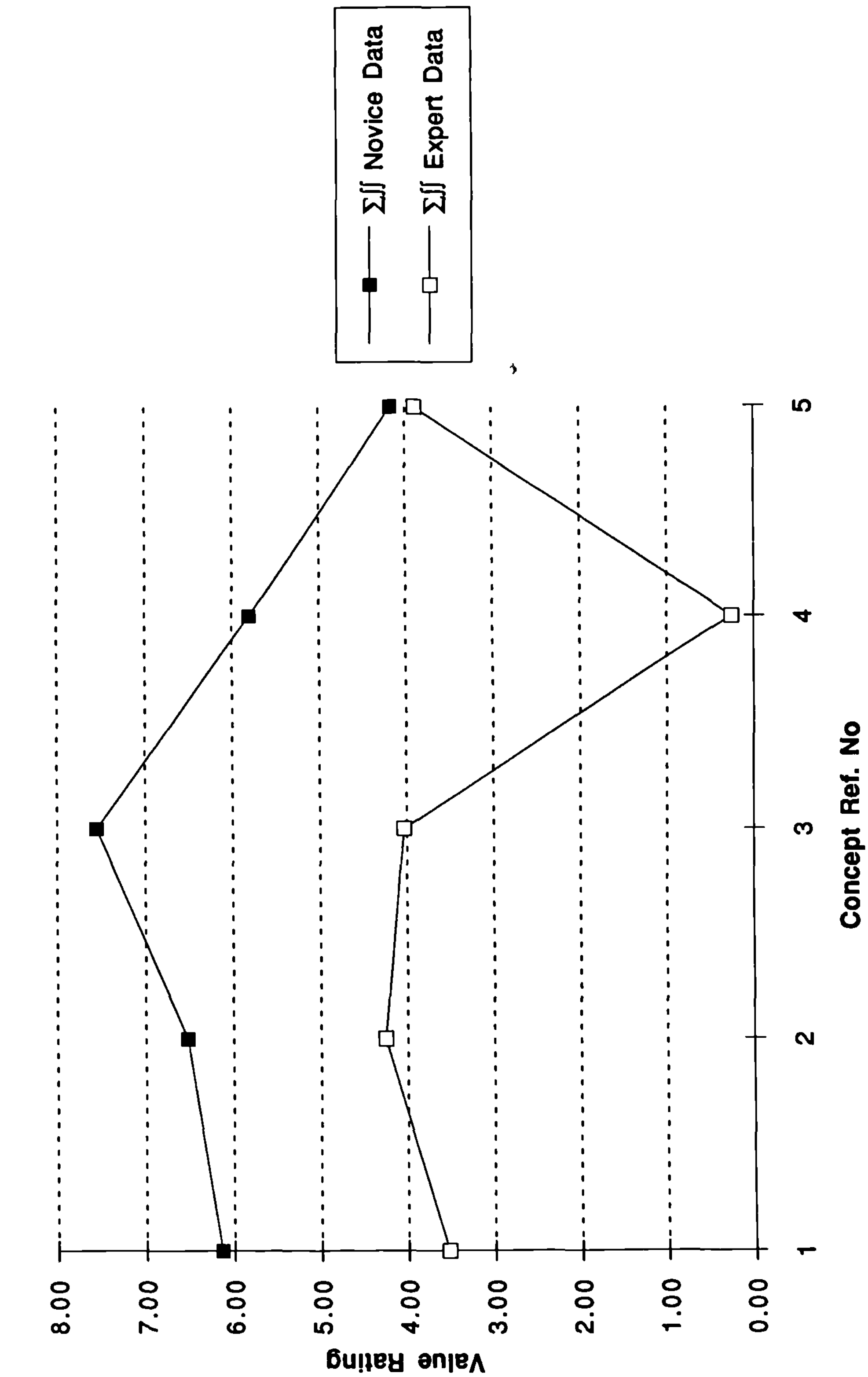


Fig. No. 5.6 CDEM Model Comparison (Experiment 1)

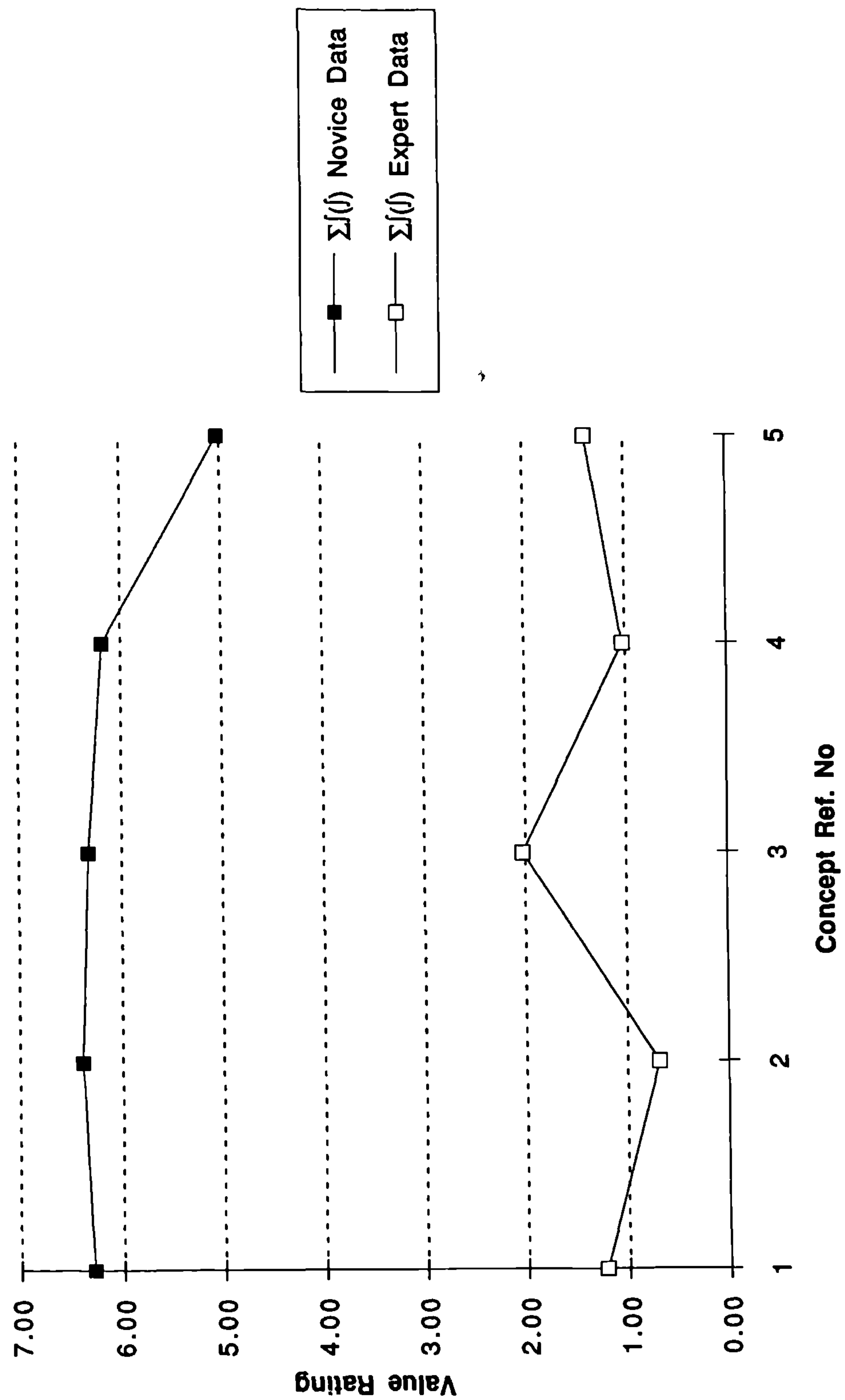


Fig. No. 5.7, CDEM Model Comparison (Experiment 1)

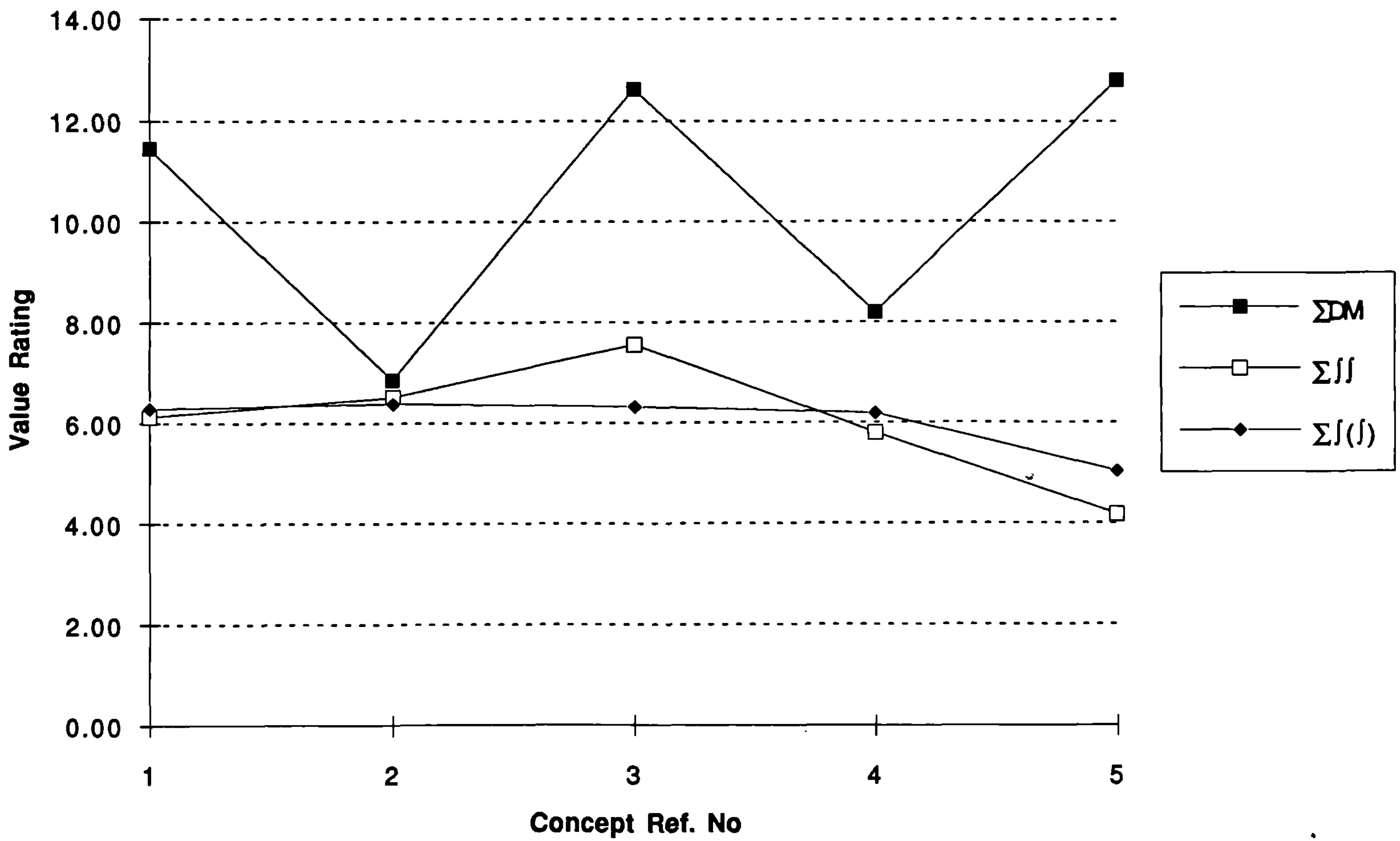


Fig. No. 5.8 CDEM Model Comparison, Experiment 1, Novice Data Only

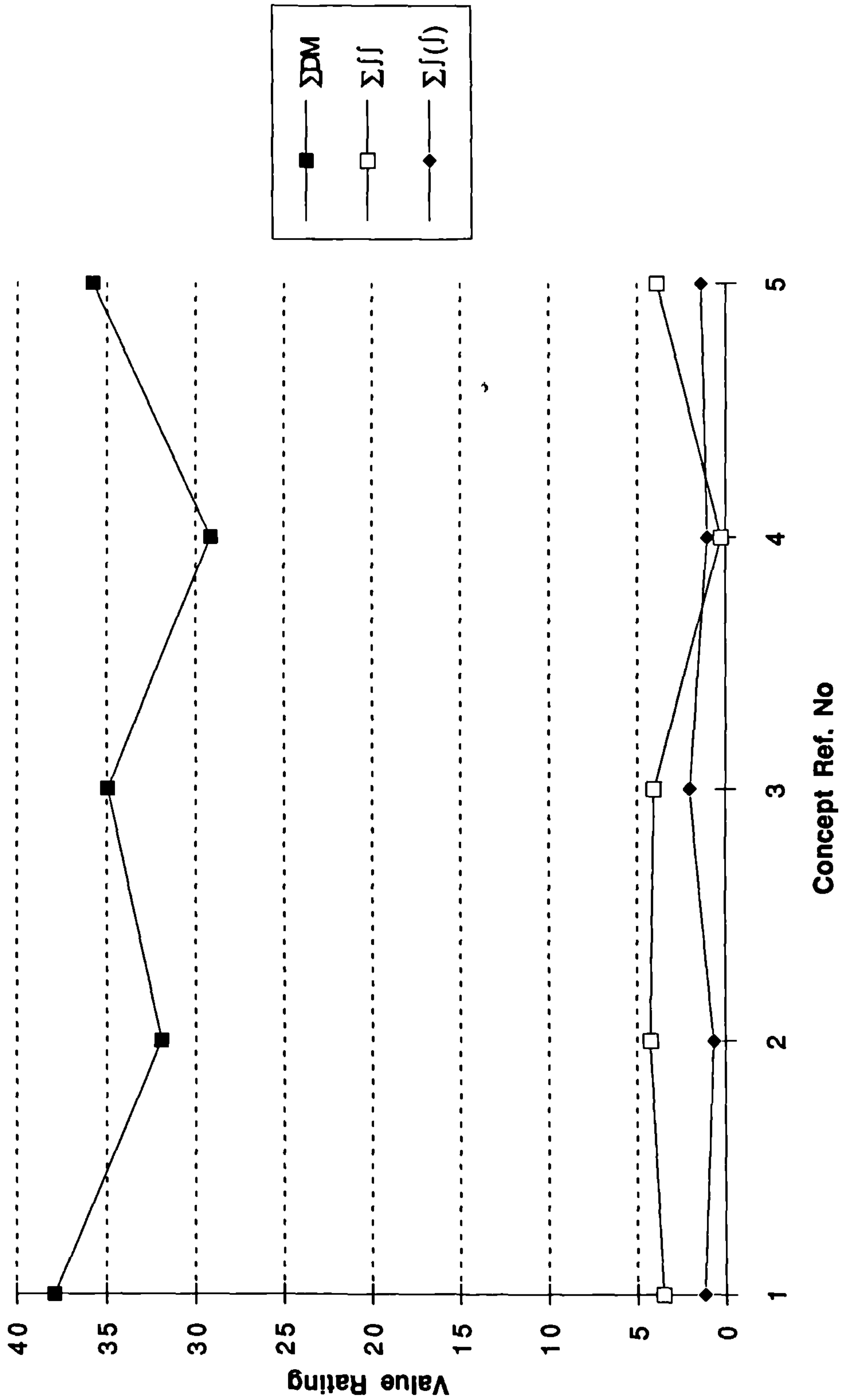


Fig. No. 5.9, CDEM Model Comparison, Experiment 1, Expert Data

Upon inspection, the above data and the accompanying figures highlight the following points of interest:

- There is a tentative link between the declared preferences of both novice and expert.
- The declared preference, of the novice subjects, does not appear to match with the data they provide as well as that of the experts.
- All three models support the declared preferences of the expert and highlight Concept 4 as providing the closest matching. Interestingly, Concept 4 was not a declared preference of the novices.

In light of the admittedly limited data, some tentative conclusions are drawn from the above initial analysis.

- If the CDFR models were used by novices using their own data, or that produced by expert groups, then one would expect them to be able to select a shortlist of concepts that would correspond with expert judgements.

- It appears that the experts may employ a type of decomposition in their evaluation and, at least with a limited number of concepts and design characteristics, this is reasonably described by the models presented.

Experiment 1 has shown that the application of a model which has as its basis the assumption that evaluation is undertaken via the decomposition of the design characteristics and that the notion that the specification provides a means of comparison at the design characteristic level has been shown to possess some validity.

Experiment 2 sought to test the evaluation models and the subjects response with an increased number of concepts and to test the objectivity of their assessments by allowing the subjects to produce their own conceptual option. The approach used in Experiment 1 was again employed to use both the novice and expert data within the CDFR models and to assess the extent to which the models continued to match the expert declared preferences.

The results are summarised as follows:

	Novice	Expert
Declared Preference	2,1,6,7,4 and 9	9
Individual Data		
ΣDM	6 and 8	4 and 8
Σ∫∫	5 and 8	4 and 8
Σ∫(∫)	5 and 8	2 and 4

Table 5.3, Summary of Results of CDFR Model Comparison (Concepts 1 to 9)

These results are further illustrated in Fig. Nos. 5.10 to 5.14.

Once again the data used in the graphs is reproduced in Table 5.2

Upon inspection, the following points can be highlighted:

- The spread of the declared novice preference increases significantly in conjunction with an increased divergence between those concepts predicted by the models using novice data and the declared preferences of the novices.

- The experts clearly favoured their own designs even though the CDFR models indicated the continued support at the design characteristic level for Concept 4 and new Concept 8.

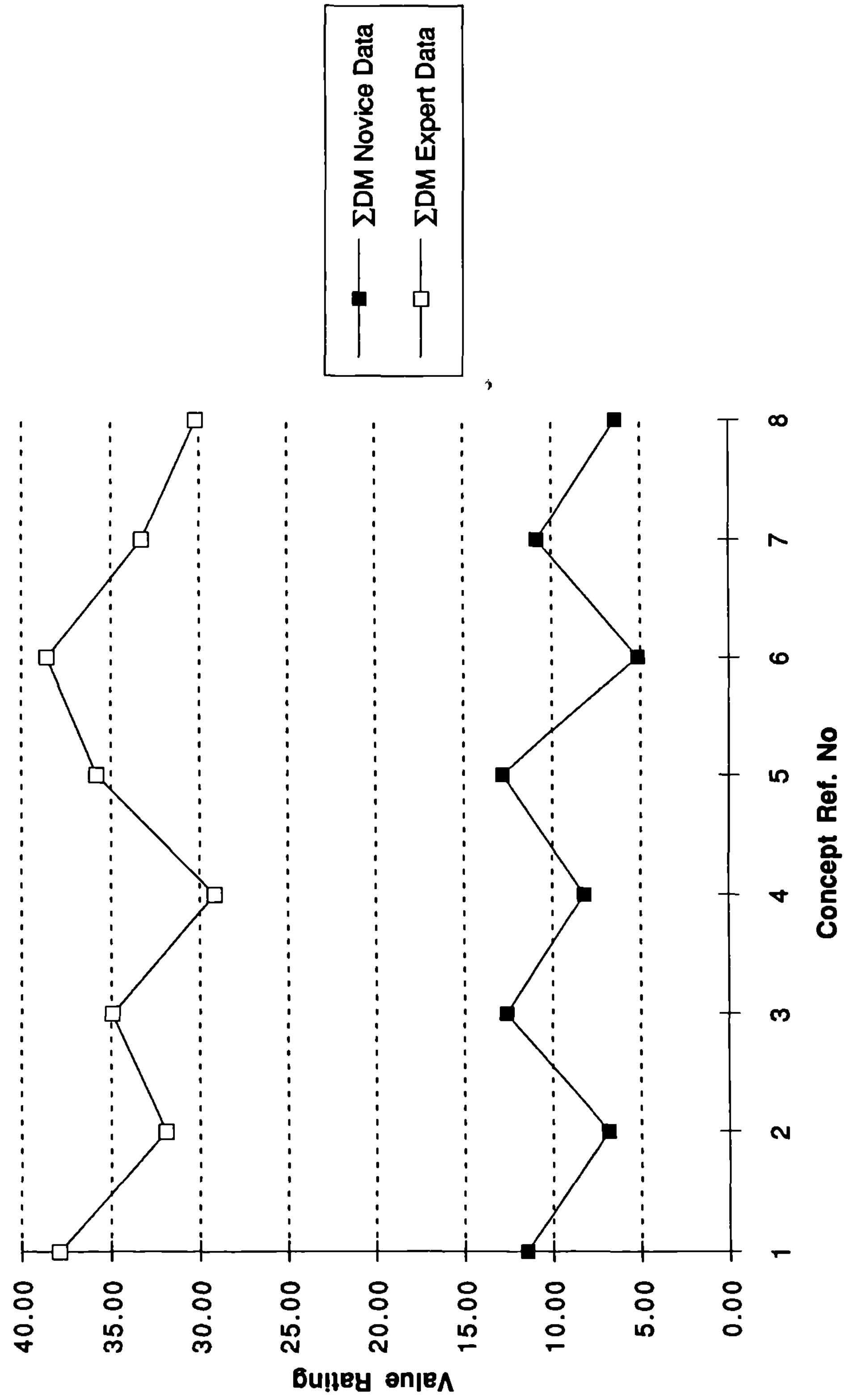


Fig. No. 5.10, CDEM Model Comparison(Experiment 2)

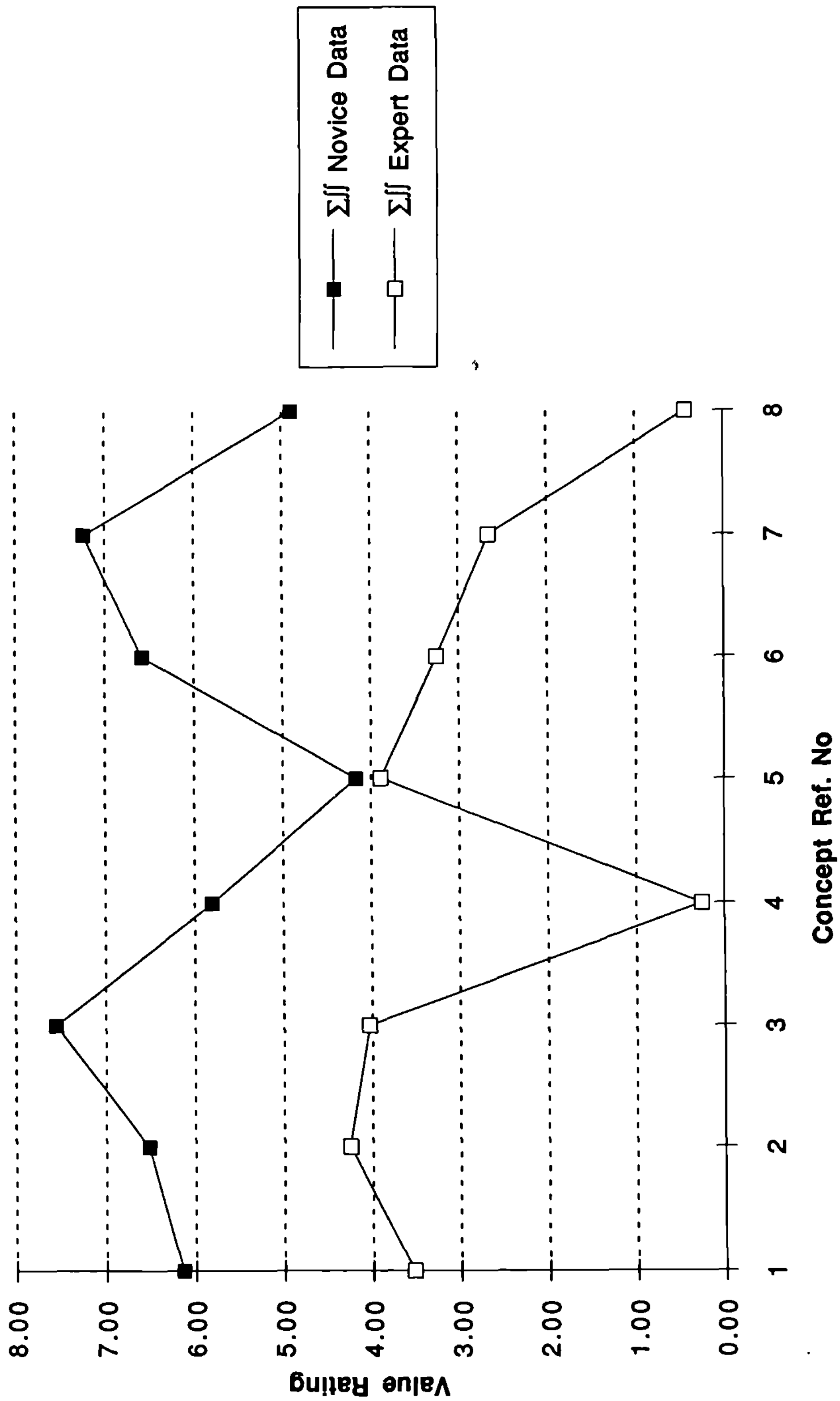


Fig. No. 5.11, CDEM Model Comparisons (Experiment 2)

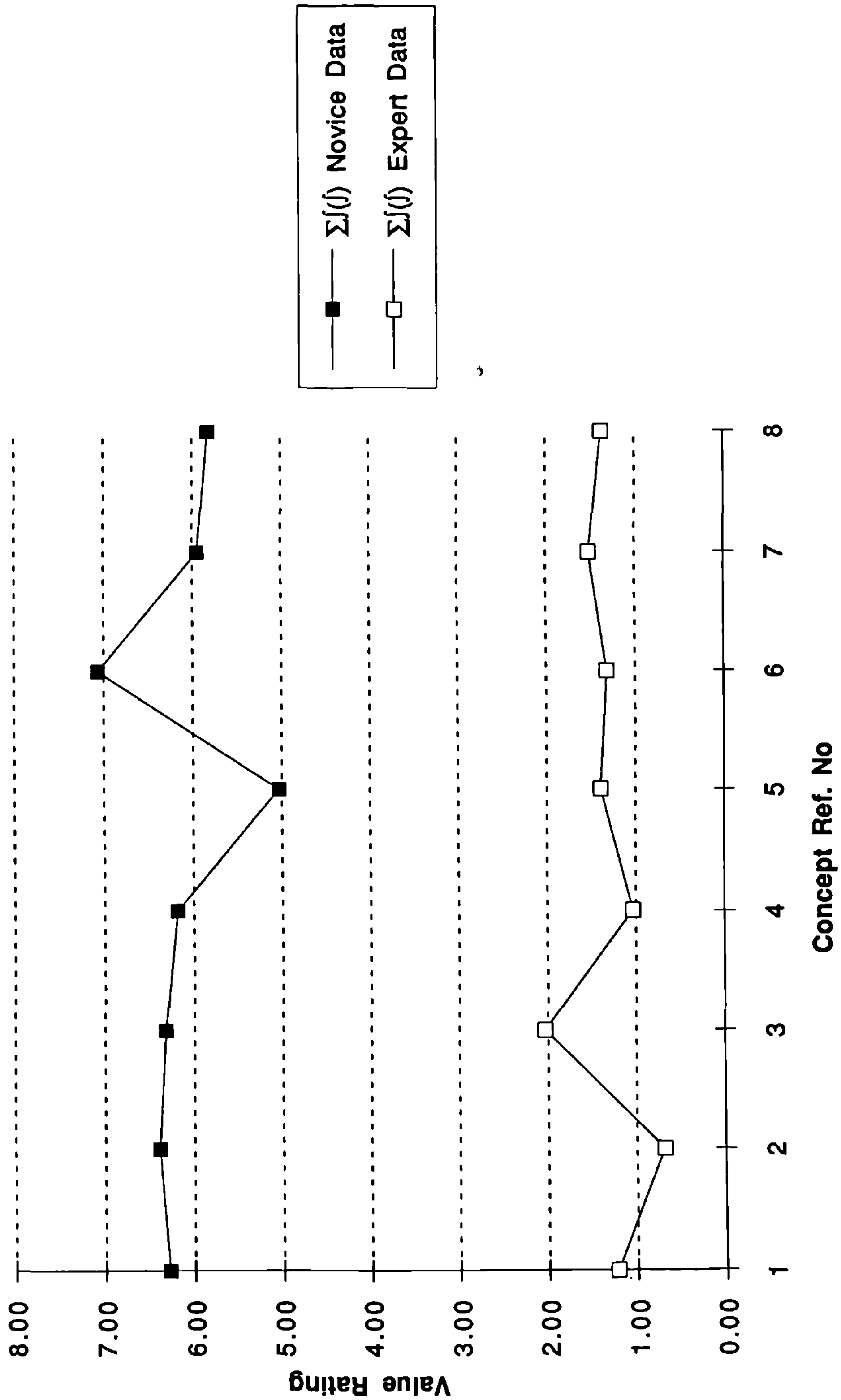


Fig. No. 5.12, CDEM Model Comparisons (Experiment 2)

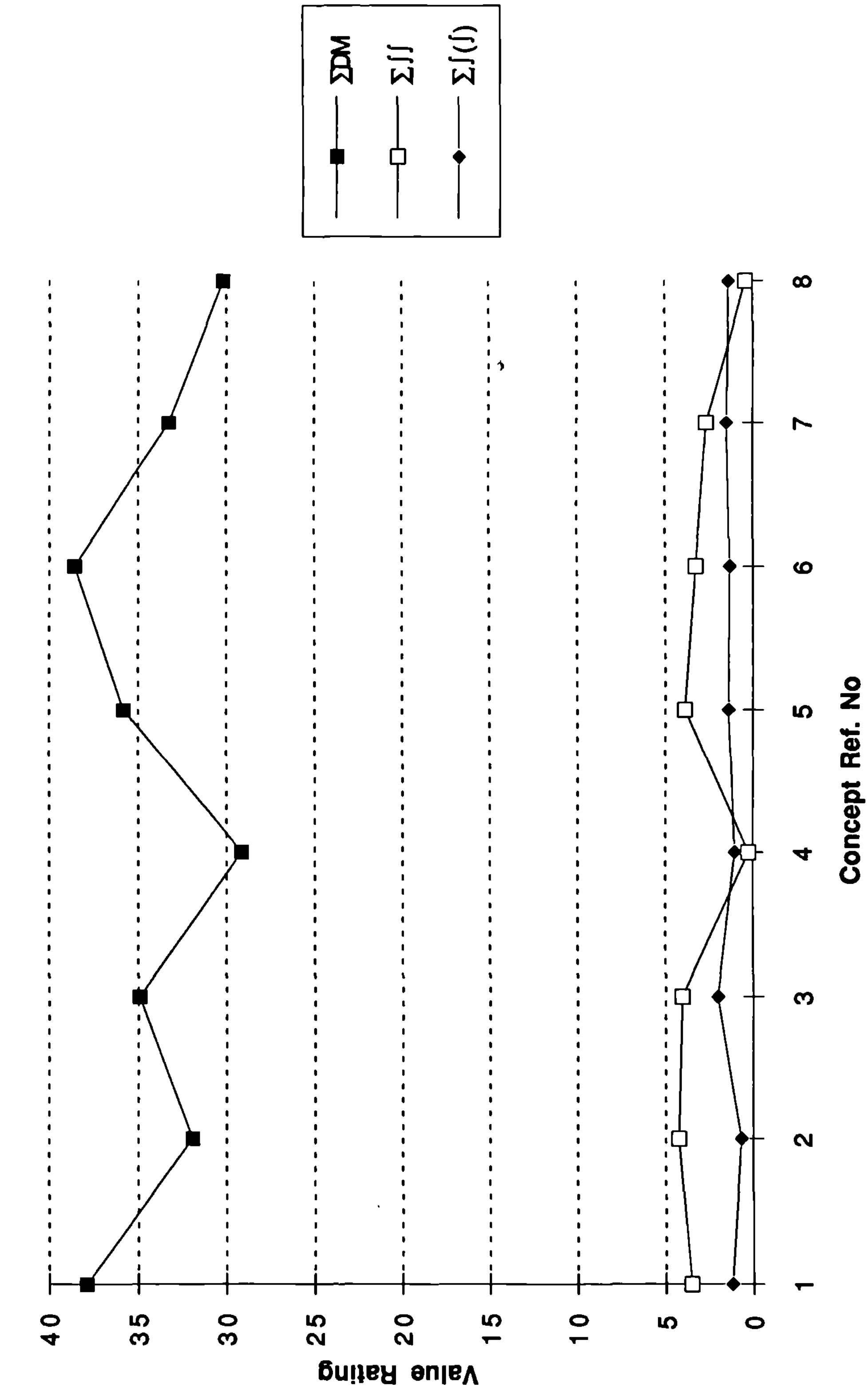


Fig. No. 5.13, CDEM Model Comparison, Experiment 2 (Expert Data Only)

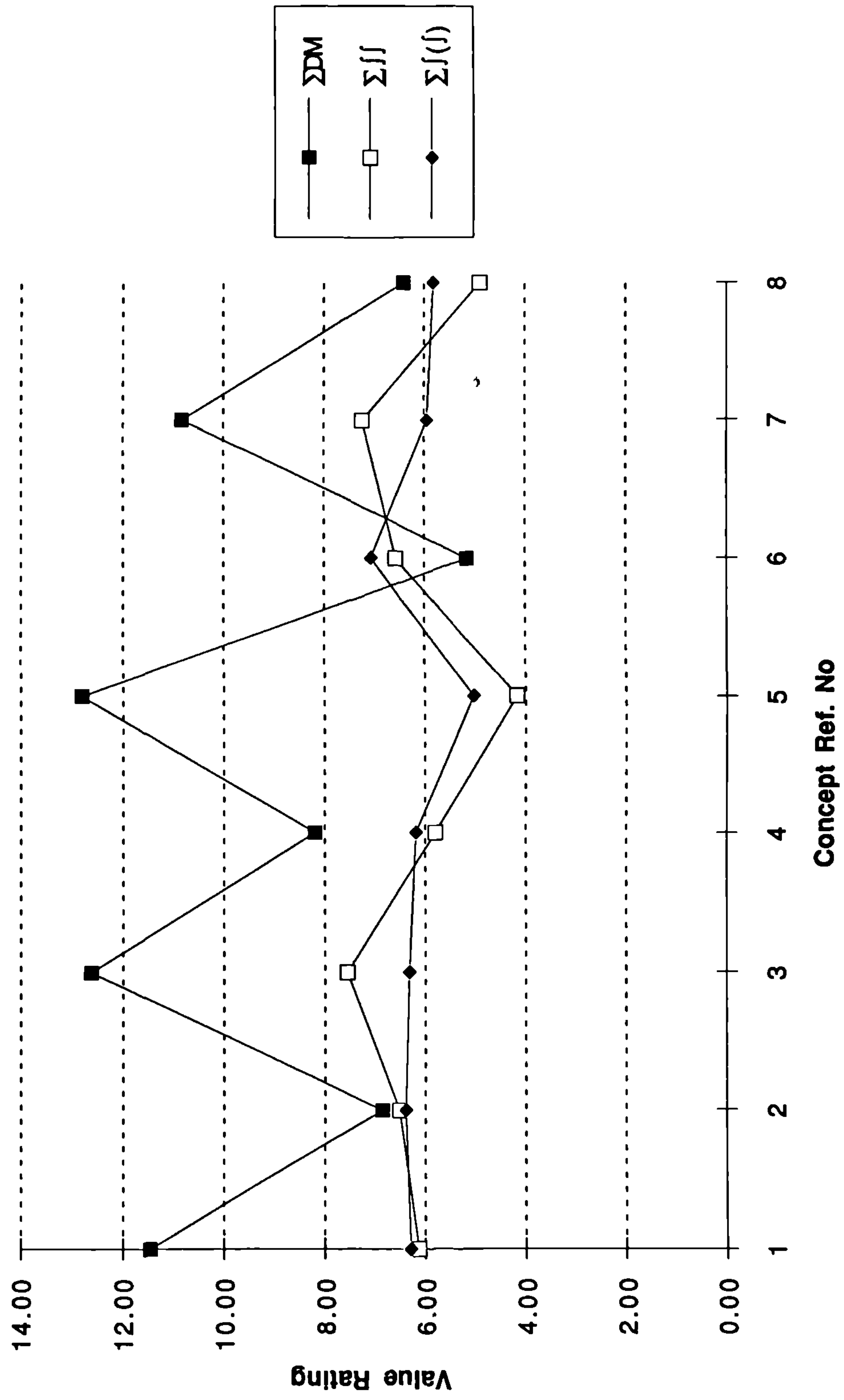


Fig. No. 5.14, CDEM Model Comparison, Experiment 2 (Novice Data Only)

- There is also an indication that the $\Sigma\int(\int)$ model is less sensitive when compared with both the ΣDM and $\Sigma\int\int$ models [Fig. No. 5.13 and 5.14].

Once more some tentative conclusions may be drawn from the above observations:

- As the number of concept options increases the lack of a structured approach within the novice subjects leads to a divergence of declared preferences. Perhaps their lack of confidence also prevents them from going too far towards their own design ideas?

- At the design characteristic level, the novice judgement when used in conjunction with the CDFR models continues, though to a slightly lesser extent, to match with expert data

- The question of the ability of subjects to remain objective in their assessments once they become personally involved in the creation of options is shown, particularly by the experts, to be of concern. However, a recognition of this lack of objectivity supports the need for a conceptual design evaluation methodology which continues to highlight concepts worthy of development.

- The previous point also sheds some light on the underlying reason for the dichotomy of descriptive and prescriptive models of the design process. Simply, there appears to be a threshold, in terms of the number of criteria and conceptes, above which human evaluators can no longer maintain objectivity. Hence studies of the activities of designers show a tendency to focus on very few concepts that are developed by evolution. On the other hand prescriptive models advocate the generation of a large number of conceptual options which human evaluators cannot manageobjectively. This observation supports the hypothesis that evaluation methods are essential tools to allow designers to operate effectively with prescriptive design strategies..

Application of the Conceptual Design Solution Rating (CDSR) Models

In order to test the option of considering the developed CDFR models to be suitable to describe a Conceptual Design Solution, the models were modified using a simple Loss function. As can be seen from the results summarised in Table 5 and illustrated in Fig. Nos. 5.15 to 5.17, the modification does not affect the identification of those concepts with the greatest degree of match with their design specification

CDSR Models

Declared Preference	Novice	Expert
	2,1,6,7, 4 and 9	9
ΣDM.Loss	6 and 8	2,4 and 8
Σ∫∫.Loss	5 and 8	4 and 8
Σ∫(∫).Loss	5 and 8	2 and 4

Table 5.4, Summary of Results of CDSR Model Comparison (Concepts 1 to 9)

The Conceptual Design Solution Rating provides a comparitive quality measure that indicates the extent to which thecurrent state of a solution concept is meeting the requirements of the desired state. Ultimately this loss may be measurable in cost terms. That is the potential financial loss to society of a design solution not meeting the requirements defined for it. This loss may manifest itself in a number of ways:

- Sales targets not achieved
- Manufacturing costs higher than desired.
- Redesign costs incurred
- Excessive number of design changes made at the latter, more expensive, stages of the design process.
- Excessive development time

Conceptual Design Solution Rating (CDSR)
CDEM Model Comparison

Concepts	ΣʃʃLoss N&E	Novice ΣʃʃLoss	Exp ΣʃʃLoss	ΣDM.Loss N&E	Novice ΣDM.Loss	Exp ΣDM.Loss	Σʃ(ʃ).Loss N&E	Novice Σʃ(ʃ).Loss	Exp Σʃ(ʃ).Loss
1	7.28	3.90	3.11		13.48	167.90		4.40	0.51
2	4.29	4.21	4.04		5.58	126.00		3.81	0.24
3	7.12	6.68	3.26		20.21	167.40		4.64	0.74
4	4.01	3.62	0.02		6.05	141.90		4.13	0.35
5	2.73	2.01	3.38		17.34	164.00		3.13	0.67
6	5.06	4.24	2.51		2.59	173.40		4.66	0.65
7	8.62	6.55	2.11		17.52	164.40		4.24	0.47
8	4.12	2.74	0.05		4.70	143.30		3.65	0.41
9									
10									

Table 5.5, CDSR Model Comparison (Data)

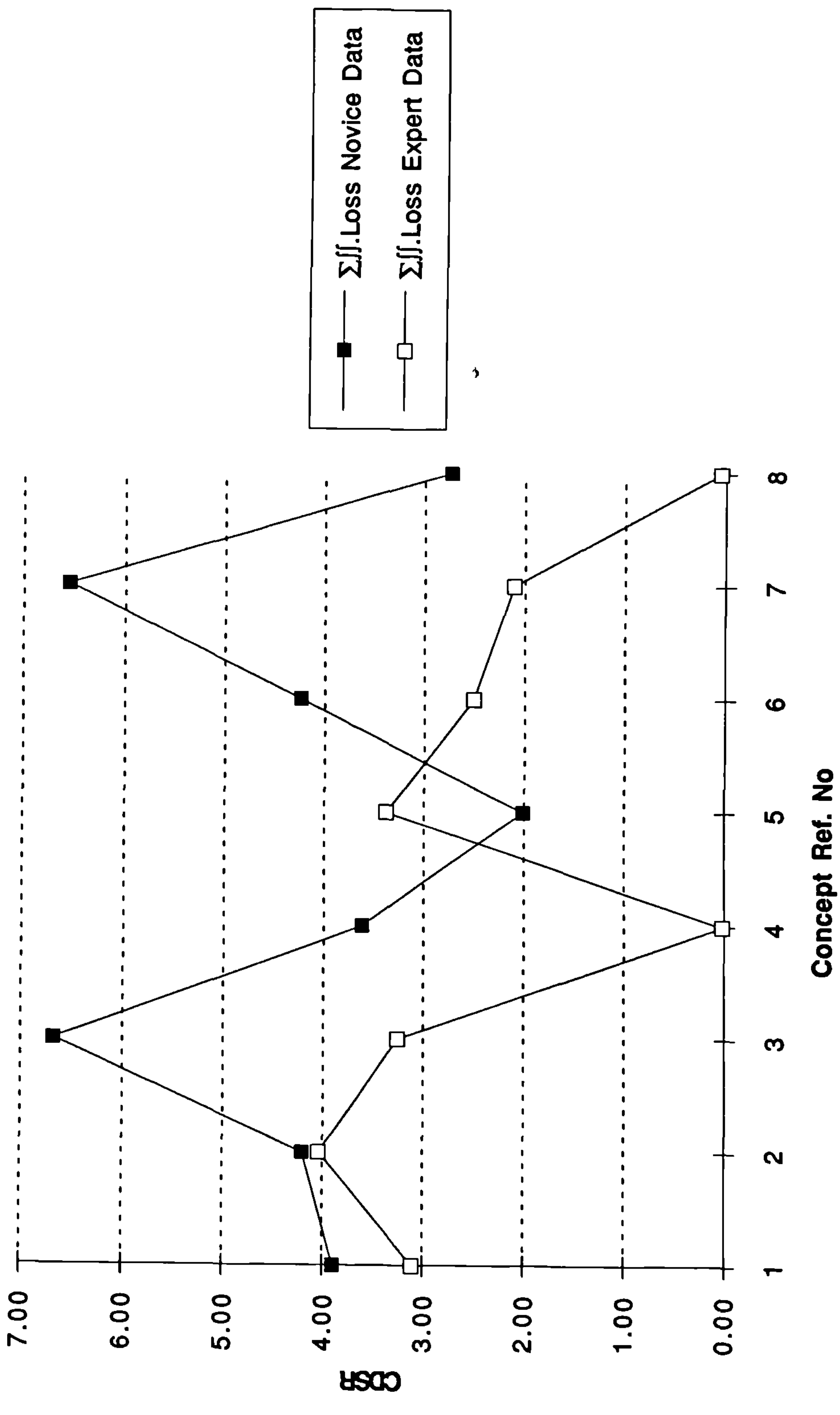


Fig. No.5.15, CDSR Model Comparison

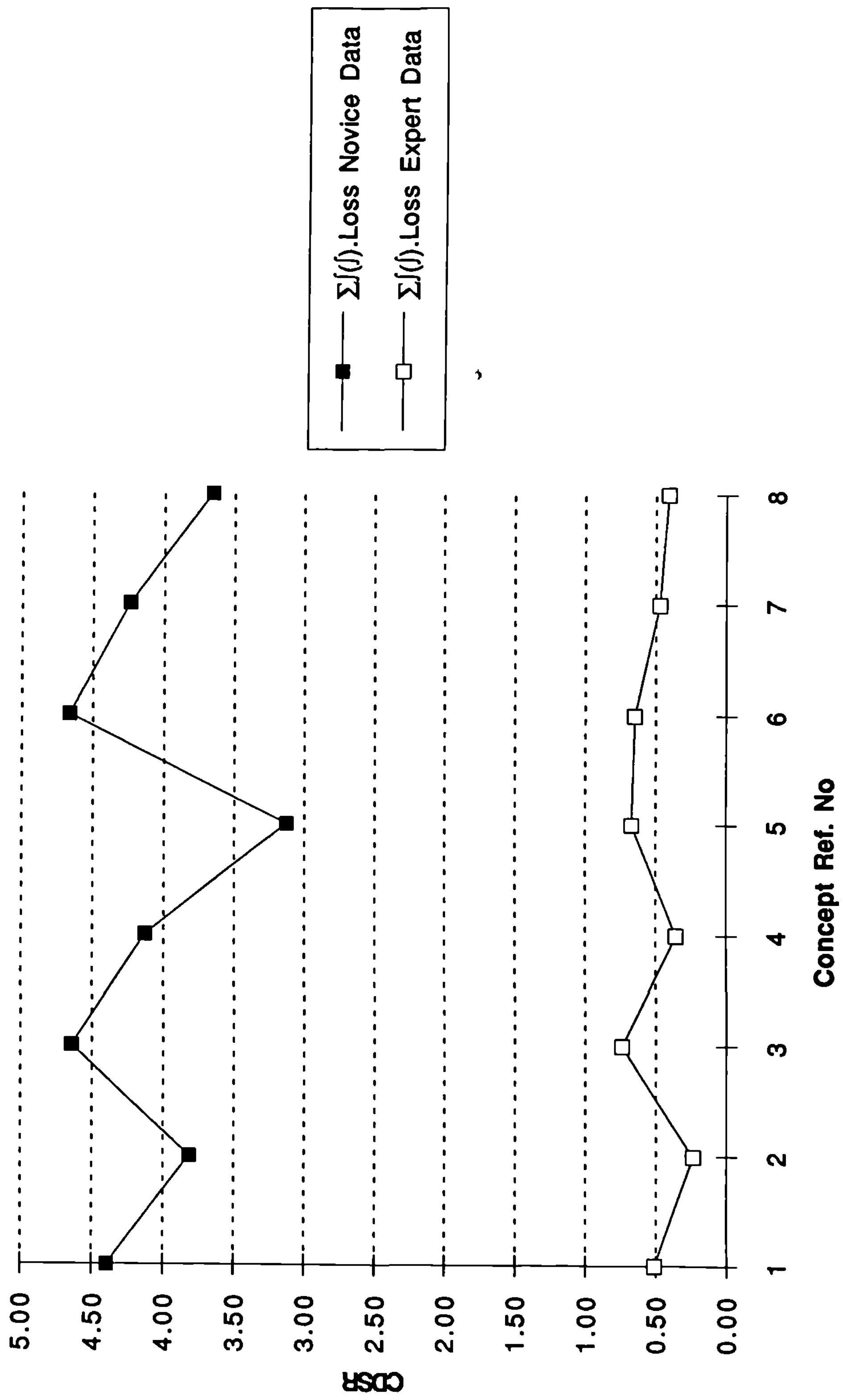


Fig. No. 5.16, CDSR Model Comparison

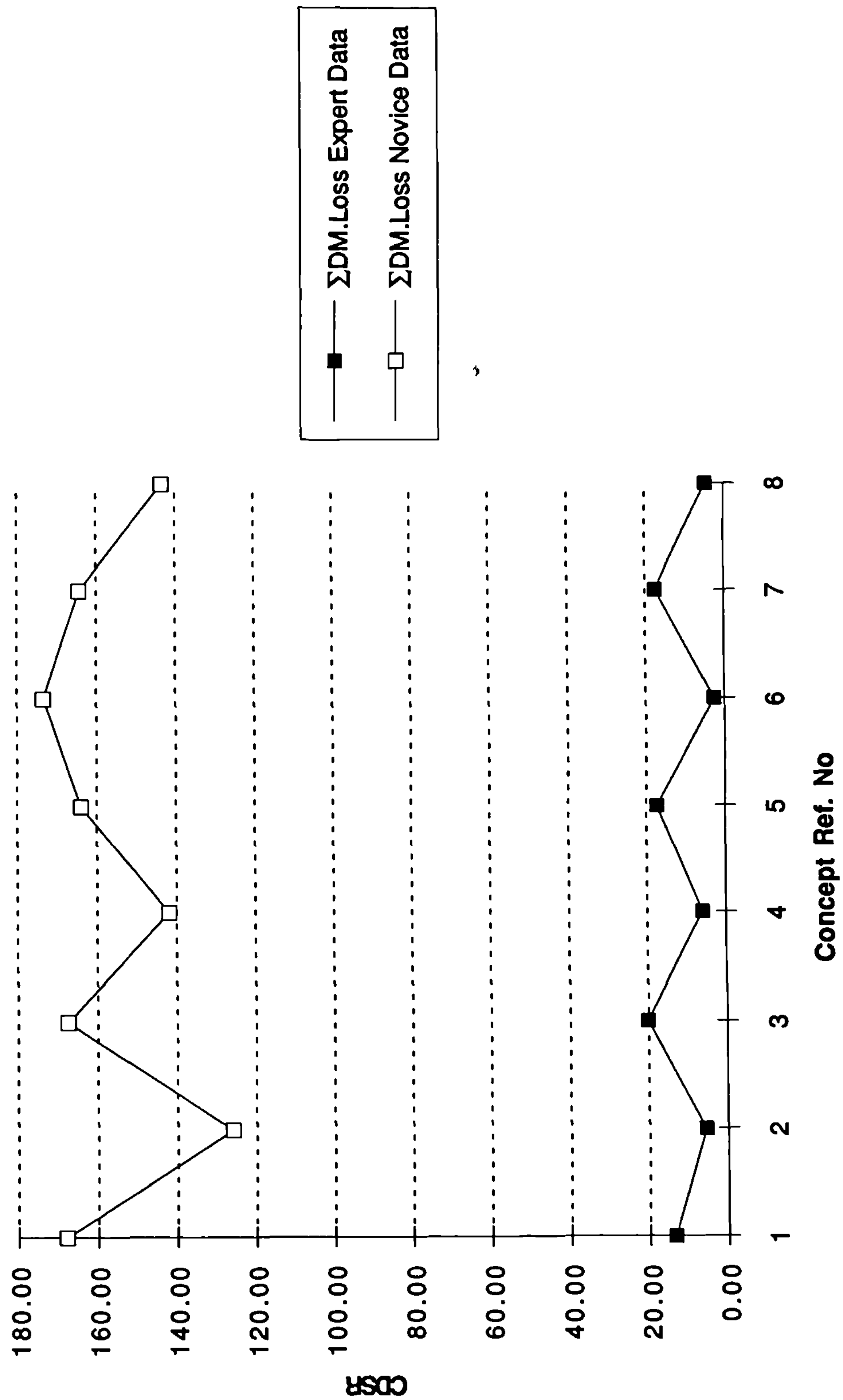


Fig. No. 5.17, CDSR Model Comparison

Chapter 6 *Conclusions and Recommendations for Future Work*

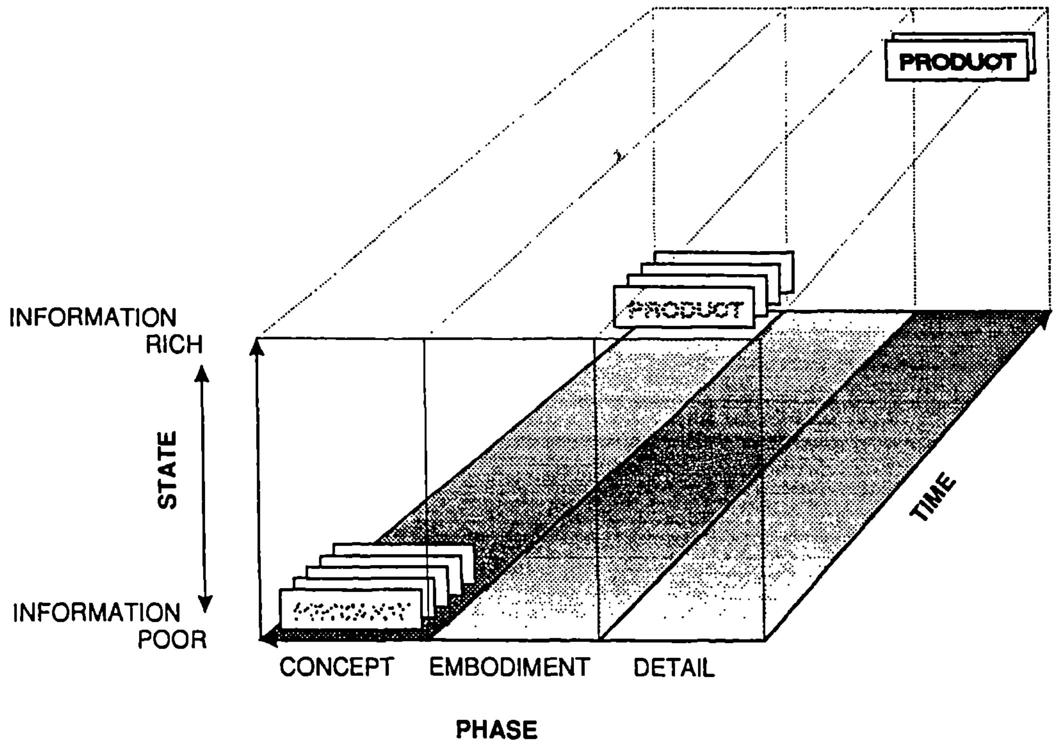
This thesis has attempted to report the results of a research project whose task was the investigation of the evaluation activity within the conceptual design phase of the engineering design process. The research has been guided by the working hypothesis stated in chapter 1, and reproduced below.

'A conceptual design evaluation method can be proposed which will enable the automatic evaluation of technologically innovative conceptual design options. In turn this will enable the mechanisms of innovation, assist in the reduction of design timescales, permit traceability of design decisions, and provide commercial success with the minimum of development time.'

The nature of design research and its current immaturity acts to blur the focus of any proposed research hypothesis. In a small way this research has sought to address some of the wider issues of design research in parallel with the main topic of investigation. For example, the experimental strategy adopted within this project is a significant departure from those previously employed. It is different in that it attempts to isolate a specific design activity rather than analyse the results of a complete design process and then try to draw conclusions about specific activities undertaken within the process. The questions that inevitably arise from this centre around the concern that through isolation of an activity one obtains a different response from the subjects than would otherwise be the case. It is, however, difficult to see how design research can usefully progress without ideas being tested to provide at least an indication of efficacy before advocating the application of any such technique within an industrial environment. Before designers adopt any new technique they need to be sure that it is going to provide a tangible benefit. It is the author's belief that design researchers to date have avoided this issue not because they don't agree with it but rather that they have become fixated with trying to solve the big problem without first solving the smaller ones. As stated in chapter 1, the traditional view has led to a proliferation of models of the design process whose benefit has not been and perhaps cannot be demonstrated. Equally, there is evidence that researchers have largely tended to develop their design process models in apparent ignorance of developments elsewhere. The result has been that the common issues have not been sufficiently emphasised and that consequently research activity has become diffused with no clear research strategy developing. The big question that needs to be faced by design researchers is how can one demonstrate that adopting any particular approach, process, method or whatever will provide a better or more appropriate design outcome This thesis is hopefully a small step in addressing this issue.

The conclusions from chapter 2 itemise the perceived requirements of design evaluation activity which appear to be commonly expected to be employed within the process models reviewed. It was important that this investigation was able to re-examine the need for evaluation activity and to build upon the expectations of established and emerging design process models A review of current evaluation models, chapter 3, highlighted the lack of any particular method which could by itself meet the expected requirements. This observation highlighted what may be a further shortcoming in design research strategy adopted to date. That is, to view design methods as being static rather than dynamic tools to be employed at various phases within the design process and to be adaptable to deal with the changes of state of the product of the design process. To achieve this dynamic quality requires that a clear view is maintained of the phase-state relationships within the design process. The Conceptual Design Evaluation Methodology (CDEM) developed within this thesis (Chapter 4) seeks to achieve this clear view. It does this by being comprised of a number of features from individual methods currently recognised in the literature that are seen to be appropriate for application within the conceptual phase. So, if the phase-state approach is adopted then one would expect that the mix of techniques may well change as the state of the design changes and progresses through each design phase. This idea is graphically represented in Fig. 6.1. Equally within each phase it may be appropriate for the methodology to be modifiable in order to reflect a particular focus adopted by the designers. For example, one particular mutation of a methodology may highlight innovative ideas with potential while others may more readily reflect a low risk idea. This particular issue was revealed whilst testing the

PHASE - STATE - ACTIVITY MODEL



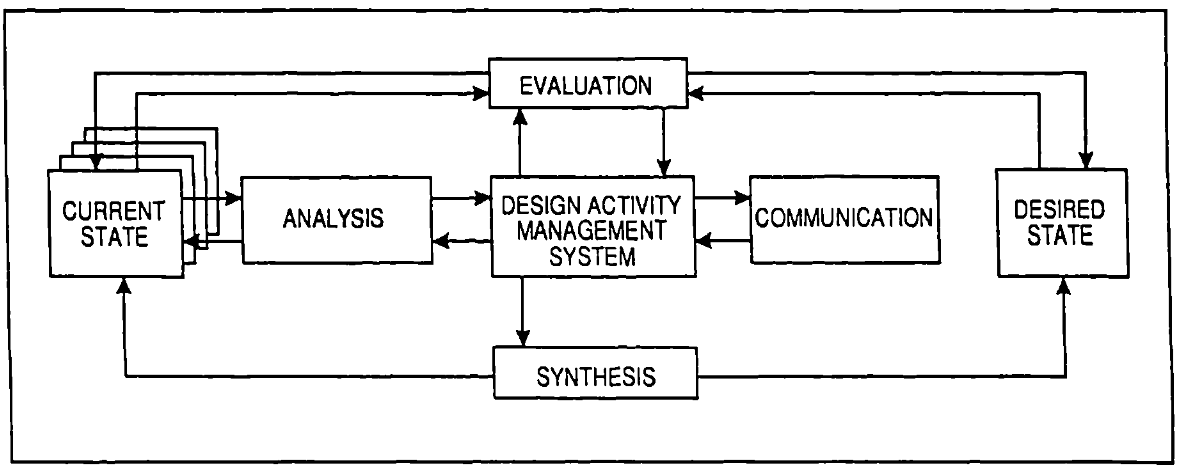


Fig. No. 6.1

CDEM approach within a controlled design experiment (Chapter 5). All the model variations tested were able to parallel the declared preference of experienced designers thus securing the validity of the methodology, at least within the limited subject group available. Each model variant was able not only to reflect experienced views to a limited degree but was also able to highlight those ideas with potential and which may otherwise be lost.

A further advantage cited for CDEM is its inherent capacity for traceable decision making and design tool effectiveness assessment. This has never been available before or substantially addressed within the literature. With the adoption of concurrent engineering philosophy comes the need to be able to more effectively select the design methods and tools well in advance of the design activity in order to meet the needs of the design strategy. This selection can only be done with confidence if past experience of their application can be effectively assessed. The traceability feature of CDEM is a step towards providing this facility.

The limitations of the experimental environment have already been discussed with the main concern being over the lack of opportunity to ensure the reliability of the methodology. This requires further controlled testing with different subjects with varying experience.(see recommendations for future work). A further point to be noted, with hindsight, is that it would have been better to further control the experiment by limiting the response of the subjects to a psychometric scale only, adopting the findings of Hyde and Stauffer [1990]. This would permit more straightforward data collection and handling, a factor that will be increasingly important if increased numbers of subjects were to be tested. Once again, however, it would be important for the methodology to maintain its flexibility in this regard since as information about the design increased it may become advantageous to modify the value rating scales accordingly thus perhaps moving from a psychometric scale to a unit scale as the design moves from the conceptual into the embodiment phase. It would also have been informative to be able to include the various evaluation methods, cited in the literature and reviewed in chapter 3, in the experimental programme thus providing for the first time a comparative measure of all the methods available to the designer. A difficulty with this approach is the diversity of format demanded of the judgmental information.

In light of the above conclusions it is appropriate that the working hypothesis be modified to reflect the actual deliverables of this research project:

'A Conceptual Design Evaluation Methodology can be proposed that can contribute towards the development of computer-based evaluation of technologically innovative conceptual design options. The methodology should be able to reflect the designers preference while highlighting other options with developmental potential. and be flexible to the point of providing variant methodologies for further application within other phases of the design process reflecting the needs of the design strategy.'

Recommendations for future work in developing CDEM.

Step 2 of the CDEM indicates that a way to obtain information about a concept is to use Case-Based reasoning to project the concept forward in time such that it can be compared with known tried and tested design solutions that are similar in some way to the concept and therefore can provide data regarding the possible values that might be attributed to certain design characteristics.

This is all very well, but how are the cases to be identified and what mechanisms can be used to search for and select these cases?

According to Umeda [1992], designs may be compared against three interactive headings:

- Functional
- Behavioural
- Structure

It is possible to classify the individual design characteristics under these headings and graph their interaction and interdependence.

The resulting interdependence graph could provide a mechanism for search within a database of known design solutions. The degree of match of graphs will of course vary as will the number. However this may provide the potential for retrieval of a distribution of potential values for a particular design characteristic. This distribution can be used in the CDFR equation.

This approach would effectively utilise an amalgam of the following reasoning methods:

- Case-based reasoning
- Model-based reasoning
- Characteristic-based reasoning

A similar approach is of course used to initially identifying the target values for a design in the Quality Function Deployment (QFD) method. A further interesting point is that the same approach may be adopted as a data gathering tool for the creation of the supporting database.

The above approach has many advantages among which is the possibility of having enhanced traceability of design decision making since each step of the approach is transparent.

Although this research has attempted to develop a methodology that has the potential for implementation within a computer environment it has not been possible, given time and resources available, to take the next step towards linking it with a CAD/Database capability. It is envisaged that this linking would provide the possibility of a designer creating a number of variant designs and for these to be analysed using the extended version of CDEM initially in the form of an interactive spreadsheet. Ideas on techniques that might be employed to enable this linking are given in the previous section.

Implications for future design research

Not only are there specific conclusions to be drawn from the results of the research described in this thesis, there are also implications for future generic design research activity that can be highlighted. Prominent among these implications is the identification and selection of appropriate design research methods. Two specific issues have been identified:

- The role of decomposition of the design activity as an aid to design research.
- The role of experimental design research techniques.

Much emphasis continues to be placed on researching the design process as a whole utilising methods such as protocol analysis (Ehrlenspiel and Dylla 1993). However, to date, this 'total' approach has led mainly to a proliferation of descriptive design process models that are neither subsequently tested, validated or integrated into any coherent design system. This, in part, must be due to the complexity of the task. An improved understanding of the strategies used in design has emerged but a demonstrable improvement of the design output from the application of such strategies is missing. Decomposition of the design process into researchable elements is an important precursor to the objective of ensuring the testing, validity and reliability of design hypotheses. Simply the separation of the design process into readily observable elements will lead to an enhanced fundamental understanding of the underlying mechanisms influencing design outcomes. These more manageable elements also enable testing of a design hypothesis across a wider range of design environments. Only by this rigorous testing will the validity and reliability, of the hypothesis, be assured However, the obvious difficulty, arising from the strategy of decomposition, is the need for eventual recomposition. The concern here is whether the combination of a number of separate but validated elements will naturally recombine into a coherent and effective design process. This is a genuine concern but one which could be effectively addressed if the design research community were to agree a coherent design research strategy based upon a accepted framework for design, perhaps of the type established for the

SERC funded Engineering Design Research Centre (EDRC). Such a framework for design would need to be dynamic and to be capable of developing in parallel with the results of the research activity that it seeks to guide. Given time an increasingly robust design framework could evolve and provide a sound foundation for the emergence of a design science.

As previously stated, both the validity and reliability of any design hypothesis can only be secured via rigorous testing within a controlled experimental environment. Once again this requirement provides the design research community with substantial challenges. The experimental approach, described in Chapter 5 of this thesis, is widely used due to the availability of willing human subjects with the time and enthusiasm to endure the rigour of the experimental process. Transferring such an approach to an industrially based environment is both potentially extremely expensive and fraught with the dangers of lack of control of the experimental conditions. However, if design research is to grow then these difficulties must be overcome. Equally increasing efforts could be made in developing computer based experimental environments that can initially be used to test well defined design hypotheses but which may develop in the future to permit the testing of substantial activities associated with the design process.

Implications for future design practice and strategy

It is the author's view that not only is it a requirement of design research to providing increasing understanding of the underlying mechanisms influencing the quality of the outcome of the design process but it is also necessary to ensure that the factors influencing the adoption of any new design method ,or strategy, are addressed. Professional designers will only adopt a new method if it is either going to save them time or if it is demonstrably going to improve the quality of the output of the design process. To meet both these demands may require a cultural change from professional designers. This is implied in the specific conclusions resulting from the research described above. In the future the designer will be required to view design methods not as static but rather as being dynamic in nature with a need to clearly match the design state and the design process phase (Fig. 6.1). Inevitably this leads to a need to also match the method mix to the adopted design strategy. This is not the intuitive approach to design as revealed in descriptive design process models. However it is a consequence of the requirements for improved design outcomes as revealed within prescriptive models of the design process. Equally the implications for the development of a robust concurrent design strategy are significant in that it is essential that any such strategy take account of the increasing flexibility and proficiency required in successfully matching design phase, design state, design activity and design method within an overall design strategy. There is therefore a need to move towards a better representation of the integration of previously separate descriptive and prescriptive models of the design process.

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Appendix A

Experimental Investigation of the Evaluation Activity within the Conceptual Design Phase of the Engineering Design Process.

G.Green

Dear Colleague/Student,

Thank you for agreeing to take part in the following controlled artificial design experiment which forms an essential part of the above design research project.
You should spend **2 hours or less** on this activity.

The design experiment consists of two related parts, as follows:

Experiment. 1
In this part of the experiment five conceptual designs of a horn for a motor-car are given along with their related Product Design Specification and a brief written description of each concept.

You are required to examine each concept and then complete all the sections of the Standard Record Sheets for Exp. 1 with reference to the following notes:

- State briefly your design experience in section 'Subject Exp.'

- Complete the first three columns, (entitled - Design Characteristic (DC), Design Characteristic Units (DCU) and Design Characteristic Target Value (DCT)) primarily using data given in the Product Design Specification. An example of how the record sheet is to be completed is given below. This example also seeks to further clarify the terminology used.

Terminology:
Design Characteristic (DC): is a recognisable feature that the proposed design must ultimately possess.(e.g Cost)
Design Characteristic Units (DCU): are the units used to measure the characteristic. (e.g £)
Design Characteristic Target(DCT): is the desired absolute value or value range that must be ultimately achieved by the proposed design. (e.g £10)
Design Characteristic Estimate (DCE): is the value, or value range, that you judged the proposed design currently possesses or will ultimately possess. (e.g £11 or £8 - £12)

- You may add other Design Characteristics you judge to be appropriate but do not exceed the number of rows given in the record sheet.

- If you consider that you can't enter a value for any particular Design Characteristic then please use a five point scale, where 5 = excellent and 1 = poor. Once again, the example provided will help to explain how this scale may be applied.

Experimental Investigation of the Evaluation Activity within the Conceptual Design Phase of the Engineering Design Process.

G.Green

Example

EXP 1 **STD. RECORD SHEET** *G. Green* SHT. 1

GROUP NO. 1

DATE 20.4.93

SUBJECT AGE 19 20 19

TIME 14·00 – 16·00

SUBJECT EXP. 2ND YEAR MECHANICAL ENGINEERING STUDENTS.

PART 1

DESIGN CHARACTERISTIC (DC)	DC UNITS (DCU)	DC TARGET VALUE (DCT)	DC ESTIMATED VALUE (DCE) — CONCEPT REF. NOs 1	2	3	4	5	6	7	8	9	10
COST	£	MIN.	10	9	8	7	6					
WEIGHT	N	≤ 5	8	7	3	3/4	3					
SIZE	—	1 — 5	2	3	4	3	2					
NOISE LEVEL	dBA	105 – 125	125	150	120	80	90					
MANUFACTURE	—	1 — 5	3	5	4	3	2					
MAINTENANCE	—	1 — 5	2	4	5	1	3					
COMPLEXITY	—	1 — 5	1	4	3	2	4					
RELIABILITY	—	1 — 5	5	5	4	2	3					

PART 2

Indicate concept which, in your opinion, most clearly meets the requirements of the P.D.S.

ENTER CONCEPT No. #

State, briefly, why you believe that this concept most clearly meets the requirements of the P.D.S.

Because it . . . .

Experimental Investigation of the Evaluation Activity within the Conceptual Design Phase of the Engineering Design Process.

G.Green

Experiment. 2

In this part of the design experiment you are required to generate your own conceptual design solution to the Product Design Specification for the motor-car horn. It should be drawn to the same level of detail, and be given a brief description, as the concepts given in Exp. 1 You should also assign the following Concept Reference Numbers to your own design **(9)**.
You will next be given a further three concepts which will have the Concept Reference Numbers 6,7,and 8.
You should now have nine conceptual designs with number 9 being generated by yourself.

Next, the process undertaken in Exp.1 should now be repeated and the results added to the Exp. 2 Standard Record Sheet (2 of 5). Complete the other sections of this sheet as before but give particular attention to **Part 2** of this sheet.

Next, move on to Standard Record Sheet (Sht. 3 of 5) and (Sht. 4 of 5). Complete the top section of the sheet as before and then complete Section 3 as directed. Your modified Concept should now be given the Reference Number 10.

Next, move to Sht 5 of 5 and complete all parts as before. Note once again that Concepts number 9 and 10 are your own initial concept idea and the modified version of your selected concept respectively.

The experiment is now complete, please ensure you return all documents to the researcher concerned.

Thank You For Your Help

Experimental Investigation of the Evaluation Activity within the Conceptual Design Phase of the Engineering Design Process.

G.Green

Product Design Specification

Background:
The product being designed against the following Product Design Specification is to be manufactured by a major supplier to the UK car manufacturing industry (e.g Lucas)

- To capable of being applied to all types of modern motor-car
- To be appropriate for mass production.
- To be able to produce noise level between 105-125 dBA.
- To be able to produce noise at frequency between 2 - 5kHz.
- To be easily installed
- To be easily maintained
- To weigh no more than 5N, ideally to be minimised.
- To be resistant to corrosion and water.
- To be resistant to extremes of temperature.
- To be resistant to vibration, shock and acceleration.
- Minimum overall dimensions preferred.
- To exhibit a life in service of no less than four years.
- Minimum manufacturing cost preferred.
- Number of parts to be minimised.
- Power consumption to be minimised.
- To have minimum response time.
- To be maintenance free within defined life in service.

Concept Descriptions

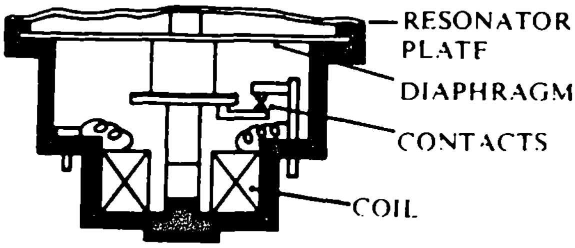
1. Electromagnetic diaphragm: the diaphragm is attached to the vibrating shaft driven by a rapidly changing magnetic field thereby creating noise.

2. Aeroacoustic horn: high speed rotary vanes force air out through nozzles producing noise.

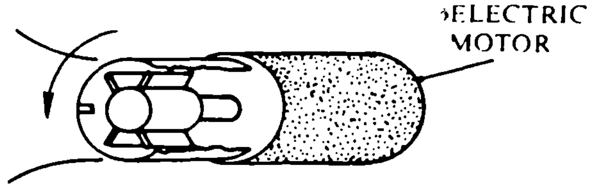
3. Tape driven horn: recorded impulses on electromagnetic tape are picked up, amplified and broadcast.

4. Wire and toothed wheel: teeth on the wheel pluck the taut wire in rapid succession producing monotonic noise.

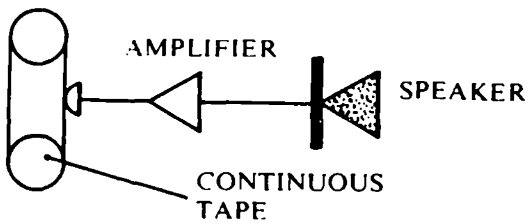
5. Rubber bulb: solenoid is magnetised and demagnetised alternately. Magnetic core moved up and down compressing and releasing the bulb to force air through reeds to produce noise.


RESONATOR PLATE
DIAPHRAGM
CONTACTS
COIL

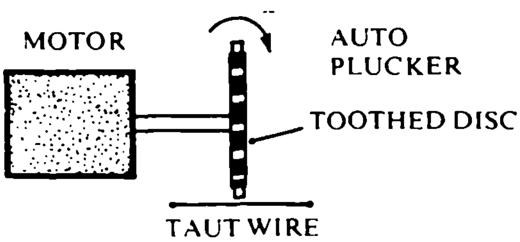
1


ELECTRIC MOTOR

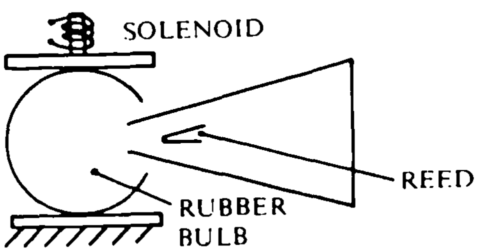
2


AMPLIFIER
SPEAKER
CONTINUOUS TAPE

3


MOTOR
AUTO PLUCKER
TOOTHED DISC
TAUT WIRE

4


SOLENOID
REED
RUBBER BULB

5

G. Green
SHT. 1

EXP 1 **STD. RECORD SHEET**

GROUP NO. DATE

SUBJECT AGE TIME

SUBJECT EXP.

PART 1

DESIGN CHARACTERISTIC (DC)	DC UNITS (DCU)	DC TARGET VALUE (DCT)	DC ESTIMATED VALUE (DCE)									
			CONCEPT REF. NOs									
			1	2	3	4	5	6	7	8	9	10

PART 2

Indicate concept which, in your opinion, most clearly meets the requirements of the P.D.S.

ENTER CONCEPT No.

State, briefly, why you believe that this concept most clearly meets the requirements of the P.D.S.

EXP 2 **STD. RECORD SHEET** *G. Green* SHT. 1 of 5

GROUP NO.		DATE	
SUBJECT AGE		TIME	
SUBJECT SEX		LOC'N	
SUBJECT EXP.			

SECTION 1

Each Group should produce a Conceptual Design Solution to the P.D.S. given and communicate the solution within the format specified and within the boundaries of the following box:

CONCEPT REF. No.

SECTION 2

Initial evaluation of the above concept using the approach used on EXP.1 and outlined on the following page.

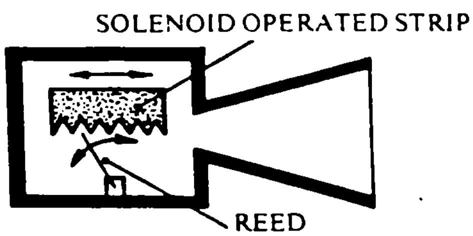
cont'd

Concept Descriptions (cont'd)

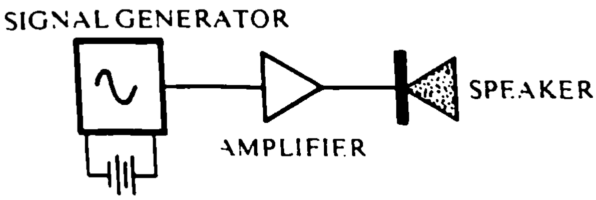
6. Reed: to an fro motion of the rack plucks the reed to produce noise.

7. Signal Generator: signal is produced by the signal generator, amplified and broadcast.

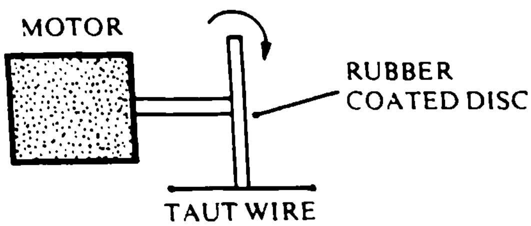
8. Wire and Disc: motor-driven rubber-coated disc continuously rubs against a taut wire to produce noise.



6



7



8

EXP 2
Section 2 (cont'd)

STD. RECORD SHEET

G. Green
SHT. 2 of 5

GROUP NO. | DATE
SUBJECT AGE | TIME
SUBJECT SEX | LOC'N
SUBJECT EXP.

PART 1

DESIGN CHARACTERISTIC (DC)	DC UNITS (DCU)	DC TARGET VALUE (DCT)	DC ESTIMATED VALUE (DCE) CONCEPT REF. NOs									
			1	2	3	4	5	6	7	8	9	10

PART 2

Indicate concept which, in your opinion, most clearly meets the requirements of the P.D.S.

ENTER CONCEPT No.

State, briefly, why you believe that this concept most clearly meets the requirements of the P.D.S.

G. Green
SHT. 3 of 5

EXP 2 **STD. RECORD SHEET**

GROUP NO. [ ] DATE [ ]

SUBJECT AGE [ ] [ ] [ ] TIME [ ]

SUBJECT SEX [ ] [ ] [ ] LOC'N [ ]

SUBJECT EXP. [ ]

SECTION 3

CONCEPT REF. No. [ ]

Suggest how your selected concept may be modified in order to beneficially alter the percieved value of a particular design characteristic. Re-draw the concept, with your changes incorporated, within the format specified and within the boundaries of the following box:

MODIFIED CONCEPT REF. No. [ ]

cont'd

EXP 2 STD. RECORD SHEET *G. Green* SHT. 4 of 5

SECTION 3 Cont'd

Summarise, in the following box, the analysis (if any) undertaken either to
a) support your modification or
b) to obtain more information about the design characteristic being addressed

A/.

B/.

EXP 2

SECTION 4

STD. RECORD SHEET

G. Green
SHT. 5 of 5

GROUP NO. | DATE

SUBJECT AGE | TIME

SUBJECT EXP.

PART 1

DESIGN CHARACTERISTIC (DC)	DC UNITS (DCU)	DC TARGET VALUE (DCT)	DC ESTIMATED VALUE (DCE)									
			CONCEPT REF. NOs									
			1	2	3	4	5	6	7	8	9	10

PART 2

Indicate concept which, in your opinion, most clearly meets the requirements of the P.D.S.

ENTER CONCEPT No.

State, briefly, why you believe that this concept most clearly meets the requirements of the P.D.S.

EXP 2

SECTION 4

STD. RECORD SHEET

G. Green
SHT. 5 of 5

GROUP NO. SAFA

DATE 29.4.93.

SUBJECT AGE 38

TIME 11 30 AM.

SUBJECT EXP. PROF. ENG.
MECH. DES OF ONE-OFF HEAVY ENG. EQPT.

PART 1

DESIGN CHARACTERISTIC (DC)	DC UNITS (DCU)	DC TARGET VALUE (DCT)	DC ESTIMATED VALUE (DCE) CONCEPT REF. NOs 1	2	3	4	5	6	7	8	9	10
FLEXIBILITY	–	1–5	3	3	4	3	4	2	4	3	5	3
COST	£	4	4	3	2	4	5	4	4	4	6	6
SIZE	–	1–5	2	3	4	4	3	2	4	3	3	5
NOISE LEVEL	dBA	105–125	120	110	100	110	120	125	115	105	120	110
RELIABILITY	–	1–5	4	3	3	3	3	4	3	3	3	4
WEIGHT	N	5	6	5	3	4	4	5	3	4	2	3
LIFE	YEARS	4	10	6	3.	4	4	8	4	4	4	5
SHOCK RESIST	g	10g	15g	10g	8g	10g	15g	15g	10g	15g	15g	20g
PRODUCTION	–	1–5	3	3	5	4	3	4	5	4	3	4
ANTI-THEFT	–	1–5	4	3	3	3	4	5	3	3	4	3

PART 2

Indicate concept which, in your opinion, most clearly meets the requirements of the P.D.S.

ENTER CONCEPT No. 10

State, briefly, why you believe that this concept most clearly meets the requirements of the P.D.S.

RELIABILITY, SHOCK RESISTANCE AND SMALL SIZE

Appendix B

Subject A. Data Analysis

Experiment No. **1** | **Subject Age** **22** | **Subject Experience** **Year 3 Engineering stude**

Design Characteristic (DC)	DC Units (DCU)	DC Target (DCT)	DC Estimated Value (DCE) – Concept Reference Numbers: 1	2	3	4	5	6	7	8	9	10
Cost	£	Minimise	10	8	9	6	7					
Weight	N	<5	4	4	3	3	3					
Size		1 to 5	3	5	1	2	4					
Noise Level	dBA	105-125	120	120	105	105	107					
Manufacture		1 to 5	2	4	1	5	3					
Maintenance		1 to 5	1	4	2	5	3					
Complexity		1 to 5	1	4	2	5	3					
Reliability		1 to 5	4	5	2	3	1					
Life in Service	Years	>4	9	10	5	4	7					
Power		1 to 5	2	4	3	5	1					
Response Time		1 to 5	5	3	2	1	4					
Durability		1 to 5	4	5	1	2	3					
Selected Concept												

Experiment No. 2A

Design Characteristic (DC)	DC Units (DCU)	DC Target (DCT)	1	2	3	4	5	6	7	8	9	10
Cost	£	Minimise	8	5	6	2	4	3	7	1	9	
Weight	N	<5	3	3	4	1	2	2	4	1	2.5	
Size		1 to 9	7	6	1	8	3	5	2	9	4	
Noise Level	dBA	105-125	110	120	105	105	107	105	110	105	115	
Manufacture		1 to 9	3	4	1	8	6	7	2	9	5	
Maintenance		1 to 9	3	7	1	8	5	6	2	9	4	
Complexity		1 to 9	1	4	2	9	7	6	3	8	5	
Reliability		1 to 9	5	9	3	7	1	4	2	6	8	
Life in Service	Years	>4	9	10	5	4	7	5	6	4	8	
Power		1 to 9	6	7	2	8	4	3	1	9	5	
Response Time		1 to 9	9	6	3	1	7	5	4	2	8	
Durability		1 to 9	8	9	1	4	5	6	2	3	7	
Selected Concept												

Experiment No. 2B

Design Characteristic (DC)	DC Units (DCU)	DC Target (DCT)	1	2	3	4	5	6	7	8	9	10
Cost	£	Minimise	9	6	7	2	4	3	8	1	10	5
Weight	N	<5	3	3	4	1	2	2	4	1	2.5	3
Size		1 to 10	8	7	1	9	3	5	2	10	4	6
Noise Level	dBA	105-125	120	120	105	105	107	105	110	105	115	115
Manufacture		1 to 10	3	4	1	9	7	8	2	10	5	6
Maintenance		1 to 10	3	7	1	9	5	6	2	10	4	8
Complexity		1 to 10	1	4	2	10	8	6	3	9	5	7
Reliability		1 to 10	5	10	3	2	1	4	2	6	8	4
Life in Service	Years	>4	8	9	5	4	7	5	6	4	8	10
Power		1 to 10	6	8	2	9	4	3	1	10	5	7
Response Time		1 to 10	10	6	2	1	7	5	4	2	9	8
Durability		1 to 10	8	9	1	4	5	6	2	3	7	10
Selected Concept												

Subject B Data Analysis

Experiment No.	**Subject Ages**	**Subject Experience**
1	**22,28,22**	**Year 4 Engineering students**

Design Characteristic (DC)	DC Units (DCU)	DC Target (DCT)	DC Estimated Value (DCE) Concept Reference Numbers 1	2	3	4	5	6	7	8	9	10
Cost	£	Minimise	6	5	10	4	2					
Weight	N	<5	4	3	3	2	1.5					
Size		1 to 5	3	5	1	4	2					
Noise Level		1 to 5	5	2	4	1	3					
Manufacture		1 to 5	1	5	2	4	3					
Maintenance		1 to 5	4	5	1	2	3					
Complexity		1 to 5	1	5	2	4	3					
Reliability		1 to 5	5	4	1	2	3					
Environment		1 to 5	5	4	2	3	1					
Response Time		1 to 5	5	3	1	2	4					
Selected Concept												

Experiment No. 2A

Cost	£	Minimise	6	5	10	4	2	7	6	4	5	
Weight	N	<5	4	3	3	2	1.5	2	3	2	3	
Size		1 to 10	5	9	1	8	4	2	6	7	3	
Noise Level	dBA	1 to 10	9	3	8	1	5	2	6	4	7	
Manufacture		1 to 10	1	7	2	5	4	3	8	6	9	
Maintenance		1 to 10	6	7	1	5	2	3	8	4	9	
Complexity		1 to 10	1	9	2	7	4	3	5	8	6	
Reliability		1 to 10	7	6	1	4	3	2	9	5	8	
Environmental		1 to 10	9	8	4	6	1	5	2	7	3	
Response Time		1 to 10	7	3	6	1	5	4	8	2	9	
Selected Concept												

Experiment No. 2B

Selected Concept												

Subject C Data Analysis

Experiment No.	**Subject Ages**	**Subject Experience**
1	**19,23,19**	**Year 2 Engineering students**

Design Characteristic (DC)	DC Units (DCU)	DC Target (DCT)	DC Estimated Value (DCE) Concept Reference Numbers 1	2	3	4	5	6	7	8	9	10
Cost	£	Minimise	8	6	10	4	3					
Weight	N	<5	4	2	5	2	3					
Size		1 to 5	4	3	2	3	5					
Noise Level		1 to 5	4	4	3	1	3					
Production		1 to 5	3	3	1	4	4					
Maintenance		1 to 5	4	4	1	4	4					
Simplicity		1 to 5	2	3	1	4	4					
Reliability		1 to 5	5	3	2	2	4					
Power Supply		1 to 5	5	5	5	5	5					
Compatability		1 to 5	4	4	4	4	4					
Selected Concept												

Experiment No. 2A

Design Characteristic (DC)	DC Units (DCU)	DC Target (DCT)	1	2	3	4	5	6	7	8	9	10
Cost	£	Minimise	8	6	10	4	3	8	10	5	6	
Weight	N	<5	4	2	5	2	3	3	2	2	2	
Size		1 to 5	4	3	2	3	5	3	1	3	4	
Noise Level		1 to 5	4	4	3	1	3	3	4	2	4	
Production		1 to 5	3	3	1	4	4	3	1	4	3	
Maintenance		1 to 5	4	4	1	4	4	4	2	3	4	
Simplicity		1 to 5	2	3	1	4	4	3	1	4	4	
Reliability		1 to 5	5	3	2	2	4	4	3	2	3	
Power Supply		1 to 5	5	5	5	5	5	5	5	5	5	
Compatability		1 to 5	4	4	4	4	4	4	4	4	4	
Selected Concept												

Experiment No. 2B

Design Characteristic (DC)	DC Units (DCU)	DC Target (DCT)	1	2	3	4	5	6	7	8	9	10
Cost	£	Minimise										
Weight	N	<5										
Size		1 to 10										
Noise Level	dBA	105-125										
Manufacture		1 to 10										
Maintenance		1 to 10										
Complexity		1 to 10										
Reliability		1 to 10										
Life in Service	Years	>4										
Power		1 to 10										
Response Time		1 to 10										
Durability		1 to 10										
Selected Concept												

Subject D Data Analysis

Experiment No. 1 **Subject Ages** **Subject Experience** **Year 2 Engineering students**

Design Characteristic (DC)	DC Units (DCU)	DC Target (DCT)	DC Estimated Value (DCE) / Concept Reference Numbers: 1	2	3	4	5	6	7	8	9	10
Portability		1 to 5	5	5	4	3	2					
Production		1 to 5	5	5	4	5	3					
Noise Level	dBA	105-125	105	120	80	60	50					
Installation		1 to 5	5	4	2	2	2					
Corrosion		1 to 5	5	5	3	2	2					
Weight	N	<5N	3.5	3	1	3	2					
Vibration		1 to 5	5	4	2	1	2					
Size	mm^3	10^3	300	600	200	400	>DCT					
Complexity		1 to 5	2	4	2	4	5					
Response Time		1 to 5	5	4	5	4	3					
Maintenance		1 to 5	5	5	5	3	2					
Cost	£	<£10	10	20	15	10	5					
Selected Concept												

Experiment No. 2A

Design Characteristic (DC)	DC Units (DCU)	DC Target (DCT)	1	2	3	4	5	6	7	8	9	10
Portability		1 to 5	5	5	4	3	2	5	4	3	5	
Production		1 to 5	5	5	4	5	3	5	4	4	5	
Noise Level	dBA	105-125	105	120	80	60	50	50	90	50	100	
Installation		1 to 5	5	4	2	2	2	5	2	2	5	
Corrosion		1 to 5	5	5	3	2	2	5	3	3	3	
Weight	N	<5N	3.5	3	1	3	2	2	2	3	>5	
Vibration		1 to 5	5	4	2	1	2	2	1	1	2	
Size	mm^3	10^3	300	600	200	400	>DCT	200	200	400	DCT	
Complexity		1 to 5	2	4	2	4	5	5	3	4	4	
Response Time		1 to 5	5	4	5	4	3	2	5	4	4	
Maintenance		1 to 5	5	5	5	3	2	3	4	3	3	
Cost	£	<£10	10	20	15	10	5	5	15	10	12	
Selected Concept												

Experiment No. 2B

Selected Concept												

Subject E Data Analysis

Experiment No.	**Subject Ages**	**Subject Experience**
1	**19,18,23**	**Year 1 Engineering students**

Design Characteristic (DC)	DC Units (DCU)	DC Target (DCT)	DC Estimated Value (DCE) — Concept Reference Numbers 1	2	3	4	5	6	7	8	9	10
Cost	£	Minimise	4	2	1	3	5					
Noise Level	dBA	105-125	4	5	3	1	2					
Weight	N	<5N	5	2	3	1	2					
Reliability		1 to 5	4	5	3	2	1					
Size		1 to 5	5	3	4	2	1					
Response Time		1 to 5	5	2	3	1	4					
Manufacture		1 to 5	3	4	2	1	5					
Complexity		1 to 5	4	2	1	3	5					
Installation		1 to 5	5	4	2	1	3					
Selected Concept			■									

Experiment No. 2A

DC	DCU	DCT	1	2	3	4	5	6	7	8	9	10
Cost	£	Minimise	4	2	1	3	5	3	1	2	4	
Noise Level	dBA	105-125	4	5	3	1	2	1	4	2	3	
Weight	N	<5N	5	2	3	1	2	3	2	1	4	
Reliability		1 to 5	4	5	3	2	1	1	3	2	4	
Size		1 to 5	5	3	4	2	1	1	4	3	2	
Response Time		1 to 5	5	2	3	1	4	2	4	1	3	
Manufacture		1 to 5	3	4	2	1	5	1	2	3	4	
Complexity		1 to 5	4	2	1	3	5	1	2	3	4	
Installation		1 to 5	5	4	2	1	3	4	2	1	3	
Selected Concept											■	

Experiment No. 2B

DC	DCU	DCT	1	2	3	4	5	6	7	8	9	10
Cost	£	Minimise	4	2	1	3	5	3	1	2	5	4
Noise Level	dBA	105-125	4	5	3	1	2	1	5	2	3	4
Weight	N	<5N	5	2	3	1	2	3	2	1	5	4
Reliability		1 to 5	4	5	3	2	1	1	3	2	4	5
Size		1 to 5	5	3	4	2	1	1	5	4	2	3
Response Time		1 to 5	5	2	3	1	4	2	4	1	3	3
Manufacture		1 to 5	3	4	2	1	5					
Complexity		1 to 5	4	2	1	3	5	1	2	3	4	4
Installation		1 to 5	5	4	2	1	3	5	2	1	3	4
Selected Concept			■									

Subject F Data Analysis

Experiment No.	**Subject Ages**	**Subject Experience**
1	**18,18,19**	**Year 1 Engineering students**

Design Characteristic (DC)	DC Units (DCU)	DC Target (DCT)	DC Estimated Value (DCE) — Concept Reference Numbers: 1	2	3	4	5	6	7	8	9	10
Cost		1 to 5	1	3	4	3	5					
Noise		1 to 5										
Frequency		1 to 5										
Response Time		1 to 5	5	1	4	5	1					
Wearability		1 to 5	5	4	2	3	1					
Installation		1 to 5										
Maintenance		1 to 5	5	4	2	3	1					
Weight		1 to 5	2	1	3	2	4					
Manufacture		1 to 5	1	3	2	3	3					
Power		1 to 5	4	1	3	1	2					
Size		1 to 5										
Selected Concept												

Experiment No. 2A

Design Characteristic (DC)	DC Units (DCU)	DC Target (DCT)	1	2	3	4	5	6	7	8	9	10
Cost		1 to 5	1	3	4	3	5	3	3	4	3	
Noise		1 to 5							5		5	
Frequency		1 to 5							5		5	
Response Time		1 to 5	5	1	4	5	1	4	5	3	5	
Wearability		1 to 5	5	4	2	3	1	1	5	1	5	
Installation		1 to 5										
Maintenance		1 to 5	5	4	2	3	1	1	5	1	5	
Weight		1 to 5	2	1	3	2	4	3	2	3	2	
Manufacture		1 to 5	1	3	2	3	3	2	4	4	4	
Power		1 to 5	4	1	3	1	2	4	4	2	4	
Size		1 to 5										
Selected Concept											■	

Experiment No. 2B

Design Characteristic (DC)	DC Units (DCU)	DC Target (DCT)	1	2	3	4	5	6	7	8	9	10
Cost		1 to 5	1	3	4	3	5	3	3	4	3	
Noise		1 to 5							5		5	
Frequency		1 to 5							5		5	
Response Time		1 to 5	5	1	4	5	1	4	5	3	5	
Wearability		1 to 5	5	4	2	3	1	1	5	1	5	
Installation		1 to 5										
Maintenance		1 to 5	5	4	2	3	1	1	5	1	5	
Weight		1 to 5	2	1	3	2	4	3	2	3	2	
Manufacture		1 to 5	1	3	2	3	3	2	4	4	4	
Power		1 to 5	4	1	3	1	2	4	4	2	4	
Size		1 to 5										
Selected Concept											■	

Subject G Data Analysis

Experiment No.	**Subject Ages**	**Subject Experience**
1	**18,18,18**	**Year 1 Engineering students**

Design Characteristic (DC)	DC Units (DCU)	DC Target (DCT)	DC Estimated Value (DCE) – Concept Reference Numbers 1	2	3	4	5	6	7	8	9	10
Noise Level	dBA	105-125	125	150	120	80	90					
Installation		1 to 5	3	5	2	4	1					
Weight	N	<5	1	2	5	4	3					
Corrosion		1 to 5	5	4	3	2	1					
Size		1 to 5	1	3	4	5	2					
Reliability		1 to 5	3	4	5	2	1					
Cost	£	Minimise	1	2	3	4	5					
Complexity		1 to 5	1	5	4	3	2					
Selected Concept				■								

Experiment No. 2A

Design Characteristic (DC)	DC Units (DCU)	DC Target (DCT)	1	2	3	4	5	6	7	8	9	10
Noise Level	dBA	105-125	125	150	120	80	90	110	115	120	125	
Installation		1 to 5	3	5	2	4	1	5	2	4	3	
Weight	N	<5	1	2	5	4	3	4	3	2	5	
Corrosion		1 to 5	5	4	3	2	1	3	4	2	5	
Size		1 to 5	1	3	4	5	2	3	5	4	2	
Reliability		1 to 5	3	4	5	2	1	3	2	4	5	
Cost	£	Minimise	1	2	3	4	5	3	2	5	4	
Complexity		1 to 5	1	5	4	3	2	4	2	5	3	
Selected Concept								■				

Experiment No. 2B

Design Characteristic (DC)	DC Units (DCU)	DC Target (DCT)	1	2	3	4	5	6	7	8	9	10
Noise Level	dBA	105-125	125	150	120	80	90	110	115	120	125	117
Installation		1 to 10	2	10	3	7	5	8	4	6	1	9
Weight		1 to 10	1	5	7	3	6	9	8	4	2	10
Corrosion		1 to 10	8	6	3	2	1	4	5	7	9	10
Size		1 to 10	2	6	4	7	3	8	5	10	1	9
Reliability		1 to 10	5	10	6	4	2	7	8	3	1	9
Cost	£	Minimise	2	6	4	9	10	5	3	8	1	7
Complexity		1 to 10	2	5	6	9	3	7	4	10	1	8
Selected Concept												■

Subject H Data Analysis

Experiment No.	**Subject Ages**	**Subject Experience**
1	**19**	**Year 1 Engineering students**

Design Characteristic (DC)	DC Units (DCU)	DC Target (DCT)	DC Estimated Value (DCE) Concept Reference Numbers 1	2	3	4	5	6	7	8	9	10
Cost		1 to 5	2	2	3	3	4					
Weight		1 to 5	1	1	4	3	5					
Reliability		1 to 5	3	4	4	4	3					
Maintenance		1 to 5	1	4	3	4	2					
Noise Level		1 to 5	2	3	4	3	2					
Size		1 to 5	1	3	3	3	2					
Selected Concept												

Experiment No. 2A

Design Characteristic (DC)	DC Units (DCU)	DC Target (DCT)	1	2	3	4	5	6	7	8	9	10
Cost		1 to 5	2	2	3	3	4	4	2	5	3	
Weight		1 to 5	1	1	4	3	5	5	2	4	4	
Reliability		1 to 5	3	4	4	4	3	2	4	4	3	
Maintenance		1 to 5	1	4	3	4	2	2	4	3	2	
Noise Level		1 to 5	2	3	4	3	2	2	4	3	2	
Size		1 to 5	1	3	3	3	2	4	3	3	3	
Selected Concept												

Experiment No. 2B

Design Characteristic (DC)	DC Units (DCU)	DC Target (DCT)	1	2	3	4	5	6	7	8	9	10
Cost		1 to 5	2	2	3	3	4	4	2	5	3	3
Weight		1 to 5	1	1	4	3	5	5	2	4	4	3
Reliability		1 to 5	3	4	4	4	3	2	4	4	3	4
Maintenance		1 to 5	1	4	3	4	2	2	4	3	2	5
Noise Level		1 to 5	2	3	4	3	2	2	4	3	2	3
Size		1 to 5	1	3	3	3	2	4	3	3	3	3
Selected Concept												

Subject I Data Analysis

Experiment No.	**Subject Ages**	**Subject Experience**
1	**18**	**Year 1 Engineering students**

Design Characteristic (DC)	DC Units (DCU)	DC Target (DCT)	DC Estimated Value (DCE) — Concept Reference Numbers: 1	2	3	4	5	6	7	8	9	10
Cost	£	Minimise	12	9	11	8	10					
Weight	N	<5	5	4	3	4	3					
Size		1 to 5	3	4	4	3	4					
Maintenance		1 to 5	5	5	2	4	4					
Reliability		1 to 5	4	4	3	5	4					
Noise Level	dBA	105-125	120	125	120	105	115					
Manufacture		1 to 5	2	3	2	4	4					
Corrosion		1 to 5	5	5	4	3	3					
Power		1 to 5	3	4	4	2	2					
Complexity		1 to 5	1	3	2	5	4					
Response Time		1 to 5	5	3	4	4	4					
Selected Concept				(shaded)								

Experiment No. 2A

Design Characteristic (DC)	DC Units (DCU)	DC Target (DCT)	1	2	3	4	5	6	7	8	9	10
Cost	£	Minimise	12	9	11	8	10	10	11	8	11	
Weight	N	<5	5	4	3	4	3	4	3	4	5	
Size		1 to 5	3	4	4	3	4	4	3	4	2	
Maintenance		1 to 5	5	5	2	4	4	5	3	4	3	
Reliability		1 to 5	4	4	3	5	4	4	3	4	4	
Noise Level	dBA	105-125	120	125	120	105	115	105	125	115	105	
Manufacture		1 to 5	2	3	2	4	4	4	3	4	4	
Corrosion		1 to 5	5	5	4	3	3	4	4	3	2	
Power		1 to 5	3	4	4	2	2	3	4	3	2	
Complexity		1 to 5	1	3	2	5	4	4	2	5	4	
Response Time		1 to 5	5	3	4	4	4	5	4	4	4	
Selected Concept				(shaded)								

Experiment No. 2B

Design Characteristic (DC)	DC Units (DCU)	DC Target (DCT)	1	2	3	4	5	6	7	8	9	10
Cost	£	Minimise	12	9	11	8	10	10	11	8	11	12
Weight	N	<5	5	4	3	4	3	4	3	4	5	3
Size		1 to 5	3	4	4	3	4	4	3	4	2	4
Maintenance		1 to 5	5	5	2	4	4	5	3	4	3	5
Reliability		1 to 5	4	4	3	5	4	4	3	4	4	5
Noise Level	dBA	105-125	120	125	120	105	115	105	125	115	105	125
Manufacture		1 to 5	2	3	2	4	4	4	3	4	4	4
Corrosion		1 to 5	5	5	4	3	3	4	4	3	2	4
Power		1 to 5	3	4	4	2	2	3	4	3	2	3
Complexity		1 to 5	1	3	2	5	4	4	2	5	4	4
Response Time		1 to 5	5	3	4	4	4	5	4	4	4	5
Selected Concept												(shaded)

Subject J Data Analysis

Experiment No.	Subject Ages	Subject Experience
1	18,18,19	Year 1 Engineering students

Design Characteristic (DC)	DC Units (DCU)	DC Target (DCT)	DC Estimated Value (DCE)									
			Concept Reference Numbers									
			1	2	3	4	5	6	7	8	9	10
Cost	£	Min Value	5	4	3	1	2					
Noise Level		1 to 5	2	1	1	5	4					
Size		1 to 5	2	2	2	3	5					
Weight	N	<5	3	4	1	4	3					
Reliability		1 to 5	2	3	2	3	3					
Simplicity		1 to 5	4	2	5	1	2					
Maintenance		1 to 5	3	4	5	4	3					
Durability		1 to 5	3	3	5	5	3					
Selected Concept				▒								

Experiment No. 2A

Design Characteristic (DC)	DC Units (DCU)	DC Target (DCT)	1	2	3	4	5	6	7	8	9	10
Cost	£	Min Value	5	4	3	1	2	2	3	1	4	
Noise Level		1 to 5	2	1	1	5	4	5	1	5	1	
Size		1 to 5	2	2	2	3	5	5	2	3	2	
Weight	N	<5	3	4	1	4	3	2	1	4	1	
Reliability		1 to 5	2	3	2	3	3	5	2	5	2	
Simplicity		1 to 5	4	2	5	1	2	2	4	1	5	
Maintenance		1 to 5	3	4	5	4	3	4	2	5	2	
Durability		1 to 5	3	3	5	5	3	4	2	4	2	
Selected Concept									▒			

Experiment No. 2B

Selected Concept												

Subject K data Analysis

Experiment No.	**Subject Ages**	**Subject Experience**
1	**17**	**Year1 Engineering students**

Design Characteristic (DC)	DC Units (DCU)	DC Target (DCT)	DC Estimated Value (DCE)									
			Concept Reference Numbers									
			1	2	3	4	5	6	7	8	9	10
Cost	£	Minimise	10	9	8	7	6					
Weight	N	<5	7	6	2	5	2					
Size		1 to 5	3	2	4	5	3					
Noise Level	dBA	105-125	125	145	100	90	90					
Manufacture		1 to 5	3	5	4	3	2					
Maintenance		1 to 5	2	5	2	4	3					
Complexity		1 to 5	1	4	2	4	2					
Reliability		1 to 5	5	5	2	4	1					
Parts		1 to 5	1	4	2	5	3					
Resistance		1 to 5	5	4	1	3	1					
Installation		1 to 5	5	5	1	4	2					
Production		1 to 5	3	4	2	5	2					
Selected Concept						■						

Experiment No. 2A

Cost	£	Minimise	10	9	8	7	6	8	12	7	8	
Weight	N	<5	2	6	2	5	2	7	7	7	6	
Size		1 to 5	3	2	4	5	3	4	3	4	3	
Noise Level	dBA	105-125	125	145	100	90	90	125	120	90	120	
Manufacture		1 to 5	3	5	4	3	2	3	1	4	4	
Maintenance		1 to 5	2	5	2	4	3	4	1	4	4	
Complexity		1 to 5	1	4	2	4	2	4	1	3	5	
Reliability		1 to 5	5	5	2	4	1	4	3	4	5	
Parts		1 to 5	1	4	2	5	3	5	1	5	3	
Resistance		1 to 5	5	4	1	3	1	5	2	5	3	
Installation		1 to 5	5	5	1	4	2	4	1	4	2	
Production		1 to 5	3	4	2	5	2	4	2	4	4	
Selected Concept								■				

Experiment No. 2B

Cost	£	Minimise	10	9	8	7	6	8	12	7	8	9
Weight	N	<5	2	6	2	5	2	7	7	7	6	7
Size		1 to 5	3	2	4	5	3	4	3	4	3	3
Noise Level	dBA	105-125	125	145	100	90	90	125	120	90	120	140
Manufacture		1 to 5	3	5	4	3	2	3	1	4	4	3
Maintenance		1 to 5	2	5	2	4	3	4	1	4	4	4
Complexity		1 to 5	1	4	2	4	2	4	1	3	5	5
Reliability		1 to 5	5	5	2	4	1	4	3	4	5	5
Parts		1 to 5	1	4	2	5	3	5	1	5	3	3
Resistance		1 to 5	5	4	1	3	1	5	2	5	3	5
Installation		1 to 5	5	5	1	4	2	4	1	4	2	4
Production		1 to 5	3	4	2	5	2	4	2	4	4	3
Selected Concept								■				

Subject Exp 1 Data Analysis

Experiment No.	Subject Ages	Subject Experience
1	38	Professional Engineer

Design Characteristic (DC)	DC Units (DCU)	DC Target (DCT)	DC Estimated Value (DCE) Concept Reference Numbers 1	2	3	4	5	6	7	8	9	10
Portability		1 to 5	3	3	4	3	4					
Cost	£	<4	4	3	2	4	5					
Size		1 to 5	2	3	4	4	3					
Noise Level	dBA	105-125	120	110	100	110	120					
Reliability		1 to 5	4	3	3	3	4					
Weight	N	<5	6	5	3	4	4					
Life	Years	>4	10	6	3	4	4					
Shock Resist	g's	10g	15	10	8	10	15					
Production		1 to 5	3	3	5	4	3					
Anti-theft		1 to 5	4	3	3	3	4					
Selected Concept							▒					

Experiment No. 2A

Design Characteristic (DC)	DC Units (DCU)	DC Target (DCT)	1	2	3	4	5	6	7	8	9	10
Portability		1 to 5	3	3	4	3	4	2	4	3	5	
Cost	£	<4	4	3	2	4	5	4	4	4	6	
Size		1 to 5	2	3	4	4	3	2	4	3	3	
Noise Level	dBA	105-125	120	110	100	110	120	125	115	105	120	
Reliability		1 to 5	4	3	3	3	3	4	3	3	3	
Weight	N	<5	6	5	3	4	4	5	3	4	2	
Life	Years	>4	10	6	3	4	4	8	4	4	4	
Shock Resist	g's	10g	15	10	8	10	15	15	10	15	15	
Production		1 to 5	3	3	5	4	3	4	5	4	3	
Anti-theft		1 to 5	4	3	3	3	4	5	3	3	4	
Selected Concept											▒	

Experiment No. 2B

Design Characteristic (DC)	DC Units (DCU)	DC Target (DCT)	1	2	3	4	5	6	7	8	9	10
Portability		1 to 5	3	3	4	3	4	2	4	3	5	3
Cost	£	<4	4	3	2	4	5	4	4	4	6	6
Size		1 to 5	2	3	4	4	3	2	4	3	3	5
Noise Level	dBA	105-125	120	110	100	110	120	125	115	105	120	110
Reliability		1 to 5	4	3	3	3	3	4	3	3	3	4
Weight	N	<5	6	5	3	4	4	5	3	4	2	3
Life	Years	>4	10	6	3	4	4	8	4	4	4	5
Shock Resist	g's	10g	15	10	8	10	15	15	10	15	15	20
Production		1 to 5	3	3	5	4	3	4	5	4	3	4
Anti-theft		1 to 5	4	3	3	3	4	5	3	3	4	3
Selected Concept												▒

Subject Exp 2 data Analysis

Experiment No.	**Subject Ages**	**Subject Experience**
1	**47**	**Professional Engineer**

Design Characteristic (DC)	DC Units (DCU)	DC Target (DCT)	DC Estimated Value (DCE) — Concept Reference Numbers: 1	2	3	4	5	6	7	8	9	10
Cost	£	Minimise	5	7	6	5	6					
Weight	N	<5	3	5	4	4	5					
Size		1 to 5	3	2	3	4	1					
Noise Level		1 to 5	4	4	4	3	2					
Manufacture		1 to 5	3	3	3	4	2					
Maintenance		1 to 5	3	4	2	4	3					
Complexity		1 to 5	2	3	2	4	3					
Reliability		1 to 5	2	4	2	2	2					
Life	Years	>4	15	15	5	5	10					
No. of Parts	Units	Minimise	12	4	20	5	10					
Selected Concept						▒						

Experiment No. 2A

Design Characteristic (DC)	DC Units (DCU)	DC Target (DCT)	1	2	3	4	5	6	7	8	9	10
Cost	£	Minimise	5	7	6	5	6	6	6	5	5	
Weight	N	<5	3	5	4	4	5	5	4	4	5	
Size		1 to 5	3	2	3	4	1	3	3	4	3	
Noise Level		1 to 5	4	4	4	3	2	2	4	3	4	
Manufacture		1 to 5	3	3	3	4	2	2	3	4	4	
Maintenance		1 to 5	3	4	2	4	3	2	2	4	4	
Complexity		1 to 5	2	3	2	4	3	2	2	4	4	
Reliability		1 to 5	2	4	2	2	2	2	3	2	4	
Life	Years	>4	15	15	5	5	10	5	5	5	10	
No. of Parts	Units	Minimise	12	4	20	5	10	8	17	5	4	
Selected Concept											▒	

Experiment No. 2B

Design Characteristic (DC)	DC Units (DCU)	DC Target (DCT)	1	2	3	4	5	6	7	8	9	10
Cost	£	Minimise	5	7	6	5	6	6	6	5	5	7
Weight	N	<5	3	5	4	4	5	5	4	4	5	5
Size		1 to 5	3	2	3	4	1	3	3	4	3	3
Noise Level		1 to 5	4	4	4	3	2	2	4	3	4	5
Manufacture		1 to 5	3	3	3	4	2	2	3	4	4	3
Maintenance		1 to 5	3	4	2	4	3	2	2	4	4	3
Complexity		1 to 5	2	3	2	4	3	2	2	4	4	3
Reliability		1 to 5	2	4	2	2	2	2	3	2	4	3
Life	Years	>4	15	15	5	5	10	5	5	5	10	5
No. of Parts	Units	Minimise	12	4	20	5	10	8	17	5	4	13
Selected Concept											▒	

Subject Exp 3 Data Analysis

Experiment No.	**Subject Ages**	**Subject Experience**
1	**49**	**Electronic technician**

Design Characteristic (DC)	DC Units (DCU)	DC Target (DCT)	DC Estimated Value (DCE) — Concept Reference Numbers 1	2	3	4	5	6	7	8	9	10
Noise Level		105dB	105									
Cost	£	20	20									
Corrosion		1 to 5	3									
Vibration		1 to 5	4									
Selected Concept												

Experiment No. 2A

Design Characteristic (DC)	DC Units (DCU)	DC Target (DCT)	1	2	3	4	5	6	7	8	9	10
Power	W	100							100			
Cost	£	20							30			
Selected Concept												

Experiment No. 2B

Design Characteristic (DC)	DC Units (DCU)	DC Target (DCT)	1	2	3	4	5	6	7	8	9	10
Power	W	100										100
Cost	£	20										30
Selected Concept												

Appendix C

Design Experiment 1																	
Design Specification Data Comparison with Concept (Novice Only) Data																	
Des. Spec						Prod.		Simp.		Life in		Resp.	Corr.	Porta.			
	Cost	Weight	Size	Noise	Noise	Manuf.	Maint.	Compl.	Relia.	Service	Power	Time	Dura.	Compa.	Install.	Freq.	
	S	N	S	dBA	NS	S	S	S	NS	Yrs	S	S	S	S	S	kHz	
S.D	1.58	1.58	1.00	7.91	1.58	0.71	0.71	0.71	1.58	2.83	0.71	0.71	1.00	1.00	0.71	1.29	
Median	3.00	3.00	4.00	115.00	3.00	4.50	4.50	4.50	3.00	6.00	4.50	4.50	4.00	4.00	4.50	3.50	
L(s)	1.00	1.00	3.00	105.00	1	4.00	4.00	4.00	1.00	4.00	4.00	4.00	3.00	3.00	4.00	2.00	
H(s)	5.00	5.00	5.00	125.00	5	5.00	5.00	5.00	5.00	8.00	5.00	5.00	5.00	5.00	5.00	5.00	
h(s)	0.25	0.25	0.50	0.05	0.25	1.00	1.00	1.00	0.25	0.25	1.00	1.00	0.50	0.50	1.00	0.33	
Concept 1																	
S.D	3.57	1.6675	1.25	8.2158	1.3416	1.309	1.6583	1.2693	1.0541	0	1.29	0	0.7868	0	1		
Median	8	4	3	120	4	2.5	4	1	4	9	3.5	5	5	4	5		
L(m)	1	1	1	105	2	1	1	1	2	9	2	5	3	4	3		
H (m)	12	7	5	125	5	5	5	4	5	9	5	5	5	4	5		
h(m)	0.15	0.2236	0.26	0.1007	0.2492	0.252	0.2242	0.25623	0.2812	1	0.25	1	0.3254	1	0.29		
Des Margin	1.28	0.44	0.62	0.44	0.48	1.34	0.28	2.41	0.53	1.06	0.68	0.71	0.79	0.00	0.41	Σ DM =	11.46
∫h(s).∫h(m)	0.61	0.89	0.52	1.00	0.56	0.25	0.22	0.00	0.63	0.25	0.25	0.00	0.65	0.00	0.29	Σ[∫∫] =	6.135
∫∫ Loss	0.37	0.80	0.27	1.00	0.31	0.06	0.05	0.00	0.40	0.06	0.06	0.00	0.42	0.00	0.08	Σ∫∫Loss	3.90
DM.Loss	1.64	0.1894	0.39	0.1923	0.2326	1.806	0.0769	5.80263	0.2769	1.125	0.46	0.5	0.6176	0	0.17	ΣDMLoss	13.48
∫(∫)	0.61	0.8942	0.52	1	0.7477	0.252	0.2242	0	0.8435	0	0.25	0	0.6509	0	0.29	Σ∫(∫)=	6.283
Concept 2																Σ∫(∫).Loss	4.395
SD	5.28	1.5492	1.14	14.405	1.5811	0.926	0.527	1.13039	0.7817	0	1.73	1.033	0.7071	0.7071	0.58		
Median	5	3	3	125	3	4	4	4	4	10	4	3	4	4.5	4.5		
L(m)	2	1	2	120	1	3	4	2	3	10	1	1	3	4	4		
H(m)	20	6	5	150	5	5	5	5	5	10	5	4	5	5	5		

h(m)	0.13	0.2319	0.27	0.0761	0.2296	0.3	0.3976	0.27152	0.3265	1	0.22	0.284	0.3433	0.3433	0.38		
Des. Margin	0.36	0.00	0.66	0.61	0.00	0.43	0.57	0.38	0.57	1.41	0.27	1.20	0.00	0.41	0.00	Σ DM =	6.86
∫h(s).∫h(m)	0.28	0.93	0.54	0.10	0.92	0.30	0.40	0.27	0.33	1.00	0.22	0.00	0.69	0.17	0.38	Σ[∫∫] =	6.519
∫∫ Loss	0.08	0.86	0.29	0.01	0.84	0.09	0.16	0.07	0.11	1.00	0.05	0.00	0.47	0.03	0.14	Σ∫∫Loss	4.21
DM.Loss	0.13	0	0.44	0.3704	0	0.184	0.3214	0.14063	0.3214	2	0.07	1.436	0	0.1667	0	ΣDMLoss	5.58
∫(∫)	0.38	0.9277	0.54	0.3803	0.9183	0.3	0.3976	0.27152	0.653	0	0.22	0	0.6866	0.3433	0.38	Σ∫(∫)=	6.396
																Σ∫(∫).Loss	3.814
Concept 3																	
SD	4.43	1.3416	1.41	16.583	1.2247	1.165	1.5092	1.23603	1.2247	0	1	1.472	1.4079	0	0.5		
Median	8	3	3.5	105	3	2	2	2	2	5	4	3.5	2.5	4	2		
L(m)	1	1	1	80	1	1	1	1	1	5	3	1	1	4	1		
H(m)	15	5	5	120	4	4	5	5	5	5	5	5	5	4	2		
h(m)	0.14	0.2492	0.24	0.0709	0.2608	0.267	0.235	0.25965	0.2608	1	0.29	0.238	0.2433	1	0.41		
Des Margin	1.06	0.00	0.29	0.54	0.00	1.83	1.50	1.76	0.50	0.35	0.41	0.61	0.87	0.00	2.89	Σ DM =	12.62
∫h(s).∫h(m)	0.55	1.00	0.49	0.80	0.59	0.00	0.23	0.26	1.00	0.00	0.29	0.24	0.49	0.00	1.63	Σ[∫∫] =	7.556
∫∫ Loss	0.30	0.99	0.24	0.64	0.34	0.00	0.06	0.07	1.00	0.00	0.08	0.06	0.24	0.00	2.67	Σ∫∫Loss	6.68
DM.Loss	1.13	0	0.08	0.2963	0	3.365	2.25	3.08219	0.25	0.125	0.17	0.375	0.7545	0	8.33	ΣDMLoss	20.21
∫(∫)	0.55	0.9969	0.49	1	0.7825	0	0.235	0.25965	1	0	0.29	0.238	0.4866	0	0	Σ∫(∫)=	6.322
Concept 4																Σ∫(∫).Loss	4.642
SD	2.64	1.1832	1.06	18.908	1.7889	1.302	0.866	1.22474	1.118	0	2.06	1.722	1	0.7071	1.5		
Median	4	3	3	90	1	4	4	4	3	4	3.5	3	3	3.5	3		
L(m)	1	1	2	60	1	1	2	1	2	4	1	1	2	3	1		
H(m)	10	5	5	105	5	5	5	5	5	4	5	5	5	4	4		
h(m)	0.18	0.2654	0.28	0.0664	0.2158	0.253	0.3102	0.26085	0.273	1	0.2	0.22	0.2887	0.3433	0.24		
Des. Margin	0.33	0.00	0.69	1.22	0.84	0.34	0.45	0.35	0.00	0.71	0.46	0.81	0.71	0.41	0.90	Σ DM =	8.20
∫h(s).∫h(m)	0.71	1.00	0.56	0.00	0.86	0.25	0.31	0.26	0.61	0.00	0.20	0.22	0.58	0.17	0.00	Σ[∫∫] =	5.743
∫∫ Loss	0.51	1.00	0.31	0.00	0.75	0.06	0.10	0.07	0.38	0.00	0.04	0.05	0.33	0.03	0.00	Σ∫∫Loss	3.62
DM.Loss	0.11	0	0.47	1.4881	0.7018	0.114	0.2	0.125	0	0.5	0.21	0.649	0.5	0.1667	0.82	ΣDMLoss	6.05
∫(∫)	0.71	1.0615	0.56	0	0.8633	0.253	0.3102	0.26085	0.819	0	0.2	0.22	0.5774	0.3433	0	Σ∫(∫)=	6.181

Concept 5																∑∫(∫).Loss	4.131
SD	2.3	1.0023	1.52	25.066	0.8367	0.916	0.9718	1.22474	1.3229	0	1.73	1.211	0.991	1.4142	0.82		
Median	5	3	2.5	90	3	3	3	3	3	7	2	4	1.5	3	2		
L(m)	2	1.5	1	50	2	2	1	2	1	7	1	1	1	2	1		
H(m)	10	5	5	115	4	5	4	5	4	7	5	4	3	4	3		
h(m)	0.19	0.2883	0.23	0.0577	0.3156	0.302	0.2928	0.26085	0.251	1	0.22	0.262	0.29	0.2427	0.32		
Des. Margin	0.72	0.00	0.82	0.95	0.00	1.30	1.25	1.06	0.00	0.35	1.34	0.36	1.78	0.58	2.31	∑ DM =	12.81
∫h(s).∫h(m)	0.43	0.88	0.47	0.29	0.32	0.30	0.00	0.26	0.56	0.00	0.22	0.00	0.00	0.12	0.32	∑[∫∫] =	4.17
∫∫ Loss	0.18	0.78	0.22	0.08	0.10	0.09	0.00	0.07	0.32	0.00	0.05	0.00	0.00	0.01	0.10	∑∫∫Loss	2.01
DM.Loss	0.51	0	0.68	0.9047	0	1.68	1.5577	1.125	0	0.125	1.79	0.127	3.1532	0.3333	5.36	∑DMLoss	17.34
∫(∫)	0.57	1.0092	0.47	0.5766	0.6312	0.302	0	0.26085	0.753	0	0.22	0	0	0.2427	0	∑∫(∫)=	5.033
																∑∫(∫).Loss	3.127

Design Experiment 1																	
Design Specification Data Comparison with Concept (Expert Only) Data																	
Des. Spec						Prod.		Simp.		Life in		Resp.	Corr.	Porta.			
	Cost	Weight	Size	Noise	Noise	Manuf.	Maint.	Compl.	Relia.	Service	Power	Time	Dura.	Compa.	Install.	Freq.	
	S	N	S	dBA	NS	S	S	S	NS	Yrs	S	S	S	S	S	kHz	
S.D	1.58	1.58	1.00	7.91	1.58	0.71	0.71	0.71	1.58	2.83	0.71	0.71	1.00	1.00	0.71	1.29	
Median	3.00	3.00	4.00	115.00	3.00	4.50	4.50	4.50	3.00	6.00	4.50	4.50	4.00	4.00	4.50	3.50	
L(s)	1.00	1.00	3.00	105.00	1	4.00	4.00	4.00	1.00	4.00	4.00	4.00	3.00	3.00	4.00	2.00	
H(s)	5.00	5.00	5.00	125.00	5	5.00	5.00	5.00	5.00	8.00	5.00	5.00	5.00	5.00	5.00	5.00	
h(s)	0.25	0.25	0.50	0.05	0.25	1.00	1.00	1.00	0.25	0.25	1.00	1.00	0.50	0.50	1.00	0.33	
Concept 1																	
S.D	0.71	2.1213	0.71	0	0	0	0	0	1.4142	0	0	0	0	0	0		
Median	4.5	4.5	2.5	120	4	3	3	2	3	0	0	0	0	3	0		
L(m)	4	3	2	120	4	3	3	2	2	0	0	0	0	3	0		
H (m)	5	6	3	120	4	3	3	2	4	0	0	0	0	3	0		
h(m)	0.34	0.1982	0.34	1	1	1	1	1	0.2427	0	0	0	0	1	0		
Des Margin	0.87	0.57	1.22	0.63	0.63	2.12	2.12	3.54	0.00	2.12	6.36	6.36	4.00	1.00	6.36	Σ DM =	37.91
∫h(s).∫h(m)	0.09	0.20	0.00	0.00	0.00	1.00	1.00	1.00	0.24	0.00	0.00	0.00	0.00	0.00	0.00	Σ[∫∫] =	3.527
∫∫ Loss	0.01	0.04	0.00	0.00	0.00	1.00	1.00	1.00	0.06	0.00	0.00	0.00	0.00	0.00	0.00	Σ∫∫Loss	3.11
DM.Loss	0.75	0.3214	1.5	0.4	0.4	4.5	4.5	12.5	0	4.5	40.5	40.5	16	1	40.5	ΣDM.Loss	167.9
∫(∫)	0.34	0.3964	0	0	0	0	0	0	0.4855	0	0	0	0	0	0	Σ∫(∫)=	1.225
Concept 2																Σ∫(∫).Loss	0.511
SD	2.83	0	0.71	0	0	0	0	0	0.7071	0	0	0	0	0	0		
Median	5	5	2.5	110	4	3	3	3	3.5	15	0	0	0	3	0		
L(m)	3	5	2	110	4	3	3	3	3	15	0	0	0	3	0		
H(m)	7	5	3	110	4	3	3	3	4	15	0	0	0	3	0		

h(m)	0.17	1	0.34	1	1	1	1	1	0.3433	1	0	0	0	1	0		
Des. Margin	0.62	1.26	1.22	0.63	0.63	2.12	2.12	2.12	0.29	3.18	6.36	6.36	4.00	1.00	0.00	Σ DM =	31.93
∫h(s).∫h(m)	0.17	0.00	0.00	0.00	0.00	1.00	1.00	1.00	0.09	1.00	0.00	0.00	0.00	0.00	0.00	Σ[∬] =	4.257
∬ Loss	0.03	0.00	0.00	0.00	0.00	1.00	1.00	1.00	0.01	1.00	0.00	0.00	0.00	0.00	0.00	Σ∬Loss	4.04
DM.Loss	0.38	1.6	1.5	0.4	0.4	4.5	4.5	4.5	0.0833	10.13	40.5	40.5	16	1	0	ΣDM.Loss	126
∫(∫)	0.34	0	0	0	0	0	0	0	0.3433	0	0	0	0	0	0	Σ∫(∫)=	0.687
																Σ∫(∫).Loss	0.236
Concept 3																	
SD	2.83	0.7071	0.71	0	0	1.414	0	0	0.7071	1.414	0	0	0	0	0		
Median	4	3.5	3.5	100	4	4	2	2	2.5	4	0	0	0	4	0		
L(m)	2	3	3	100	4	3	2	2	2	3	0	0	0	4	0		
H(m)	6	4	4	100	4	5	2	2	3	5	0	0	0	4	0		
h(m)	0.17	0.3433	0.34	1	1	0.243	1	1	0.3433	0.243	0	0	0	1	0		
Des Margin	0.31	0.29	0.41	1.90	0.63	0.32	3.54	3.54	0.29	0.63	6.36	6.36	4.00	0.00	6.36	Σ DM =	34.94
∫h(s).∫h(m)	0.39	0.09	0.17	1.00	0.00	0.24	1.00	1.00	0.09	0.06	0.00	0.00	0.00	0.00	0.00	Σ[∬] =	4.033
∬ Loss	0.15	0.01	0.03	1.00	0.00	0.06	1.00	1.00	0.01	0.00	0.00	0.00	0.00	0.00	0.00	Σ∬Loss	3.26
DM.Loss	0.1	0.0833	0.17	3.6	0.4	0.1	12.5	12.5	0.0833	0.4	40.5	40.5	16	0	40.5	ΣDM.Loss	167.4
∫(∫)	0.51	0.3433	0.34	0	0	0.243	0	0	0.3433	0.243	0	0	0	0	0	Σ∫(∫)=	2.03
Concept 4																Σ∫(∫).Loss	0.737
SD	0.71	0	0	0	0	0	0	0	0.7071	0.707	0	0	0	0	0		
Median	4.5	4	4	110	3	4	4	4	2.5	4.5	0	0	3	0	0		
L(m)	4	4	4	110	3	4	4	4	2	4	0	0	3	0	0		
H(m)	5	4	4	110	3	4	4	4	3	5	0	0	3	0	0		
h(m)	0.34	1	1	1	1	1	1	1	0.3433	0.343	0	0	1	0	0		
Des. Margin	0.87	0.63	0.00	0.63	0.00	0.71	0.71	0.71	0.29	0.51	6.36	6.36	1.00	4.00	6.36	Σ DM =	29.15
∫h(s).∫h(m)	0.09	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.09	0.09	0.00	0.00	0.00	0.00	0.00	Σ[∬] =	0.257
∬ Loss	0.01	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.01	0.01	0.00	0.00	0.00	0.00	0.00	Σ∬Loss	0.02
DM.Loss	0.75	0.4	0	0.4	0	0.5	0.5	0.5	0.0833	0.265	40.5	40.5	1	16	40.5	ΣDM.Loss	141.9
∫(∫)	0.34	0	0	0	0	0	0	0	0.3433	0.343	0	0	0	0	0	Σ∫(∫)=	1.03

Concept 5																Σ∫(∫).Loss	0.354
SD	0.71	0.7071	1.41	0	0	0	0	0	1.4142	4.243	0	0	0	0	0		
Median	5.5	4.5	2	120	2	2	3	3	3	7	0	0	0	4	0		
L(m)	5	4	1	120	2	2	3	3	2	4	0	0	0	4	0		
H(m)	6	5	3	120	2	2	3	3	4	10	0	0	0	4	0		
h(m)	0.34	0.3433	0.24	1	1	1	1	1	0.2427	0.14	0	0	0	1	0		
Des. Margin	1.44	0.87	1.15	0.63	0.63	3.54	2.12	2.12	0.00	0.20	6.36	6.36	4.00	0.00	6.36	Σ DM =	35.80
∫h(s).∫h(m)	0.00	0.09	0.00	0.00	0.00	1.00	1.00	1.00	0.24	0.56	0.00	0.00	0.00	0.00	0.00	Σ[∫∫] =	3.889
∫∫ Loss	0.00	0.01	0.00	0.00	0.00	1.00	1.00	1.00	0.06	0.31	0.00	0.00	0.00	0.00	0.00	Σ∫∫Loss	3.38
DM.Loss	2.08	0.75	1.33	0.4	0.4	12.5	4.5	4.5	0	0.038	40.5	40.5	16	0	40.5	ΣDM.Loss	164
∫(∫)	0	0.3433	0	0	0	0	0	0	0.4855	0.561	0	0	0	0	0	Σ∫(∫)=	1.389
																Σ∫(∫).Loss	0.668

Design Experiment 2A																	
Design Specification Data Comparison with Concept (Expert) Data																	
Des. Spec						Prod.		Simp.		Life in		Resp.	Corr.	Porta.			
	Cost	Weight	Size	Noise	Noise	Manuf.	Maint.	Compl.	Relia.	Service	Power	Time	Dura.	Compa.	Install.	Freq.	
	S	N	S	dBA	NS	S	S	S	NS	Yrs	S	S	S	S	S	kHz	
S.D	1.58	1.58	1.00	7.91	1.58	0.71	0.71	0.71	1.58	2.83	0.71	0.71	1.00	1.00	0.71	1.29	
Median	3.00	3.00	4.00	115.00	3.00	4.50	4.50	4.50	3.00	6.00	4.50	4.50	4.00	4.00	4.50	3.50	
L(s)	1.00	1.00	3.00	105.00	1	4.00	4.00	4.00	1.00	4.00	4.00	4.00	3.00	3.00	4.00	2.00	
H(s)	5.00	5.00	5.00	125.00	5	5.00	5.00	5.00	5.00	8.00	5.00	5.00	5.00	5.00	5.00	5.00	
h(s)	0.25	0.25	0.50	0.05	0.25	1.00	1.00	1.00	0.25	0.25	1.00	1.00	0.50	0.50	1.00	0.33	
Concept 6																	
S.D	1.41	0.00	0.71	0.00	0.00	1.41	0.00	0.00	1.41	2.12	0.00	0.00	0.00	0.00	0.00		
Median	5.00	5.00	2.50	125.00	2.00	3.00	2.00	2.00	3.00	6.50	0.00	0.00	0.00	2.00	0.00		
L(m)	4.00	5.00	2.00	125.00	2.00	2.00	2.00	2.00	2.00	5.00	0.00	0.00	0.00	2.00	0.00		
H (m)	6.00	5.00	3.00	125.00	2.00	4.00	2.00	2.00	4.00	8.00	0.00	0.00	0.00	2.00	0.00		
h(m)	0.24	1.00	0.34	1.00	1.00	0.24	1.00	1.00	0.24	0.20	0.00	0.00	0.00	1.00	0.00		
Des Margin	0.94	1.26	1.22	1.26	0.63	0.95	3.54	3.54	0.00	0.14	6.36	6.36	4.00	2.00	6.36	Σ DM =	38.58
∫h(s).∫h(m)	0.06	0.00	0.00	0.00	0.00	0.00	1.00	1.00	0.24	0.45	0.00	0.00	0.00	0.50	0.00	Σ[∫∫] =	3.249
∫∫ Loss	0.00	0.00	0.00	0.00	0.00	0.00	1.00	1.00	0.06	0.20	0.00	0.00	0.00	0.25	0.00	Σ∫∫Loss	2.51
DM.Loss	0.89	1.6	1.5	1.6	0.4	0.9	12.5	12.5	0	0.02	40.5	40.5	16	4	40.5	ΣDM.Loss	173.4
∫(∫)	0.24	0	0	0	0	0	0	0	0.4855	0.595	0	0	0	0	0	Σ∫(∫)=	1.323
Concept 7																Σ∫(∫).Loss	0.648
SD	1.41	0.71	0.71	0.00	0.00	1.41	0.00	0.00	0.00	0.71	0.00	0.00	0.00	0.00	0.00		
Median	5.00	3.50	3.50	115.00	4.00	4.00	2.00	2.00	3.00	4.50	0.00	0.00	0.00	4.00	0.00		
L(m)	4.00	3.00	3.00	115.00	4.00	3.00	2.00	2.00	3.00	4.00	0.00	0.00	0.00	4.00	0.00		
H(m)	6.00	4.00	4.00	115.00	4.00	5.00	2.00	2.00	3.00	5.00	0.00	0.00	0.00	4.00	0.00		

h(m)	0.24	0.34	0.34	1.00	1.00	0.24	1.00	1.00	1.00	0.34	0.00	0.00	0.00	1.00	0.00		
Des. Margin	0.94	0.29	0.41	0.00	0.63	0.32	3.54	3.54	0.00	0.51	6.36	6.36	4.00	0.00	6.36	Σ DM =	33.27
∫h(s).∫h(m)	0.06	0.09	0.17	0.00	0.00	0.24	1.00	1.00	0.00	0.09	0.00	0.00	0.00	0.00	0.00	Σ[∫∫] =	2.647
∫∫ Loss	0.00	0.01	0.03	0.00	0.00	0.06	1.00	1.00	0.00	0.01	0.00	0.00	0.00	0.00	0.00	Σ∫∫Loss	2.11
DM.Loss	0.89	0.0833	0.17	0	0.4	0.1	12.5	12.5	0	0.265	40.5	40.5	16	0	40.5	ΣDM.Loss	164.4
∫(∫)	0.24	0.3433	0.34	0	0	0.243	0	0	0	0.343	0	0	0	0	0	Σ∫(∫)=	1.515
																Σ∫(∫).Loss	0.471
Concept 8																	
SD	0.71	0.00	0.71	0.00	0.00	0.00	0.00	0.00	0.71	0.71	0.00	0.00	0.00	0.00	0.00		
Median	4.50	4.00	3.50	105.00	3.00	4.00	4.00	4.00	2.50	4.50	0.00	0.00	0.00	3.00	0.00		
L(m)	4.00	4.00	3.00	105.00	3.00	4.00	4.00	4.00	2.00	4.00	0.00	0.00	0.00	3.00	0.00		
H(m)	5.00	4.00	4.00	105.00	3.00	4.00	4.00	4.00	3.00	5.00	0.00	0.00	0.00	3.00	0.00		
h(m)	0.34	1.00	0.34	1.00	1.00	1.00	1.00	1.00	0.34	0.34	0.00	0.00	0.00	1.00	0.00		
Des Margin	0.87	0.63	0.41	1.26	0.00	0.71	0.71	0.71	0.29	0.51	6.36	6.36	4.00	1.00	6.36	Σ DM =	30.19
∫h(s).∫h(m)	0.09	0.00	0.17	0.00	0.00	0.00	0.00	0.00	0.09	0.09	0.00	0.00	0.00	0.00	0.00	Σ[∫∫] =	0.429
∫∫ Loss	0.01	0.00	0.03	0.00	0.00	0.00	0.00	0.00	0.01	0.01	0.00	0.00	0.00	0.00	0.00	Σ∫∫Loss	0.05
DM.Loss	0.75	0.4	0.17	1.6	0	0.5	0.5	0.5	0.0833	0.265	40.5	40.5	16	1	40.5	ΣDM.Loss	143.3
∫(∫)	0.34	0	0.34	0	0	0	0	0	0.3433	0.343	0	0	0	0	0	Σ∫(∫)=	1.373
Concept 9																Σ∫(∫).Loss	0.471
SD																	
Median																	
L(m)																	
H(m)																	
h(m)																	
Des. Margin																Σ DM =	0.00
∫h(s).∫h(m)																Σ[∫∫] =	0
∫∫ Loss																Σ∫∫Loss	0.00
DM.Loss																ΣDM.Loss	0
∫(∫)																	

Design Experiment 2A																	
Design Specification Data Comparison with Concept (Novice) Data																	
Des. Spec						Prod.		Simp.		Life in		Resp.	Corr.	Porta.			
	Cost	Weight	Size	Noise	Noise	Manuf.	Maint.	Compl.	Relia.	Service	Power	Time	Dura.	Compa.	Install.	Freq.	
	S	N	S	dBA	NS	S	S	S	NS	Yrs	S	S	S	S	S	kHz	
S.D	1.58	1.58	1.00	7.91	1.58	0.71	0.71	0.71	1.58	2.83	0.71	0.71	1.00	1.00	0.71	1.29	
Median	3.00	3.00	4.00	115.00	3.00	4.50	4.50	4.50	3.00	6.00	4.50	4.50	4.00	4.00	4.50	3.50	
L(s)	1.00	1.00	3.00	105.00	1	4.00	4.00	4.00	1.00	4.00	4.00	4.00	3.00	3.00	4.00	2.00	
H(s)	5.00	5.00	5.00	125.00	5	5.00	5.00	5.00	5.00	8.00	5.00	5.00	5.00	5.00	5.00	5.00	
h(s)	0.25	0.25	0.50	0.05	0.25	1.00	1.00	1.00	0.25	0.25	1.00	1.00	0.50	0.50	1.00	0.33	
Concept 6																	
S.D	2.70	1.57	1.35	28.59	1.52	1.85	1.51	1.51	1.30	0.00	0.96	1.37	1.55	0.71	0.58		
Median	4.00	3.00	4.00	105.00	2.00	3.00	4.00	4.00	4.00	5.00	3.50	4.00	4.50	4.50	4.50		
L(m)	2.00	2.00	1.00	50.00	1.00	1.00	1.00	1.00	1.00	5.00	3.00	2.00	1.00	4.00	4.00		
H (m)	10.00	7.00	5.00	125.00	5.00	7.00	6.00	6.00	5.00	5.00	5.00	5.00	6.00	5.00	5.00		
h(m)	0.18	0.23	0.25	0.05	0.23	0.21	0.23	0.23	0.25	1.00	0.30	0.25	0.23	0.34	0.38		
Des Margin	0.32	0.00	0.00	0.34	0.46	0.76	0.30	0.30	0.49	0.35	0.84	0.33	0.27	0.41	0.00	Σ DM =	5.16
∫h(s).∫h(m)	0.40	0.52	0.50	1.00	0.94	0.21	0.23	0.23	1.00	0.00	0.30	0.25	0.46	0.17	0.38	Σ[∫∫] =	6.588
∫∫ Loss	0.16	0.27	0.25	1.00	0.88	0.05	0.06	0.06	1.00	0.00	0.09	0.06	0.21	0.03	0.14	Σ∫∫Loss	4.24
DM.Loss	0.1	0	0	0.1136	0.2083	0.573	0.09	0.09	0.2384	0.125	0.71	0.106	0.0733	0.1667	0	ΣDM.Loss	2.59
∫(∫)	0.53	0.6919	0.5	1	0.9376	0.212	0.235	0.23498	1	0	0.3	0.247	0.4633	0.3433	0.38	Σ∫(∫)=	7.064
Concept 7																Σ∫(∫).Loss	4.663
SD	4.80	1.62	1.33	13.51	1.51	1.20	1.27	1.00	0.71	0.00	1.73	0.52	1.30	0.00	0.50		
Median	7.00	2.00	3.00	115.00	4.00	2.50	3.00	2.00	3.00	6.00	4.00	4.00	3.50	4.00	2.00		
L(m)	1.00	1.00	1.00	90.00	1.00	1.00	1.00	1.00	2.00	6.00	1.00	4.00	2.00	4.00	1.00		
H(m)	15.00	7.00	5.00	125.00	5.00	4.00	5.00	4.00	4.00	6.00	5.00	5.00	5.00	4.00	2.00		

h(m)	0.13	0.23	0.25	0.08	0.24	0.26	0.26	0.29	0.34	1.00	0.22	0.40	0.25	1.00	0.41		
Des. Margin	0.79	0.44	0.60	0.00	0.46	1.44	1.03	2.04	0.00	0.00	0.27	0.57	0.30	0.00	2.89	Σ DM =	10.83
∫h(s).∫h(m)	0.53	0.91	0.50	1.00	0.94	0.00	0.26	0.00	0.34	0.00	0.22	0.40	0.51	0.00	1.63	Σ[∫∫] =	7.235
∫∫ Loss	0.28	0.82	0.25	1.00	0.89	0.00	0.07	0.00	0.12	0.00	0.05	0.16	0.26	0.00	2.67	Σ∫∫Loss	6.55
DM.Loss	0.63	0.1954	0.36	0	0.2098	2.074	1.0658	4.16667	0	0	0.07	0.326	0.0927	0	8.33	ΣDM.Loss	17.52
∫(∫)	0.53	0.9078	0.5	1	0.9411	0	0.2562	0	0.6866	0	0.22	0.402	0.5059	0	0	Σ∫(∫)=	5.946
																Σ∫(∫).Loss	4.24
Concept 8																	
SD	2.83	1.73	2.06	28.15	1.30	1.91	2.18	2.30	1.32	0.00	3.10	1.21	1.85	0.71	1.50		
Median	5.00	3.00	3.50	105.00	3.00	4.00	4.00	4.00	4.00	4.00	4.00	2.50	3.00	3.50	3.00		
L(m)	1.00	1.00	3.00	50.00	2.00	3.00	1.00	1.00	2.00	4.00	2.00	1.00	1.00	3.00	1.00		
H(m)	10.00	7.00	9.00	120.00	5.00	9.00	9.00	8.00	6.00	4.00	9.00	4.00	7.00	4.00	4.00		
h(m)	0.17	0.22	0.20	0.05	0.25	0.21	0.20	0.19	0.25	1.00	0.16	0.26	0.21	0.34	0.24		
Des Margin	0.62	0.00	0.22	0.34	0.00	0.25	0.22	0.21	0.49	0.71	0.16	1.43	0.48	0.41	0.90	Σ DM =	6.41
∫h(s).∫h(m)	0.69	0.88	0.40	0.61	0.57	0.21	0.20	0.19	0.56	0.00	0.16	0.00	0.42	0.17	0.00	Σ[∫∫] =	4.895
∫∫ Loss	0.47	0.77	0.16	0.37	0.32	0.04	0.04	0.04	0.32	0.00	0.03	0.00	0.18	0.03	0.00	Σ∫∫Loss	2.74
DM.Loss	0.38	0	0.05	0.117	0	0.06	0.0476	0.04327	0.2353	0.5	0.02	2.034	0.2258	0.1667	0.82	ΣDM.Loss	4.70
∫(∫)	0.69	0.8774	0.4	0.8161	0.7584	0.209	0.1955	0.19046	0.753	0	0.16	0	0.4243	0.3433	0	Σ∫(∫)=	5.82
Concept 9																Σ∫(∫).Loss	3.654
SD																	
Median																	
L(m)																	
H(m)																	
h(m)																	
Des. Margin																Σ DM =	0.00
∫h(s).∫h(m)																Σ[∫∫] =	0
∫∫ Loss																Σ∫∫Loss	0.00
DM.Loss																ΣDM.Loss	0.00
∫(∫)																	