A MODEL OF THE ENGINEERING DESIGN PROCESS

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CONTENTS

CONTENTS

CONTENTS

FIGURES

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Abstract

The subject of this Thesis is that of engineering design. The primary objective of the Thesis is to produce a model of the engineering design process. This model represents the way engineering design takes place regardless of the scale of the design project or the type of object which is being designed.

The model is consensus based and has been produced through an extensive review and analysis of literature, (the literature review being completed in 1987) taken both from the field of engineering design and from disciplines concerned with related issues. In addition to the review and analysis of literature, a large number of interviews and consultations were undertaken with design experts and designers.

The Thesis is divided into three main sections. The first section is concerned with a discussion of the evidence gained through the processes of literature review and interview/consultation. The second with a description of the model and its origin. The third is concerned with a description of the means by which design takes place.

The model is essentially sequential, but has also incorporated the major elements of process type models of design. By demonstrating that an accommodation is possible between these two design theory approaches, an advance has been made into the understanding of the way in which design takes place.

The model consists of sequential stages each of which characterises a major type of activity within the process and which describe the design process from the initial perception of need through to the production of the finalised design configuration. Designs are developed by passing iteratively through these stages. Solutions and partial solutions, along with other design information are stored within the Blackboard.

The means by which designs are developed is also examined in terms of the type of aid they give the designer, and their informatic relationship to the design process.

1. Introduction

Designers are faced with the challenges of ever increasing complexity in planning and designing such items as integrated circuits, mechanical systems, chemical compounds, production processes, control and measurement systems and large buildings. Despite the demanding nature of this type of design work, most designers still approach these problems intuitively without rigorous methods for generating or evaluating designs. It is the aim of this thesis to demonstrate that there exists a fundamental structure common to all design and within this to concentrate special attention on to one particular area, that of generating design concepts. The specific aims and approach which will be used in this study are dealt with in detail in another section, (1.1.) at this point however it would appear useful to offer a very brief introduction to the overall area of design and relate this to the work undertaken in this study.

Design is the creative process by which one moves from perceived need to realised solution. It is a process which moves from the abstract to the concrete. It is as such also a dynamic process which concerns itself with the collection, manipulation synthesis, and representation of knowledge. It will be argued that all these elements are present in all types of design, regardless of the form, scale and complexity of that which is to be designed and regardless of the formality with which the task is undertaken. Further to this it will be argued that all engineering design is governed by a fundamental set of principles and imperatives. A framework which is the basis for all design activity will be put forward. From this framework one particular area will be taken and examined in depth. The reasons for the adoption of this approach are given in greater detail in section (3).

When one considers that all man-made articles must in some sense be designed and that man has been making things for a quite considerable length of time, the study of the process of design and the area of design in general have until comparatively recently been neglected. Now however that the study of the design process has been taken up, one of the main problems encountered has been that much of the knowledge of the design process is embodied within human experts, who are often unaware of their own cognitive processes. In addition to this, traditionally, the massive complexity of real design problems have been successfully dealt with by human experts using a heuristic approach. Thus considerable work has been needed to extract, organise and apply this knowledge.

Advances in the study of the design process have however taken place. These advances have occurred in part due to the constraining and limiting of design space and in part due to a convergence of ideals and methodologies that have given structure to previously indifferent problems. Little work however has been done to explore whether these advances are confined to a particular discipline or whether they can be generalised through analogy to other fields. One of the major aims of this thesis is an attempt to demonstrate, by analysis and synthesis of existing design theories and methodologies, that a model of engineering design is possible based upon fundamental principles.

1.1. Aims

Within this section a description of the aims of the thesis will be given. In outline these aims are,

- to produce a model of engineering design through a process of analysis and synthesis of literature relevant to the field of engineering design

- to define and relate the use of design aids to the design process

- to demonstrate the relationship between design theory, (the model), and means to design, (design aids)

- to explore in depth the methodologies and problems of concept generation,

By the production of a model of the engineering design process it will be demonstrated that fundamental principles exist which are applicable to all forms of engineering design. It will be argued that a structure exists which is applicable as a formalised methodology, and thus a crucial element of designer support in large scale or complex design, and that this structure will also serve as a vehicle for the understanding of the cognitive elements which operate within the designer. Thus the model is seen as providing support for the structuring, organisation and control of design when design takes place in any formalised manner and as a theoretical framework for the comprehension of informal design. These statements raise certain questions about the purpose and usefulness of both design models and design methodologies, as well as the relationship between the two. These issues are acknowledged and are discussed in detail within the section related to model, (3).

A second purpose which the model is to serve is to allow for an in depth analysis into the kernel of design, the generation of design concepts. By this phrase what is meant is that the core of every design is the idea or concept which it is hoped will prove the solution to the design problem. The generation of such concepts is the most essential element to the entire design process. However before it is possible to accurately discuss the methods, approaches and constraints which are involved in this process it is extremely important to understand fully, its relationship with the rest of the design process.

The definition of the relationship between design aids and the engineering design process is important in two ways. Firstly, it is only possible to fully comprehend the way in which finalised designs come about by taking a holistic view of all the elements which contribute to them. Secondly, by defining this relationship it becomes possible to integrate and thus optimize the way in which they both contribute to the process as a whole.

It would perhaps be useful at this stage to offer a definition of what exactly is meant by design aids, and contrast this to what is meant by design process. Design aids are the means to design.

They are those things which assist the designer to formulate, manipulate and represent his ideas. Such a definition includes such physical items as pencils, C.A.D. systems, graphs, literature etc., but it also includes, or allows for the possibility of, methodologies and procedures etc., which may well be considered non-physical aids.

The design process is the structured relationship of information which exist separately to design aids but to which they contribute by assisting with the supply of this information. Design aids thus exist to help the designer to generate and manipulate information, the process of design determines the flow of this information.

The generation of design concepts is the most central element in the design process. The importance and place within the overall process can only be fully understood when it is presented within the context of that process, and this is gone into in considerable depth later in thesis. However it is possible to highlight its major characteristics and their relevance to design.

Design is a process which has as its initial starting point this perception of need. Before however this need can be satisfied it must to some extent be given definition. Once a need has been clearly defined it is then possible to attempt to create possible solutions. It is the generation of these possible solutions which requires the generation of design concepts. Design concepts can fulfil either minor elements of the design requirement or sub-functions and whole functions, and in the case of some design may well fulfil the entire need. It is the way in which these concepts are generated that will occupy one of the main subject areas of the thesis. Without the generation of design concepts no design can take place and as such they occupy an extremely important position within the process.

1.2. Purpose

In this section the overall motivation behind the subject area will be explained. In the previous section what will be undertaken within the thesis was explained, in this section I shall explain why these aims were chosen. The purpose of this thesis is to demonstrate through the production of a consensus based model of the design process and an in depth analysis of the major element. Within that process, the generation of design concepts, the way in which all design takes place. Thus a model of the design process will be developed which outlines the framework and main characteristic of design process, and which also describes the way in which these elements inter-relate. As a result of this it is hoped that a greater understanding of the process will be achieved. This in turn it is hoped will lead to benefit in such areas as,

- Design Education,
- The introduction and improvement of design automation,
- The optimum structuring of organisations
- The greater understanding of information flow within design.

- The greater understanding of the problems relating to concept generation

1.3. Method

The method by which the information contained in this thesis has been gathered is through an extensive study of related literature, (this study was completed in 1987) backed up by interviews and consultations with experts in the field of design. Through this work a consensus model of the design process has been built up.

The production of any consensus model does however raise certain methodological problems. By attempting to concentrate on these elements which are agreed upon within any broad area of literature one must take a fairly broad view of that which is being said. Obviously when one asserts that similar basic points are being made, but being put forward in a different manner, such assertions are always open to the criticisms of misinterpretation or misrepresentation. It is however hoped that when attempting to demonstrate basic similarities between different literature it is demonstrated that the essence of the arguments put forward within the literature does not contradict the conclusions drawn from it. This problem is common to all forms of study which base their assertions on analysis of a wide variety of literate sources. By careful argument and sensitive analysis it is believed that these problems can to the greater part be overcome.

As well as the above general methodological problems common to all consensus based studies, there are in addition problems which specifically relate to the area of design.

The purposes for which literature of design is written differ quite considerably, these differences however can be broadly speaking put under two headings, description and prescription. Literature which is written from a descriptive perspective seeks to state what in fact does happen in the design process. Alternatively prescriptive literature seeks to recommend what should happen in design. Though these two approaches differ they are not mutual exclusive groups. Literature in the former approach is usually contained in academic works, where as the other approach tends to dominate works, which fall under the category of educational literature. Any argument that these two approaches are in some way incompatible and cannot be synthesised into one coherent consensus model of the design process is however erroneous. First the two approaches share a great deal of common ground in terms of beliefs about the structure of design and the relationships of the elements which comprise the structure. Secondly although some literature seeks to describe the process and others seek to state how the process should be conducted, a majority of the literature uses a mixture of both approaches. In the majority of cases the differences between the two approaches are not about the fundamental characteristics of the process, but rather the way in which it can be fine tuned to produce better design by two application of more rigorous procedures and methodologies. This point is argued in direct reference to the literary sources within sections (2) and (3).

A second problem with regard to the use of literary material which is particular to design is that the majority of literature is based upon participant observation. By this what is meant is that the authors of such literature base their assertions upon personal, observation, experience and interpretations of the events around them. The main criticism of this form of study is that it is subjectively based, and because of this lacks the objective authority of experimentally based studies. In response to this line of argument a number of replies can however be made. Firstly the appropriating of the use of experimentally based studies into the area of the design process can be brought into question. The use of experimental methods in relation to large scale human interactive activity and creative activity in particular is extremely restricted in terms of the difficulty they present in devising appropriate tests. Secondly it is important to remember that one of the main aims of this thesis is the production of a model of the design process. When producing a theoretical framework it is not always a necessary pre-condition to draw upon experimental work. Finally if one is to construct a framework based upon a consensus of opinion one must as such draw upon that opinion. The majority of work in the area of design is of a participant observational nature and since these tend to be the observations of experts with considerable experience in the tackling of design problems it would appear to be a methodological sound approach to attempt to draw upon their knowledge.

1.4. Structure

In this section an outline will be given of the way in which the topic areas of the thesis will be constructed in relation to one another and a brief explanation given for the reasons for doing so.

The initial area which will be dealt with is that of the model. This is seen as being both an important area in its own right as well as providing the theoretical backdrop for the detailed discussions for specific areas within the design process. The production of a validated model of the design process is thus seen both as a means of describing the process as whole and as a vehicle through which such activities and sub-processes as, concept generation, the Blackboard control mechanism and design aids, can be more fully discussed. The model as such is thus seen as a key element in the construction of this thesis.

Having produced a model of the design process it is then proposed to examine the means, through which design takes place. The means to design is seen as those items and techniques through which the designer produces design. These design aids cover such areas as C.A.D. systems, the pencil, the symbolic means of representing design, the manipulation storage and transfer of information, etc. A description and definition of these means will be undertaken.

These two elements of design, the theoretical and the actual will then be integrated to produce a full description of the process and its accompanying elements.

The control element (Blackboard Model) and the knowledge area can then be discussed. These two elements between them provide the informational resources essential to design. The control element defines the relationships between the stages of the process, it also ultimately controls the selection, manipulation and synthesis of informational resources into finalised design.

The final area which will be discussed will be the generation of design concepts. Design concepts are the key element in the entire process. Without the creative generation of possible concepts capable of fulfilling the requirements no design solution is possible. Ways in which it is possible to assist this creative activity will be examined and a psychological perspective taken in terms of the nature of the process as a whole.

2. Literary Sources

This section deals with the literary sources which form the basis upon which the model of design is formed.

2.1. Introduction

The model of the design process which is presented in this thesis is a consensus model. It has been produced by a survey and analysis of a wide variety of design related research. This section deals with the sources which have been drawn upon and discusses the way in which they have influenced the production of the model.

In the production of the model an attempt has been made to identify the major areas of agreement within the majority of the literature, these will be highlighted and discussed within the following sections which deal with particular topic areas. As such a large number of sources have been drawn upon, the discussion of them has been divided up into topic areas. These areas contain literature which address similar design topics and as such within each area a number of different approaches can be identified. It will however be argued that there exists sufficient areas of agreement to allow certain generalisations to be made and common features identified.

Although there is a great deal of variety in the types of approach used to characterise types of design activity it is non-the-less possible to divide the literature into two broad classifications of approach. These consist of prescriptive design literature and descriptive design literature. Prescriptive literature attempts to state the way in which design should be undertaken. Descriptive literature, though often no less judgemental, attempts to state what in fact takes place during design. These two approaches are often seen as being fundamentally opposed in that the differences are such as to make the interchange of information between the two invalid. The division of the two approaches is however often far from absolute. Writers on the subject of design, it will be argued, often fail to make a clear distinction between the two approaches and often move back and forth between them during the course of their works. Also it will be argued that the prescription literature is based upon the experience of a designer, usually the author himself rather than an experimentally collected empirical data. It will be argued that both prescriptive and descriptive approaches can be used to form a consensus model as the differences between the two approaches are largely ones of detail. Large areas of agreement exist in terms of what is perceived as actually taking place with divergence taking place of how these things can be best undertaken.

The above it is hoped will outline the major points which will be looked at in relation to the literature discussed below.

2.2. General Design Methodologies

The terms method and methodology are widely used in design and will be used frequently in the discussions of design literature. They apply to some extent to all design, in spite of this the terms themselves are not in any real sense given a precise definition.

Every design process may be structured into a more or less complex partial process, phase and design step with the help of a general procedural model. The resulting procedural elements are also processes within which information is exchanged. Each element has a goal which may be identified within the overall process. If these processes are to progress in a planned and methodical manner towards their goals, rules of behaviour and methodical directions must exist. These are either contained in specific methods, or in working principles. At this point two issues must be addressed. The first is that it is argued that not all design takes place within a methodology. It is true that not all design takes place within a defined methodological structure. However as this section will argue, method will be present to some extent in all design, even if only in a fairly informal manner. Secondly it is argued methodological constraints hamper creativity. Within the arguments presented this possibility will be acknowledged, but only when the methodology deals too rigorously with the creative aspects of design. It will also be argued that the creative aspects of design can be enhanced by the use of methodological procedures. When considering methods, the relationship between technical knowledge and methodical procedure must be emphasised. Even the best method is not able to substitute for gaps in technical knowledge and expertise. Methods are merely one dimension in design activity.

The use of the term method to designate a particular path to reach a desired goal is not uniform in science and especially not in practical life. On the one hand, the term is applied to complicated systems of procedure which deserve the name methodology, such as value analysis or mathematical modelling. The term also applies to simple rules of behaviour such as systematic search.

For the purpose of this thesis design method will be defined as any system of methodical rules and directives that aim to determine the designer's manner of proceeding to perform a particular design activity and regulate the interaction of the designer with available technical means, or aids.

If a general method exists, then a particular procedural plan can be set up to determine the designer conduct in a design activity for a particular case. A method may be the starting point for a number of procedural plans and these can be modified to suit different problems.

2.3. Design Education

This section will be used to discuss research which has been conducted into the area of design education. The majority of research within this area has tended to firstly attempt to outline the design process, whilst at the same time offer insight into ways in which the design might better deal with the problems inherent within that process. The general method used by researcher within this field is that of participant observation, largely taking the form of introspection and observation by experienced designers.

The foremost feature of research in this area which should be noted is that there is total agreement that design is in fact a structured process. Intuition and imagination though excepted as elements contained within the process are not viewed as constituting the process as a whole. Though the descriptions of the process that are put forward differ in detail, all contain fundamentally similar traits.

A large amount of the research in this area emphasises the morphology of the process. Glegg (1969) describes the process as moving from reality to abstract symbolic and then as the design is formed returning once more to reality. Asimov (1962) also puts forward this theme of design moving from initial perception of need, to an abstraction of the problem as a search for potential solutions is made and then the process returning to the 'real' or physical as actual finalised design solutions are formed. For Asimov (1962) this morphology of design is determined by logical steps, each predeterming the next. This last point is one which will be returned to as the sequential nature of the process is more fully examined. It is however important to note that even from the simplest and most generalised statements put forward by the researchers in this area there exists the notion of sequential movement through a process. French (1985) reiterates the theme in a more defined manner by stating that design consists of clearly identifiable stages. These stages are characterised by the activities which take place within them and consist of generation of specification, generation of design concepts, the evaluation of these concepts and finally the production of the finalised design. Alger and Hays (1964) though placing greater emphasis on the roles of experience and reflection by the designer in the design process than other researchers in the area, also stress that design is a process that moves from need, through a phase mainly characterised by abstraction, towards the final realisation and implementation of design. Indeed they state that a design process does exist, just as a work-flow process seems to exist for many kinds of works, (pp 10). Again Alger and Hays also see these phases which constitute the process as being definable into stages each of which fulfils a particular purpose within the over-all process and which follow each other in a sequential manner.

Though there is general agreement that design is a process and that it does have a definable sequential structure, there are considerable differences in the way in which this structure operates, its component parts and the degree of definition which is applicable to these parts. Glegg (1969) for example offers a set of broad phases as a description of the process, stating the generation of what will take place within each. Pahl and Beitz (1984) in contrast detail the sub-components or sub-activities within clearly defined phases stating the way in which design progresses within each of the phases and stating the way in which they interact with each other and the overall process. The work of these last two authors can be used to highlight a problem which exists when attempting to discuss the sequential stages which constitute the design process. When describing the design process the description of the activity often becomes blended with prescriptive advice, on how best to improve designer performance. The distinction between what does happen and what should happen is thus not always totally clear. Cain (1969) recognizes this problem and firstly offers a generalised description of the process and then 'advocates from experience' (pp 7) the use of methodology as a way of clarifying the process and increasing the likelihood of a successful design. Cain (1969) argues similarly to Asimov that design is a logical process, and from this point of view goes on to assert that for the best design results the process should be formalised into a method. Pahl and Bietz(1984) take this theme slightly further by expressing the design process through formalised decomposition, offering a systematic method to help the design over come the problems which present themselves at each stage and sub-stage. Asimov similarly though to a lesser extent blends description and methodological advice, as does Gosling (1959). Beakley and Chilton (1974) also offer description and advice. For these two authors design is a sequential process which is described as one which moves from the general to the specific and which proceeds through the stages of, feasibility study, preliminary design and detail design, the latter resulting in the final design configuration.

What is apparent from studies of the research in this area is that in the main the basic conclusions about the nature of the design process are extremely similar. Before moving on to examine in more detail the way in which the descriptions and methods presented in this area differ in their detail a number of points can be made.

Design is a process consisting of identifiable stages. The stages exist in a sequential relationship. These stages can be decomposed in such a manner so as to allow for the implementation of some form of method. The use of methodologies is seen as assisting with the production of a successful final design. The design process can be typically described as starting from the point at which a need is perceived and actions are undertaken to try to fulfil that need. The design process moves from the initial perception of need through a phase or set of phases which can be characterised by abstraction and search. From the activities which take place within this phase a final design configuration emerges.

Though the research overwhelmingly agrees with the above points there is substantial divergence in the actual detail as to how the actual process is constructed. J. C. Jones (1963) for instance though agreeing with the basic components of the process as outlined above, places great emphasis upon the degree of complexity in the design. Complexity in design for Jones is not purely a technical consideration but rather gains the greater part of this characteristic by its relationship with the external environment within which it is to exist. Jones states, (and this is reiterated by Stevenson (1973)), that there are four levels to the complexity of a design. These can be categories by the designs relationship with, component Product, System and Community. For Jones it is the relationship between the design and each of these four different levels which creates the degree of complexity of a design.

Buhl (1960) and French (1985) alternatively are amongst those for whom the creative aspects of design constitute the major element in design as a whole. Though arguing that design is a sequential process with identifiable stages, these authors concentrate upon what is basically the core of the design process, the generation of candidate designs. Though most authors offer some guidance as to possible methods through which greater success in this stage may be obtained few do so in such detail. Pitts (1973) for example though emphasising technique as being an essential aspect of design, deals comparatively briefly with methods of generating partial or whole solutions in a systematic manner. Krick (1965) similarly though explaining both the design process and methods which can be used to advantage within it, all be it in a simplified manner again emphasises the importance of both the creative stage in the design process and the use of techniques to improve results at this stage. The aim of this particular area within the discussion of the literature is to make general similarities in the findings and conclusions drawn by the examined authors. For the purpose therefore of this discussion it is not felt necessary to fully outline the types of method and techniques advocated by the author. This conclusion is based firstly on the need for clarity and secondly as these techniques are fully discussed within their own section which deals specifically with the types of method which can be used to aid creativity during concept generation, within the section on design aids.

Much of the work in the area is quite similar and many authors appear to build on the work of previous authors. Woodson (1966) for example appears to draw heavily upon the work of Asimov (1962). Due to this fact I now propose, as it is impossible to give detailed accounts of all the authors in this area to discuss in somewhat more detail a number of authors who represent broadly similar sets of work.

A great deal of the work in the area of design education were written as introductory texts. Asimov (1962) who is one of the earliest advocates of design method and who appears to have greatly influenced many latter authors, offers a fairly structured view of the design process. For Asimov the first division which can be made in design is that of the type of design which is taking place. These types of design are classified in terms of whether a design is an evolution of a previous design solution, or whether it requires innovation. Within these two types of design Asimov asserts that the same factors will determine the outcome of the process. These factors are considered to be, available money, possible profit, time allowed, laws and standards which set the parameters of the design envelope and social feature, such as pollution, noise etc. Within these parameters however all designs follow a set of basic rules which it is claimed are determined by a natural logic.

The process of design is viewed as sequential consisting of two phases which can be sub-divided into a total of seven sub-stage. It is noted that the use of defined phases composed of sub-division is common technique used in most design literature which though a useful device for the explanation of phenomena within the design process does not always reflect the reality of the process. When discussing these stages the precise division used may not actually occur within the process and overlap may be the case.

Asimov's two phases consist of primary design, which is the initial phase and the production/consumption phase which is the implementation of the first. It is Asimov's initial phase which I propose to discuss as though important, the production phase with its emphasis on marketing, production and distribution, does not deal with the generative aspects of design which are the primary interest within the context of this thesis.

The initial phase is sub-divided into three sequential stages. These stages consist of the feasibility study, the preliminary design and the detailed design. The feasibility study consists of the definition of the design need, the identification of design problems in fulfilling this need and a study of possible ideas and concepts which could be combined to fulfil these needs. The results of the feasibility study determine the course of action within the second sub-stage, that of the preliminary design. The preliminary design concepts. These are concepts which are produced as possible solutions to each of the aspects which constitute the design requirement. The concepts are then constructed into archetypes. The archetype stage consists basically of forming groups of design concepts into possible design solutions. Analysis is the next stage during which the archetypes are tested against the previously defined requirements. Finally optimization takes place during which designs are modified and their various characteristics are enhanced or negated.

The final stage consists of the Detail design phases. During this stage the design is embodied and given exactly defined characteristics. Firstly sub-systems are constructed. This is done through the decomposition of the preliminary designs into sub-units usually defined by function. The subsystems are then produced and constructed into components. These components are then brought together to form whole assembled systems and finally the complete design is realized. Finally analysis is once again undertaken to assess performance and enable the designer to predict likely areas which will require modification in the finished product.

The above description of Asimov's ideas on design have been produced for a number of reasons. Firstly as previously stated the author is highly representative both of the general ideas put forward by a number of authors and of the general approach to design by the majority of the authors in this area. Secondly the description provides a useful point of reference in terms of other works in this field. Pahl and Bietz (1984) for instance though writing nearly twenty years after Asimov have striking similarities in their approach. Though offering greater detail in the way in which they advocate the use of systematic method in their approach, the sequential division used in their definition of design stages and the sub-phases within those appear to coincide with Asimov's thoughts in this area.

For Pahl and Bietz the design process commences with the clarification of the task. Similarly to Asimov (1962) Pahl and Bietz view the initial problem of design being that of the correct clarification of the actual problem. The actual requirements which are produced from this stage will ultimately determine the design and though it is always possible to modify requirements the importance of having a clearly defined and accurate specification requirement is emphasised. The next stage of the process is that of the conceptual design. Here design concepts are generated which could possibly fulfil the requirements. The process of concept generation is viewed as being greatly enhanced by the use of systematic method. Methods of decomposition search, synthesis and recomposition are advocated and described in some detail. Like Asimovs Preliminary design stage, Concept Generation is viewed as being the key aspect of design. However unlike Asimov's second stage Pahl and Bietz do not view embodiment as taking place within this stage. The point could be made that through using the same phrase, that of embodiment Asimov and Pahl and Bietz refer to slightly different aspect of the process. For Pahl and Bietz embodiment consists of the process which follows that of concept generation when the initial conceptual solutions are given a lose form. Asimov however sees this process as taking part within the product of archetypes, a phase which roughly corresponds with that of the production of candidate designs. In the Pahl and Bietz model however the production of candidate designs comes as the end of the conceptual design phase.

The detail design phase is Pahl and Bietz's final stage where precise detail is given to the previously developed systems and subsystems. Interestingly the Pahl and Bietz model incorporates the analysis element within each of the final three stages rather than as many models do, having it exist as a separate stage within the model.

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The notable difference between these two models would appear to be in the emphasis placed upon the use of method, rather than any fundamental difference in main characteristics of the design model.

2.4 Systems Science and Systems Engineering

Systems science and systems engineering have had a major influence upon design thinking and the way in which the entire design process is perceived. As such the literature relating systems theory to design is very considerable. In this section it is proposed therefore to discuss both systems theory in general and specifically the way in which it has contributed to the understanding of design as a whole.

There is no precise date at which it is possible to state that systems theories first appeared, though there appears to be general agreement that it is a comparatively recent paradigm. The Radio Co-operation of America, (amongst others) recognised in the 1930's the need for a systems approach in the development of a television broadcasting service. During and since the Second World War many Operations Research groups contributed both philosophy and techniques. The Rand Corporation created in 1946 by the U.S.A.F., developed an important set of techniques which it called, 'systems analysis'. Schlager (1956) found that 'the Bell Telephone Laboratories, Inc., were probably the first organisation to use the term systems engineering'. If this is true, the use of the term with roughly the present meaning began in the early 1940's. The meaning of systems engineering though probably not amenable to a clear, sharp, one sentence definition can best be characterised by listing its facets. These broadly generated are:-

- A holistic approach, viewing the problem in its totality and within its correct context.

- The decomposition of the problem into its basic functional characteristics.

- The expression of the relationship between the various decomposed elements in a formalised manner.

The above stated general characteristics could in fact be made of most of the types of systems theory. Where approaches tend to differ is in the types of techniques which might be brought to bear upon a specific problem area rather than any fundamental difference in general approach. All the areas which together form the systems approach or systems theory consist of sets of concepts and techniques which provide the means by which complex events or items can be described and analysed and from which it is believed useful information about the true relationship between the constituent parts of that item or event may be gained. By this means it is possible to model situations or mechanical problems and predict the effects of changes and detect the significancs of areas within a system which may previously have gone unnoticed.

The essence of systems theory lies in its ability to describe in abstract a situation, event or item and from this description analyse and produce possible scenarios. It is types of techniques which can be used to achieve this that basically characterise the systems approach.

A system is decomposed and abstracted to its most basic functioned units and sub-units. The relationship between these functional entities may then be described in terms of inputs and outputs of such items as signals, materials, force and information. The Input-Ouput principle forms much of what might be considered to be at the centre of a systems approach. This principle removes the limitations of a problem defined in purely technical terms and extends the definition of input, output and constraints, to include the whole situation, men, money, materials, machines and methods. It thereby provides an overall view and allows the designer to arrive at a more comprehensive, unified and long - lasting solution than any approach which considers each of the components of a system individually and in isolation from the system as a whole.

Thus, in applying a systems approach, say to a problem involving the manufacture of a chemical, the designer would not be limited to the technicality of the process, choice of materials of construction, design and performance of mechanical and electrical equipment and methods of measurement and control. The designer would in addition be concerned with,

- The problems of processing and handling of raw materials.

- The methods of transport.

- The use and disposal of finished products.

- The recruitment, training requirement and working conditions of the management and workers needed to run the plant.

- The effects of the product and its manufacture on the local environment - the noise, smell, smoke and residual pollution produced.

The more complex a design problem and the greater its potential impact on people, the more appropriate a systems approach becomes.

Though there is a very large amount of literature concerned with the systems approach most of the fundamental development of the discipline has been carried out by a comparatively small number of authors. It is to these authors that I shall now turn. Most authors agree on a number of basic issues. Firstly the general characteristics of the approach described above and secondly that the approach is a sequential one, whereby a problem is dealt a stage at a time, though the degree to which these stages are divided is an issue about which there are differences. Jenkins (1969) suggests that there are four main stages in the systems approach: analysis, synthesis, implementation and operation.

Analysis

- What is the problem and how should it be tackled?

- What is the nature of the primary system in which the problem is embedded and the wider environment in which it, in turn is contained?

- What are the objectives of these respective levels in the systems hierarchy? Are they stated clearly and are they consistent with each other?

- Has all relevant information been collected? Have all constraints been identified (and all false constraints eliminated)?

Synthesis

- What are the expected changes in the system under consideration?

- How accurate are the forecasts likely to be?

- What models can be built of part or the whole of the situation describing behaviour, processes, operating conditions etc.?
- What can be done to ensure that the best system is realised in practice?

Implementation

- Is the final design fully understood?

- Is its implementation adequately planned and its integration into the wider system properly organised?

Operation

- Have operation and maintenance procedures been prepared and put into use?

- Is there a continuing feedback of operating experience to designers and are worthwhile improvements introduced?

- Is ultimate obsolescence and replacement catered for?

Techniques of use in such a comprehensive approach are numerous. Moore (1966) lists over thirty, including Critical Examination, to get the problem right, Critical Path scheduling to plan and time the project, Management by objectives to define the aims of the entire venture and Modelling and Simulation, Risk Analysis, Reliability Studies and Control systems to aid design.

H. Chestnut (1965, 1967), one of the most referred to authors in the area, emphasises that all design should be viewed as taking place within its social context. Within this social context it is the sub-area of socio-economic relationships which Chestnut sees as exerting the greatest influence. The socio-economic area is that which concerns itself with the effects upon design of such items as marketing, distribution, sales, national and international standards and relevant legislation etc. The above mentioned factors all combine together to set limitations upon the possible design solutions prior to the design initiating the first steps. .The design preliminary activities are seen as being extremely important by Chestnut. In forming an initial design specification Chestnut argues that the first areas of concern should be those of value and need. These factors are determined by the socio-economic context within which a design is to take place. The aim of this activity is the formulation of a value model. A value model is an abstract construct designed to express the degree of desirability that any of the characteristics of a design might have. In almost all design an exact matching of a design to the value model will not be either possible or alternatively will not feasible. Because of this the value model will need to be both flexible and open to modification. It is often the case that the differing values placed upon the elements which together constitute a design will have to be placed off against one another. See fig (1). The way in which such decisions are undertaken is covered at some depth in the section dealing with decision theory (2.7.). Chestnut, as do many other systems orientated design theorists sees design as comprising of a four stage sequential process. These stages basically consist of, Formulation, Production of structure, Testing and production of Finalised solution. Churchman et al (1957) though actually listing six phases for the design process demonstrates more similarities than differences to Chestnuts view. Churchman's phases are as follows:-

1. Formulating the problem

2. Constructing a mathematical model

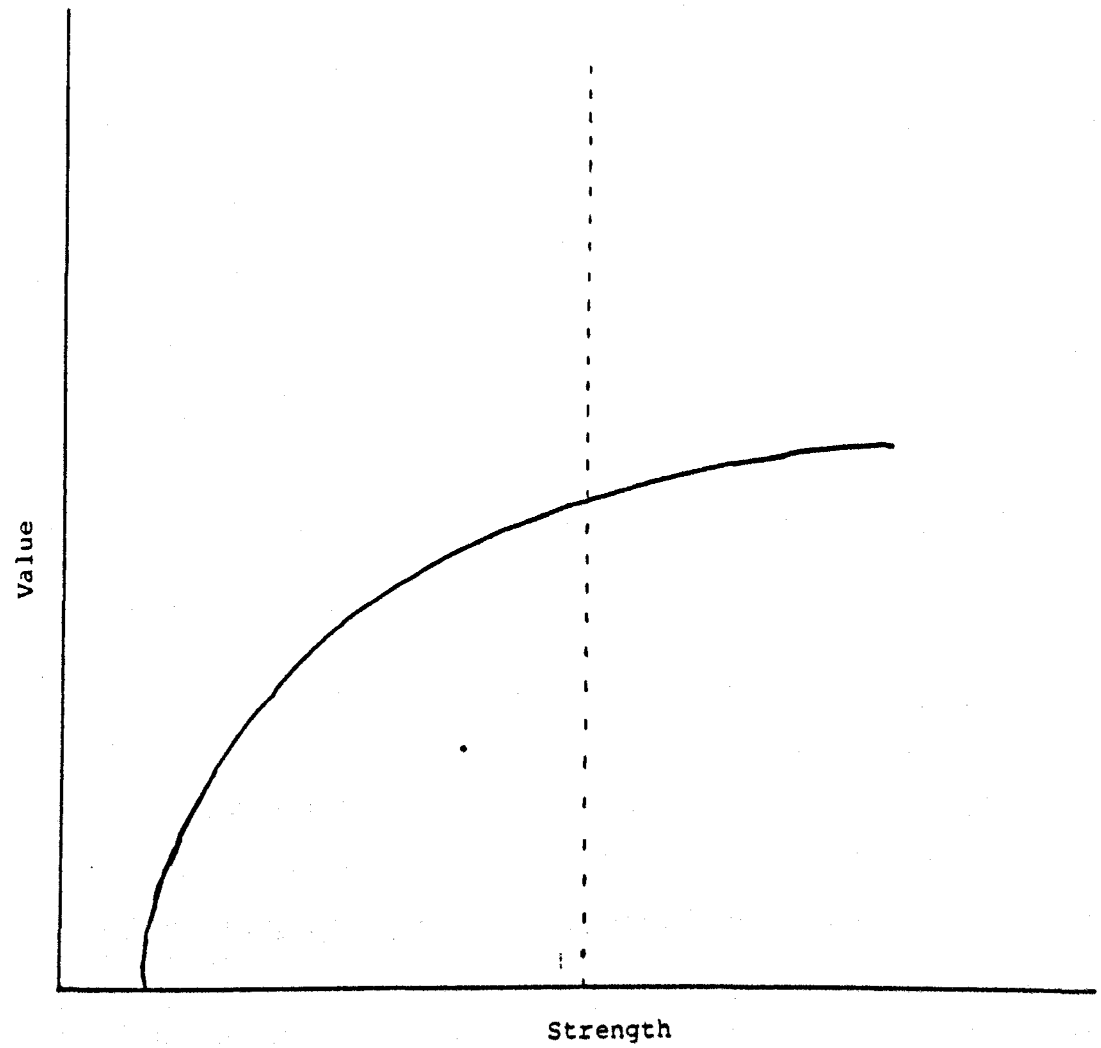
3. Deriving a solution from the model

4. Testing the model and the solution derived from it.

5. Establishing controls over the model

6. Implementation: Putting the solution to work.

Fig. 1.



The value of a particular quality (in the above example strength) may well, beyond a certain point, decrease, thus necessitating the need for a measurement of the value beyond that point relative to its value prior to that point.

(From Systems Science and Systems Eng.)

In the Chestnut process model it is the structure phase during which the greatest part of the design activity takes place. During this stage the structure of the problem is outlined. Goals, sub-goals and objectives form the basis by which the design problem is to be dealt with. Chestnut (1965) sees the main concern of the designer being that of the construction of valid models firstly of the design problem and then of the possible ways in which a solution can be achieved. He asserts that all design models will consist of variables and that it is these variables which will determine the outcome of the designer activity. A major feature of this work by Chestnut is the emphasis that he places upon both optimisation and probability as methods by which the designer can determine the relative values and needs of all the design problems constituent variables.

Wymore (1967), another leading researcher in the area, also places great emphasis upon the construction of systems models as a means to successfully accomplish a design. Wymores major concern is with ways in which a system can be described. Basically he views all systems as belonging to one of two types, the Input-Output type of system described earlier in this section and the Homomorphous. The difference between the two types of system, sometimes also referred to as hard and soft systems, as that one can be adequately described by reference to the interaction of components in terms of mathematical models and the other, soft systems cannot. The latter consist predominantly of human activity systems and all systems where there exist difficulties of description and measurement. Though homomorphous systems effect the design process and the system within which the design will take place they exercise their influence upon the process from the periphery with the substance of the design process still remaining amenable to Input-Output type systems description. Wymore describes ways in which is possible to couple together both different systems and different types of system. Wymores approach is typical of the systems approach in general towards the production of design. Systems should be decomposed into sub-system components and these sub-systems should in turn be further sub-divided into groups and sub-groups until the system is completely defined. Finally to complete this definition discreet systems which may exist within the system should be looked for. Discreet systems are those systems whose relationships between system elements are not always obvious, as in their effect upon a system. Beyond the difference in treatment and an emphasise upon the use of mathematical modelling techniques, in theory and approach Wymore differs little from the other leading researchers in this field.

Gosling another prominent and frequently referred to researcher in the area of systems also states that design will be best performed when it takes place in a structured sequential manner, (Gosling 1962, 1959). For Gosling the process of sequential design fundamentally has three major phases. These consist of generating the specification, conducting studies of feasibility and finally realisation of the completed design. Similarily to the majority of research in this area Gosling places great importance upon the way in which the description of the system and its components takes place. Importance is attached to the methods of representation which can be used and the general production of a systems model. Methods of generating design solutions are also examined. Firstly for specification Gosling advocates a description of the basic system which will be required, followed by the establishment of a value model and finally a description of the systems inputs and outputs. In addition to this an examination and statement of the general parameter within which the system will have to be made. This basically comprises of an examination of the way in which the environment within which the system will have to operate will effect that system. The generation of specification completed the feasibility phase is now undertaken. This phase is characterised by the construction of possible design solutions as systems models and comparing their performance against the requirement specification. Again, much importance can be attached to the methods and techniques which are available to the designer to assist him when making difficult evaluatory decisions.

Goode and Machol are also influential researchers who have their work frequently referred to. Goode and Machol (1957) emphasis the way in which systems descriptions often appear to be idealised and how important it is that redundancy, congestion and overloads be identified both within actual systems and in the design of systems prior to implementations. The holistic approach towards design is again put forward by these researchers as a main aspect of the systems approach which can assist the designer, Hall (1962) though writing predominantly as an education rather than purely a theoretision, is none-the-less a respected and often referred to author in this area. For Hall design is a structured process which requires the decomposition of the design problem before any attempt can be made towards the generation of a design solution. Typically the emphasis of his work lies in the description of the system through decomposition, identification of relationships, search for possible solutions and finally re-composition into a total system once again.

Systems theory as a whole contributes to the discipline of design directly by both providing its own approach and by offering supportive elements which can be incorporated into a complimentary design model. Holism which is an essential feature of systems theory specifically assists design theory by providing a method by which all possible elements which are part of and which impinge upon a system are taken into consideration. By this means both a greater understanding of the design problem can be obtained and a design produced with its parameters more fully understood prior to final implementation.

A second specific contribution is that of the understanding of the importance of decomposition of a design problem and its possible solutions. By the decomposition of complex systems or entities into simpler sub-components, simpler descriptions of function are possible and thus solutions can be drawn from a greater potential area, widening design choice etc., and making the system easier to deal with, prior to re-composition. Finally isomorphism in terms of function, structure and behaviour, is also a concept which contributes greatly towards design theory's list of potential aids and techniques. Basically what is meant by this term is that often the decomposed systems description of a particular system may also often be valid for an alternative system, for instance, electrical and mechanical systems and as such can often supply a rich source of analogous material. Systems science provides the theoretical basis upon which systems engineering has been built. Systems engineering is a discipline highly relevant to design and design theory as it possesses as its main characteristics, the design, implementation and operation of complex systems. The main contributions to design theory provided by systems science are a systematic sequential approach, a holistic approach, the use of decomposition as a method of definition, identification and generation in terms of design problems and their solutions and finally further emphasis on the exploitation of analogous areas as a source of potential solutions.

2.5. Creativity

The process of design is above all a creative process. Creativity is the essential part of all types of design, from those which are minor adaptations, to those which are totally innovative. This section will discuss the areas within the design process where creativity is at its most evident and the ways in which creative performance can be enhanced. The discussion will be divided into three main parts;

1. Creativity in problem identification

2. Innovative thinking

3. The creative design environment

The above three areas of discussion have been chosen because between them they represent the major areas of interest identified by researchers within this area. The word creativity when used in the context of design refers to those activities which require the designer to use his skills imaginatively so as to produce, or create new concepts and associations.

1. Creativity in problem identification

Problem identification forms a major part in a number of the design stages, most notably those of the generation of specification and the generation of design concepts. Seeking the correct problem to solve is an essential prelude to successful design innovation or adaption. Problem identification must start with a search for discrepancies between what is and what might be and end with a clear statement of this mismatch. Writing on the subject of originality Mackworth (1965) went so far as to suggest that problem identification is more important than problem solving.

A designer may be able to identify a problem either intuitively or by drawing upon his experience. When however this is not possible, a number of methods are available to him. One of the most powerful, and simplest methods for identifying a problem is to gather all available facts and information concerning the problem together and subject them to critical examination. This method basically takes the form of,

What?	(is at present achieved/	is proposed/	is needed)
How?	"	"	"
When?	"	"	"
Where?	"	"	"

and then asking the question, why?, to all of the answers gained. This is not the only way of twisting the problem around to gain a new perspective. Osborn (1963) gives a whole checklist to enable the designer to expand his view in order to see the problem in a different way:

Adapt?

Modify?

Magnify?

Minify?

Substitute?

Rearrange?

Reverse?

Combine?

The analytical approach of critical examination may thus help the designer to strip away irrelevancies and false assumptions and present the problem in its essence. It may also however be necessary to diverge and look around the problem again in an open ended manner so as to discover appropriate openings leading to a better description of the problem. In describing the synectics method Gordon (1961, 1964) uses the phrase 'making the strange familiar' by which he means that when the problem is reduced down to its essential features, it may be in such a form that it can be identified by analogy in a number of quite unconnected areas.

The above mentioned techniques are all aimed at enhancing the designers creativity when attempting to correctly identify the essential problems which he may encounter either when generating specification or generating design concepts. These techniques however do not apply solely to problems of identification and as such are not greatly elaborated upon in this section, but rather in the following section where their influence is substantially greater.

2. Innovative Thinking

The process by which innovative thought occurs spontaneously is one which is still little understood. Psychological explanations of the phenomena are generally vague and at best unhelpful. Indeed Jung (1910) stated that he thought that the whole area of creativity was not one to which psychological explanation could be given and advised those interested in the area to talk to artists. However though spontaneous creative thought is not well understood theoretically, the means by which creative thought can be encouraged have received considerable attention. The majority of work in the area of creativity deals in one way or another with inducing or enhancing the process. There are basically four main sets of methodology in the area of creativity: Synectics, Fundamental design method, Lateral thinking and Brainstorming. Though other individual methods exist each is reliant at some stage on one of the above.

Synectics

Synectics comes from a Greek word meaning the joining together of apparently unconnected elements, and is one of the oldest systems for stimulating creative thought. It is basically a simple method, though it covers most of the problem solving sequence. The particular characteristic of this method is an enforced withdrawal from the problem and an exercise in free association which provides new ideas for solving the problem when attention is returned to it. Gordon (1961) discusses the method in some detail. Other descriptions, Prince (1968 and 1969) and Raudsepp (1969), for instance, differ in detail but not in essence.

Synectics is generally advocated as a team approach. The first step in the Synectics method is to agree on the problem. It is suggested that this process of problem clarification and identification will often result in several possible solutions being produced. Once the problem has been identified it is then ignored. By this what is meant is that the group or individual should then proceed to explore a totally unconnected subject area. This new area however should not be chosen completely at random. Though distant from the problem area the new area should at least appear to be capable of providing useful analogies. Conceptional distance is however important as areas that are too closely related, for instance, civil engineering and mechanical engineering, may have too much over-lapping convention or knowledge for a new viewpoint to be generated.

Gordon (1961) observes that biology is the richest source of analogous problems and solutions for most types of problem.

Having discussed the original problem in the context of the new area (the analogous area) the discussion should be returned to the original problem context and new solution ideas should be forth coming. In the group situation all the researchers emphasize that the group should be as supportive to each other as possible. Criticisms are not excluded but emphasis on positive aspects of any suggestions are seen as helpful.

The Fundamental Design Method

Though the title, The Fundamental Design Method, was originally given to the group of methodologies by Matchett (1968) it is basically not just referring to Matchetts method but also to a number of similar methods and techniques. Similar ideas were put forward as early as 1958 (Barron 1958), Hudson (1968) at approximately the same time and Carrol and Thomas (1975) some years later. Many other authors have also said similar things about this creative method, though usually in a less defined manner. The Fundamental Design Method, as defined by Matchett (1968) is a highly disciplined form of thinking whereby the designer critically examines the controls and restraints which he already imposes upon himself as he starts to approach a design problem. It is a highly introspective technique. Advocates of this method argue that designers are normally bound by force of habit to a particular set of approaches to any problem. When a design problem arises which has in it some aspect that the designer recognizes, it is argued that the response to that problem will be governed to the greater extent by the approach which was previously used. The designer will in this case lose flexibility of thought and self impose controls on his approach, which he may not be aware he is doing. Unless the designer can locate and identify these restraints then he will limit and bias the range of possible design solutions he can produce. Carrol and Thomas (1975) argue that to uncover these controls the designer needs to create a model with which to describe his basic thought processes. This model should be his own personal one and will be meaningful probably only to him.

Some exercises are put forward as being helpful to the designer in exploring his mental processes. These are best used and adapted according to the person, the situation and the specific problem. Jones (1970) summaries five of these techniques as:

1. Thinking with outline strategies - sketching the broad picture before getting down to detail; standing back to get the wider view.

2. Thinking in parallel planes - taking a detached view of the separate parts of a total situation - problem, people, methods, instructions etc - and at different levels of abstraction.

3. Thinking from several view points - seeing a problem from different angles, opening it out by the use of checklists, diagrams charts, matracies.

4. Thinking with concepts - representing in some symbolic way the problem, solution and interlinking thought processes.

5. Thinking with basic elements - analysing mental processes into identifiable elements (recognize need, imagine decisions, weigh and compare, predict, back check, scan assess risk, remove obstacles, etc.).

The method is not designed to provide a standard way of tackling problems and arriving at creative solutions. Nevertheless the exercise and techniques used have been assembled by others into systematic approaches to problems. PABLA (Problem Analysis by Logical Approach System), developed by the U.K. Atomic Energy Authority and P.A.M.,(Provide a Means Diagram), developed by the Fleet Work Study Team are such systems.

These types of methodology assist designers to approach problems in a rigorous way, questioning each part in turn and displaying the logical progression of the design. Both emphasise the mental attitude needed to apply the system successfully; discipline, flexibility and awareness of the reasoning processes employed.

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Lateral Thinking

This approach provides a simple method to the approach of creativity as a mental skill. It is suggested that there are two sorts of thinking. The first sort is the most easily recognised when it leads to ideas that are obvious only after they have been thought of. This is called lateral thinking and is considered quite distinct from the second and more usual logical or vertical thinking. Lateral thinking is especially useful in generating new ideas. In vertical thinking, progress is made by one logical step following another and at any one point in the process there is a logical pathway back to the starting point. Lateral thinking, in contrast, follows a path which is uncommon, not dictated by logic alone and which by moving away from the logical pathway can often lead to new and innovative ideas. De Bono (1967, 1969, 1971) who first used the phrase and is the main advocate of this form of creative method, compares vertical thinking with the flow of water along well-defined channels: the more it flows the more likely it is to continue to do so along the same channel. Lateral thinking he claims is analogous to damming up the old channel and cutting new ones to see where the water will flow.

Lateral thinking is at its most useful when there is no previous solution to draw on, when present solutions are inadequate, or when a new view of an old problem is required. It is a mechanism for freeing the mind from habit and pre-conception and allowing an opportunity for wider exploration of solution areas. De Bono states that whereas in vertical thinking logic is in control of the thought processes, in lateral thinking the thought processes are in control of logic. Lateral thinking is for generating ideas. Vertical thinking is for developing, selecting and using such ideas.

The techniques for developing lateral thinking include:

1. The Intermediate Impossible. To break the constraining effect of logic an intermediate impossible is introduced to act as a conduit between the limits of knowledge surrounding the problem and the desired solution.

2. Random Juxtaposition. Similarly to the intermediate impossible this acts a conduit between limited knowledge and desired solution. In this case however a random

concept is introduced in the hope that some association will be made from it. This method is similar in many ways to that of synectics.

3. Searching for different ways of looking at things. Closely analogous to Critical Examination and the use of a systematic approach, this method aims to provide a new view point on the problem.

Brainstorming

This method was designed as a group activity. The method consists basically of people contributing ideas for solving a problem in a spontaneous manner. This technique was first explored by Osborn (1953) as long ago as 1938. For the method to be at its most supportive of creative innovations Taylor (1958) states that:

1. No criticism of any idea should be allowed. Judgement must be withheld until the end of the session.

2. All ideas should be welcomed.

3. The production of the greatest number of ideas should be encouraged.

4. Building on ideas to create a group chain reaction should be encouraged.

These guidelines aim to ensure that there is a relaxed environment where people can think freely and adventurously. The problem to be tackled must be stated clearly and simply, multiple problems will lead to too great a diversity of themes being persued and probably confusion. The group should be carefully balanced with as little as possible hierarchical structure. The session itself should be as informal as possible but with the rules firmly applied.

Brainstorming is useful for generating a lot of ideas for later developments into a solution. It has little or nothing to offer if the number of alternatives is restricted. To provide a supportive environment for the expression of ideas, all analysis and judgements of theme value should be suppressed during the session. Later the ideas produced can be analysed and the best chosen for possible development into solutions.

Brainstorming is one of the most widely known techniques for generating ideas. It can be used for producing information, or a list of unknowns, or further question to be asked. It requires very little training to use and can be made to be applicable to most innovation requiring problems.

The above four methodologies form the basis of the creative methods available to assist the designer. Other techniques do exist, Delphi and 653, for example, however most of them are in essence similar to one or other of the above.

3. The Creative Design Environment

The environment within which design takes place can affect creativity in a large number of ways. The design environment for the purposes of this discussion will be considered to be not just the immediate surroundings but all factors external to the designer which might in some way influence him.

The importance of immediate colleagues who provide both support and challenge, is discussed by Pelz (1967), who suggests that a stimulating tension is created between sources of stability or security on the one hand and sources of disruption or challenge on the other. Conditions of security include the opportunity for self-reliance and for the pursuit of the innovation ideas. Challenge is found in discussion and disagreement with colleagues, who may have different values and use different strategies, by periodically re-grouping teams; and by involving a person in a diversity of jobs which require new skills. Also important is what Lasswell (1959) calls a resonant relationship between the innovation and a person of similar skill and enlightenment. McPherson (1965) develops the idea of a productive partnership between the 'ideator' who produces the ideas and a 'sifter' who picks out the best of them, gets them developed and protects the ideator from criticism. Such partnerships, McPherson says, are based on mutual respect and trust, the creative partner benefiting particularly from the stimulation provided by the other and the opportunity given him to discuss his ideas with someone who though understanding them will not steal them.

Though interpersonal relations are very important to stimulate creativity, the dynamics of a design group as a whole are also extremely important. McPherson (1967) states that personal qualities that should exist within a design group should consist of those capable of, creative thinking, analytical thinking and judicial thinking. All are necessary in the innovation sequence and should all be available in the group in sufficient strength at any time. The innovative group must therefore be considered from the point of view of its intellectual composition as well as its professional and personal make-up. Creative thinking, analysers and those with balanced judgement must be mixed in such proportions that the essential optimum, risk-taking and technical exploration of the creative component is countered by the risk avoiding, backward-looking analytical component and both are assessed and a realistic judgement is made by the judicial component.

In addition to the types of character traits which should be present within a design group if innovation is to flourish, the orientation and structure of the group are also important. Likert (1961) and Pelz and Andrews (1966), who have made indepth studies into the working and make-up of effective innovative groups, all seem to be in agreement on what makes an effective group.

1. Members have a clear idea of what they are trying to achieve and are not easily diverted from that objective.

2. Individual members have a real interest in the problem and the solution. Their personal objectives are consistent with carrying it through to success.

3. Members make a full contribution according to their ability and assist each other in drawing out ideas. Co-operation and support is accepted as the way to achieving the best result.

4. Though personal competition is small, intellectual challenge is high.

5. Short-term leadership tends to rotate according to the immediate needs of the job.

6. Decisions are made by the best informed not necessarily by the most senior.

Confirmation of the validity of these general statements is provided by several investigators. Hitt (1965) proposes an environment which gives the individual freedom to explore and freedom to make mistakes, but which makes him personally responsible for his actions. Eyring (1959) speaks of the importance of a stimulating environment and includes freedom from distracting influences which deflect the designers attention away from the design issue.

The characteristics of the actual work environment in terms of respect, status, appreciation and other psychological considerations is also extremely important to maintain design creatively. McGregor (1960), Herzberg (1959) and Maslow (1954) all stress that there is more to work than its physical and intellectual content and more to reward that just money. Attention to the content of the job, enriching it by creating opportunities for taking on more demanding work and by giving greater personal control, has a beneficial effect on performance and the satisfaction of doing it, according to Herzberg (1959), Paul, Robertson and Herzberg (1969) and Smith (1969).

The policies of the company with regard to innovation are also a factor which affects creative performance. Low (1968) points out that when a company is making a major effort to become market leader with a product, or within a product area, designers appear to make a greater innovative effort.

Finally the designer education and educational environment will affect his innovative performance. Whitfield (1972) contrasts the design risk-taking culture fostered by U.S. Universities with the steadier approach used by U.K. Universities, though these differences and the general effect of early design education may be overcome by later design training by companies etc., or by a combination of any of the factors mentioned in this section.

Creativity has been discussed within this section from the point of view of its effect upon, problem identification, innovative thought and the way in which the design environment effects creativity.

The role of creativity in the identification of design problems, that is, of accurately defining them, is a vital one. The generation of the specification requirement and the design candidates, requires the designer to act in a creative manner and within this part of the section the techniques and methodological supports which exist to aid him in these activities have been discussed. The importance of the need to decompose and abstract problems to allow the designer to tackle the essence of the problem is recognised by researchers in this area and a discussion of the methodologies put forward has been undertaken.

The part of the section dealing with creativity with regard to its influences upon innovative thought and its importance throughout the design process, discusses the theories and methodologies available to the designer. Synectics, Fundamental design method, Lateral thinking and Brainstorming, are all discussed as possible aids to the creative aspects of design. It is noted that again the importance of the decomposition of a design'. problem into its functional units and sub-units to allow for analogous search for possible design solutions or solution areas, is stressed within the examined methodologies.

The relationship between design environment and creativity was also examined. From the discussion of the literature concerned with this area it can be seen that the major areas of importance are those of, maintaining the correct personnel mix, of emphasizing and maintaining challenging company aims and objectives and that the training of personnel should emphasise a degree of design risk taking.

Creativity is the vital ingredient in the design process. It impinges on all forms of generative thought connected with the process but particularly upon the generation of specification and design concepts. Though the cognitive processes which constitute the basis of creativity are as yet not fully understood, ways in which the process can be encouraged and enhanced do exist, are advocated by researchers in this area and appear to be quite successful. Creativity thus is affected both positively and negatively by both method and environment and in turn is itself a force upon the design process.

2.6. Management and Organisation

The management and organisation of design has, as designers face design problems of ever increasing complexity and cost, become an aspect of design which is of increasing importance. A great amount of the design activity which today takes place does so within the context of design teams operating within organisations. Because of this the ability to successfully co-ordinate the efforts of the designer so as to maximise the efficiency of the process is an area of ever increasing significance. There is also an awareness of the way in which managerial policies and organisational environment both affect the design process. In this section a discussion will be undertaken of the ways in which the management of design and its organisational context affect design in both positive and adverse ways.

Perhaps the most obvious way in which management affects the process of design is through what is known as Project Management.

Over the course of the last 20 to 30 years, specialised management techniques have become more sophisticated in order to manage design activities within organisations. These design activities, typically defined as projects, consist of a combination of human and material resources combined to achieve a specific purpose within an organisation. Today project management is practised in a wide variety of design environments. While the practice of project management may well have its roots in antiquity, the development of a conceptual framework of project management received much of its present character from the work conducted in this area within the aerospace and construction industries, (Clough 1972). In its earliest applications, project management took the form of an organisational arrangement consisting of integral teams of managers and designers working on a common organisational objective. Such teams provided a focal point to pull together the organisational resources to be applied to a particular project, (Cleland and King 1975).

To complement the organisational aspects of project management, specialised techniques and methodologies have been developed to facilitate the scheduling and budgetary activities of a project. Programme evaluation review techniques, progress performance reporting, project planning, network analysis and milestone charting are a few of the techniques and methodologies that have been developed to facilitate the planning and control of projects.

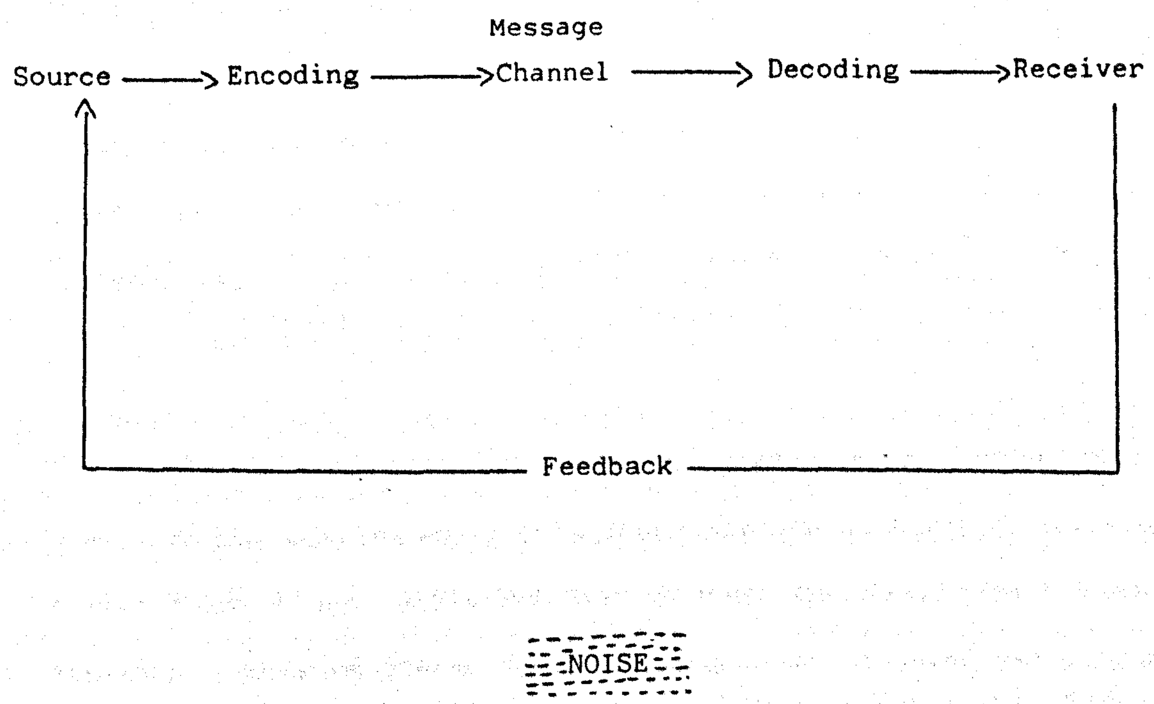
In addition to the above aspects of project management another area which can considerably affect the efficiency of a design project is that of determining the relationships of authority and responsibility. When design is taking place within the context of a design team or organisation the human relational aspects can occupy a position almost equal to that of the technical and conceptional difficulties. The precise definition of responsibilities and areas of authority can as such often lead to an easing of difficulties within a design project, (Bazil and Cook 1974). However it is also noted (Bazil and Cook 1974) that sensitivity should be used by project managers when making such decisions, firstly so as not to prevent a stifling of inventiveness and secondly so as to prevent interpersonal difficulties. This second point also bears relevance to another aspect of project management, that being of the maintenance personal commitment. The point is made in a number of works in this area, (Cleveland and Kocaoglu 1981, Low 1968, Whitfield 1972, Herzberg 1959) that the interest and commitment of the designer is essential for a design project to be successful and that this commitment should not be taken for granted.

The main way in which project management attempts to deal with the problems of authority, responsibility and personal commitment is through the use of carefully devised work packages. A work package grows out of a work-breakdown analysis that is performed on the design project. When the work-breakdown analysis is completed and the work package areas are identified, a work breakdown structure comes into existence. Stated in an alternative manner, the work breakdown structure represents the breakdown of the project objectives (Ackoff 1971). As such the design and implementation of work packages affects considerably the way in which a design process is structured in terms of informational flow and the way in which that particular design will progress. To be able to do this however the management needs to co-ordinate its activities with those related to the production of those objectives and this means that they have an important role to play in the generation of the specificational requirements. This role will consist of defining the initial need statement upon which the specification will be developed, possibly an order, or a perceived market requirement, or the need to improve an existing product or system. This need statement will gradually become further defined as it evolves to become the specification by such management criteria as costs, ease of production, speed of development, marketability etc.

In addition to this such project management skills as technical planning and forecasting will be drawn upon and affect the way in which the specification is formulated. At the specificational stage organisational considerations such as policy and recommended technical practices will also have an effect.

The practices of management and organisation also affect the design process in terms of their effect upon communications both within the process and externally to it. A model of communications has been developed by theorists in the field of communications. Though this model was not developed specifically to describe the communications activitives within the design process it is widely held that this theory is applicable to all forms of organisational communication and as such it is believed that it is applicable in a broad manner to the design process and its operating environment. Perhaps the most widely known model is described by Shannon and Weaver (1948) who were early researchers in this field but whose work is still widely held as theoretically valid. The basic ingredients of this model include a source, an encoder, a message, a channel, a receiver, feedback and noise. Other models of the communications process have been described in much the same way. Gibson et al (1973) have developed a model of this process, (See fig 2). The relevance of this to design is that it underlines the basic manner in which communication takes place and as design activity requires a great deal of communication, in many cases largely in the form of informational transference, the understanding and smooth running of the communications within and externally to the design process is essential for good design to take place. The structure and management of communication paths in many ways will affect the manner in

Fig 2.



A communications model.

Gibson L., Irancevich 3, Donnelly J. in Organisations,

Structure, Processes, Behaviour, Pub. Business Publications 1973 which the designer will progress and ultimately the final designs.

The communication system within design, though not exclusively so, deals largely with the transference of information from one aspect of the process to another. Such informational systems however, no matter how carefully planned, will be open to a number of external influences. An information system does not operate in isolation. It will usually exist as system or sub-system operating within the context of a larger, usually organisational system, (Ackoff 1971). This means that as well as designed systems of communication, there will usually exist undersigned systems, (Checkland 1981). Informal structures within an organisation may thus affect the way in which the design process works. The development of these informal systems will in turn be a by product of the organisational policies and the environment around the design process which they create.

The importance of the organisation within which designers work and the way in which it affects the environment within which a design takes place, affecting its progress and final results must be stressed. Woodward (1965, 1980) has done work in this area and though not dealing solely with the effects of organisation upon design but rather placing it within the context of an entire organisations activities, notices that the way an organisation is structured will affect the process and progress of design. The stresses and emphasis laid on different factors which 'lead' the design process will not only affect the way in which the design specification is generated but will also exert various pulls upon the operational stages of the process by promoting some and reducing the significance or effects of others.

Available or preferred systems of production, attitudes towards technical complexity, innovation and change will all affect the way in which a design process proceeds, (Leech 1972). There is however a complex interplay between organisational attitudes and policies and the effects of management techniques and abilities. The ability to predict and structure the possible outcome of all organisational activity will affect the above mentioned factors. This means that increasing importance is laid upon the skills and techniques of technical planning and forecasting.

Technological forecasting is the activity which deals with the assessment of future technologies and their development within the design team, department or organisation. Technical planning is the structuring of the necessary process by which this may be achieved. This aspect of design management, the basic principles of which have existed for approximately 30 years, (Koopman 1956) is based largely on O.R. techniques and systems based disciplines, (Murdick 1961).

The final and one of the most important areas in which management and organisation affect the process of design is that of decision. The aspect of design is viewed as being of such significance that it is discussed in greater detail and with more reference to its technical details in the next section.

Though many design decisions would appear to be solely technical and thus purely the responsibility of the designer, in many ways this is not the case. Organisational factors will affect even the designers technical decisions. The objectives of the organisation and the criteria which they place upon such things as technical change, cost, time, all affect design, often in addition to those factors taken into consideration at the time of the initial formulation of the specification. Similarly changes within the organisation either in structure or attitude (Murdick 1961) will again impinge upon the design processors. The divisions made by the allocation of work-packages as well as the allocation of responsibility and authority, are also managerial and organisational aspects which have an impact upon the production of design.

The management and organisation of design can be seen to have an effect upon the way in which the process takes place as well as shaping the possible outcomes of the project. Being largely responsible for the work divisions and official paths of communication and information flow, the way in which a design will evolve is determined by managerial and organisational policies. In addition to these environmental factors and their impact upon the process, management practices take an active part in forming the actual design. The organisational input at the specification generation stage forms the basis of the design and will determine the final design. Similarly design decisions are not purely determined in terms of their technical merit but are the product of managerial decisions and policies based upon organisational objectives.

Oakely (1984) is one of the many authors writing in this area who stress the need to clearly define design objectives from the very beginning of the design process. To achieve the best possible statement of design specification requirements, care will need to be taken to correctly organise and fully comprehend the resources available to the design activity. The management of an organisation will ultimately bear the responsibility for initiating any given design process. Because of this, it is essential that the managerial input to the specification, drawn from such areas as marketing, sales, production engineering etc., are correctly gathered and considered when taking their place as influences upon a requirement.

The integration of managerial considerations as part of a design specification requires that the design process, and this in general means the design team, should be thoughtfully situated within the structure of the company or organisation. By this what is meant is that care should be taken so as to ensure that all departmental areas within an organisation which have an influence upon a design project are included and so as to allow the fullest information flow possible between these different departments.

The organisational needs which initiate a design process may come from a wide variety of sources both internal and external to an organisation. These needs will determine such things as whether a design will be a new or innovative one or whether a developmental or variant design is required. The areas within an organisation which will determine such factors often come from the perceptions of the sales or marketing departments. The finalised resources which are available for a project are yet another factor. It becomes apparent from the literature written concerning the field that what is required if the design process is to be best served, is the use of systematic managerial methods. Oakely (1984) indicates from his research into product design that unless management makes use of methods and procedures available so as to ensure that all departments within an organisation are able to assist in the formulation of both the initial specification and any possible future modification, which may need to be undertaken as a design progresses, then specification produced may well have serious flaws.

The two main points which can be drawn from the literature on management and organisation which are of use in the building of a design model are, the need to use systematic methods to help the designer to ensure that all influences upon the designs development and implementation are considered and the importance of generating the clearest and most accurate specification requirement. By the use of systematic methods the designer is assisted by being able to conduct his activities in a manner which ensures that no important considerations are overlooked and which should help him to structure both the information available to him and also more easily define his own informational requirements.

2.7. Decision Theory

All design requires the continuous making of decisions. This requirement exists regardless of the scale or complexity of a design. Design decisions are made both intuitively by the designer and by the use of formal methods and techniques.

The technical decisions which are made by a designer will seldom be made purely on the bases of technical merit alone. Factors such as available resources, economic considerations and the need to meet deadlines will in most cases all play a part in determining a designers technical decisions. Decision in design consists of reconciling a complex set of often competing factors. To accomplish this the accurate assignment of value to the variable factors is extremely important. The formulation of what is called the value criteria is the key element to design decision.

Once a designer has been able to conceptualize the basic specification of a design he must then move on to examine ways in which he can obtain the optimum design to fulfil these specifications. To do this decisions will always have to be made to decide between the possible options open to him. At this point the value he attaches to each of the specifications elements will be the deciding factor, the aim being to maximise the overall value and as such to produce the optimum type of design to fulfil the requirements. Thus the concept of value is fundamental to the decision process.

When assigning values to each element, specification or variable, the designer is making a statement about the importance of that particular facet of the design in relation to the overall design aims. Thus something with a high level of value would be important to the design whilst something with a low (or possibly even negative) value would not be particularly of importance, or even possibly detrimental to the design aims. When assigning value to a variable the designer however has not only to look at the value of that item in terms of its importance to the final design aims, but also in relation to the relative values of other variables. The assignment of values to design variables can be done either intuitively or with the use of formal methods. The designer then must decide the relative value of each variable if he is to optimize his design. The value of an element of the specification in relation to other elements is often variable changing throughout the iterative process.

The concept of value is thus essential to the decision process as it enables the success of a design to be judged and the relationship between the elements of a design to be defined. Bross (1953) has argued that these relationships are determined by the characteristics of the possible courses of action, or strategies that are open to the designer. By the prediction of the outcome of a particular course of action and the desirability or value placed upon that outcome, the values placed upon the component qualities originally defined as desirable will vary. Sanoff (1968) similarly argues that the value placed upon the predicted outcome of a particular course of action will alter the relative values given to the elements of the initial specification. Value which is the criteria by which decisions are made is thus determined by available course of action and predicted outcome.

The prediction of outcome thus becomes a major element in the way design decisions are made. To predict the outcome of a particular course of design action, it is necessary to produce the most accurate description or model possible of that particular option. Cram (1971) argues that the system model should be as detailed as feasible for effective decisions to be made.

Bross (1953) suggest several methods by which predictions are made, as does Mack (1971) and Keeney and Raiffe (1976). These roughly can be summarised as prediction of outcome by initiative means, by the use of analogy, by drawing upon experience, by the assumption that all elements likely to effect the outcome are known and will remain constant, that any changing factors are known and can be predicted and that some factors will be unknown or uncertain. Depending upon under which of these conditions the prediction of outcome is made the relative values within the criteria will vary and thus the design decision will alter.

Decision Theory consists of the assignment of values to the various qualities and quantities which constitute the design specification, the determination of the relationships of these values with regard to possible outcomes and the methodological techniques or means by which these can be determined. It is to these methodological techniques or means that the discussion will now turn.

The selection and implementation of any technological product or system is determined mainly by the balance between its performance against the specification in technical terms and its performance against the specification in economic terms. The most common method of assessing this is by determining the ratio of technical effectiveness to cost, [E/C], or by the difference between the two [E-C]. Another method used is that of Quadratic cost, $[(I-E^2)+C^2]$, where $[I-E^2]$ can be regarded as the penalty paid as the technical performance deviates from the ideal or optimum and C is the cost of getting the systems performance back to that ideal, (English 1968).

An important element in the means to design decision is cost analysis, which is a part of the broader area of value analysis (Falcon 1964). This method determines the cost of a function within the system by the assignment of function carriers to the various sub-functions, (to measure their technological worth) and weighs this against their manufacturing cost. There are however a large number of problems with these economically based methods of decision. They pre-suppose the inability of the designs system structure to this form of investigation and there is the possibility that even if it is, that by using solely cost based assessment, important technical criteria will be overlooked. Decision procedures which incorporate the concepts of cost-benefit analysis, such as the German guideline VDI 2275, (Pahl and Bietz 1984) allow for a more comprehensive evaluation of a design to take place. These methods are orientated towards providing a more broadly based decision taking into account both the quantities and the qualitive aspects of a candidate design.

A number of varieties of this method exist, there basic structure however is similar. A candidate Ci, has a set of design characteristics which are those attributes which are relevant to the design objectives. There is generally a large number of separate criteria, K, by which design must be evaulated. In this form of decision method the criteria should be formulated as utility functions of the form UiK=UiK (ci. ... ci,n), which assigns a value, UiK to a set of design characteristics. A set of utility values is thus determined for each of the candidate designs.

It is important to stress that although the above techniques deal with partly formed or completed designs, this is not the only stage during the design process when decisions are taken. Asimow (1968) defined design as being an interactive decision making process. For Asimow the design process is interactively performed, with the design definition and detail with each repetition of the process. During this process at each stage decisions will have to be made entirely in terms of function and eventually detail. Pahl and Bietz (1980) similarly view decision as being something which takes place constantly through the process and the process being repeated, further defining the design each time.

Within the functionally decomposed design the decisions made will be largely based upon technical consideration operating within the parameters of the specification. However when the decomposed functions have been realized and it is necessary to combine the components into a total system, decision techniques may again be required to determine the optimum variant.

Decisions are taken constantly throughout the design process and will during the initial stage of iteration be based upon technical considerations, physical principles etc., or even heuristically. As a design solution begins to become more defined it becomes possible to apply the collection of methods which together constitute decision theory to enable the design to determine the most advantageous combination of system components.

2.8. Summary of Chapter Two

This chapter has primarily concerned itself with a discussion of the literature written on the subject of design. Divisions have been made within the literature based upon the concerns and approaches within and towards the subject of design. Within each of the areas a discussion of the literature has taken place and an attempt has been made to analyse the main points and from this to synthesis a consensus view of the design process as a whole. Within this section a brief summary will be given of the discussion within each of the subject areas and the way in which each of the areas has contributed towards a consensus based model of design will be highlighted.

A great deal of the literature was found to be concerned with design education. This literature varied in scope quite widely from general introductions to the design process, to dealing with specific areas of interest within that process. Similarly the orientation of the literature also varied considerably from literature which aimed at providing undergraduates with an insight to the process, to literature aimed at updating the knowledge of the professional practising designer. Finally, the literature also varied in terms of the discipline within which design was to take place, for instance, mechanical engineering, electrical engineering and civil engineering. Inspite of these differing approaches and orientations however, a large number of similarities were found to exist in terms of descriptions of the process and general practices advocated. Before moving on to describe these similarities the point should be made that within the literature of this area a further similarity exists, that being the basis from which and upon which the literature was written. The literature as a whole tended to be based upon the authors own design experience rather than upon empirical study and further, the majority of the literature both described what it viewed as the design process and prescribed ways in which the process and the the work of the designer in conjunction with this, could be improved.

The first feature of the design process which the consensus of opinion in this area agreed upon was that design is a sequential process characterised by a number of design stages, which by passing through a design gained form and definition. Eeckels (1987) description of the process is highly typical of the type of opinion put forward in this area, in the way that he states that by passing through the design process, a design moves from the abstract to the concrete. Descriptions of design in this area typically view the process as starting with a perception of need, which becomes more defined as a specification requirement is drawn up and which gradually gains specific form to realise these requirements and the process progressively becomes more concerned with actual specific detail.

The description given of the activities which typically take place within each of the design stages is also widely agreed upon. The initial stage of the process is that of the generation of the specification requirement. Differences of opinion exist as to the amount of detail which is required in the forming of the specification, but again there is wide agreement that the specification should be open to modification and change which will nearly always be required. This last point is one which applies not only to the specification requirement but also to the process as a whole. It is stressed again and again within the literature that though the design process is seen as a set of sequential stages, a design does not simply move from the initial stage to a finalized design configuration in one go and then stop. Rather the process is seen as being iterative in nature returning many times to a previous stage to modify or update the work done during that stage. This is seen as taking place in terms of all the design stages, but particularly of relevance to the specification stage which may have to be modified many times depending upon the feedback received from later stages.

After the initial generation of a specification has taken place the next stage or phase which was identified was that of the generation of possible design solutions. The discussion within the literature concerning this stage tended to differ not on the description of the fundamental characteristics of the stage, but rather in terms of the ways in which the activities are best undertaken. However even within the differences of prescription as to the best means by which the activities associated with this stage should be undertaken, there exists a large body of like minded opinion. The need to decompose the problem into abstract functions is one practice widely advocated, so as to allow for the widest possible area of solutions possible. The differences which exist with regard to this are not of basic principle but rather on the best methods and degree to which these should be done.

The final stages of the design process are again broadly agreed upon in terms of function and the types of activities which characterise them. These are the analysis of the possible design solution and the taking of decisions as to whether or not implementation of the design should take place. Again the iterative nature of the process is stressed. Though in terms of the sequential structure of the process these two stages, which for some authors are seen as constituting only one stage (Cain 1969, Krick 1965), appear at the end of the process, the way in which they affect the development of a design is continuous as the development of a design takes place interatively by passing again and again through the stages of the process.

In terms of its contribution to the development of a model of the design process, the literature on design education provides a number of important features. Firstly, it identifies the nature of the process as being a sequential and iterative one consisting of a number of identifiable design stages which are characterised by both function and their relationship towards the other design stages. The design process is initiated by the perception of need and gradually moves towards a detailed finalised design solution by interatively proceeding through the design stages and the corresponding activities which characterise them.

The contribution of systems science and systems engineering to the development of a model of the design process differs to that of design education in a number of ways. Firstly the basic orientation within this area is basically similar for all the literature. The differences which do exist tend to take the form of diversity in the degree of detail and selection of particular aspects of the process for the greatest discussion. Systems theory is characterised by its approach towards problems and as such much of the contribution made by this area to the model can be drawn not only from works written directly concerning design but also from works outlining the general approach.

The literature written from this perspective on the subject of design recognises that design consists of sequential and interactive stages. Where however systems theory makes its major contributions towards a model of the proceeds of design is in terms of offering techniques and theoretic validity to the decomposition of design problems. By allowing for the description of entities in terms of abstract functions systems theory allows the designer a greater solution search area as well providing him with techniques by which to more accurately describe an abstract system. Systems theory however does not only prove to be of relevance in terms of the generation of possible design solutions. The holistic approach of systems theory also contributes to a fuller understanding of the factors which affect the production of the initial requirement specification. By encouraging the designer to look for all factors which can have an influence upon a design a greater understanding of factors which should be considered when formulating the specification can be obtained. Similarly systems models can provide information to assist in the analysis and decision stages. Overall systems theory reinforces the notion of design as consisting of sequential stages which are gone through in an interactive manner and hightens the awareness that for the best possible design solution to be obtained it is necessary to decompose the design problem into its basic functional units and sub-units.

The literature which concerns itself with the creative aspects of design concentrates its efforts in a number of areas. These could be broadly described as the ways in which creatively within the process can be enhanced and ways in which the design environment can be modified to offer the greatest degree of support for those activities. The literature concentrates largely upon ways in which new or innovative design takes place. The need to decompose a design problem down to an abstract form is again recognised and emphasised as a necessity if good design is to take place. The literature largely concentrates upon methods of achieving innovative thought advocating many practices which have this as their primary objectives. Though much of the literature concentrates upon the area of the generation of possible design solutions, emphasis is also placed upon the creative aspects of the generation of the specification requirement. The majority of the literature which concerns itself with this aspect of design, (a notable exception being French 1971, 1985) concerns itself only briefly with notions of the process as a whole, concentrating most of its concern in the specification and concept generation stages.

The literature drawn from the area of the management and organisation of design contributes towards the model of the design process in two main ways. Firstly it emphasises the importance of the specification stage which gives direction to all future activities within the process. Secondly it highlights the advantages of approaching design through the use of systematic methods. Both these points aim to create the greatest possible economy in terms of design effort by attempting to structure the activity as rigorously as possible. Because of this the view generally expressed within the literature is that the process of design is a sequential one consisting of various stages each characterised by specific types of activity.

Oakely (1984) is in many ways typical of the literature to be found in this area. The importance of management in the formulation of the specification requirement is greatly emphasised and the use of method advocated so as to ensure that the activity is best co-ordinated with all the other areas within an organisation which are likely to either affect or be affected by the design process and the final design which this produces. In addition to this organisational factors are also considered, stressing the importance of the positioning of a design team within an organisation so as to create the best mix of information flow to and from the team.

The literature which concerns itself with decision theory is predominantly concerned with techniques and methods of support the designer when decisions are required. These decisions are asserted to take place both throughout the design processes as a whole, often taken in an informed or heuristic manner and formally at a particular stage at the end of the design sequence. In addition to this the literature from this area also makes another important contribution to the model of the design process by emphasising the need to create a value model or value criteria. The value model or criteria assists the designer by allowing him to make judgement about a proposed design against the specification requirement. By this means a designer may determine the relative importance of any one, or group, of features within the specification either against its own individual merits or against other aspects of the requirement. The major contribution then of literature from this area to the model of the design process is that for the designer to be able to correctly make any decisions during the design process, it is essential for him to have a value criteria against which these decisions can be made.

The model of the design process which becomes apparent from the analysis of the literature is one which can be described as follows. The design process is sequential in nature consisting of a number of stages. The design is formed by passing through these stages in an interactive manner gradually gaining form until a suitable finalised design has been realised. The stages of the design process consist of, the formulation of a value criteria or model, the generation of the specification requirement, the generation of candidate solutions, the analysis of the performance of the candidate solutions, the evaluation of the candidate solutions performance against the specification requirement and the taking of decisions as to whether to continue or terminate the process.

3. The Model

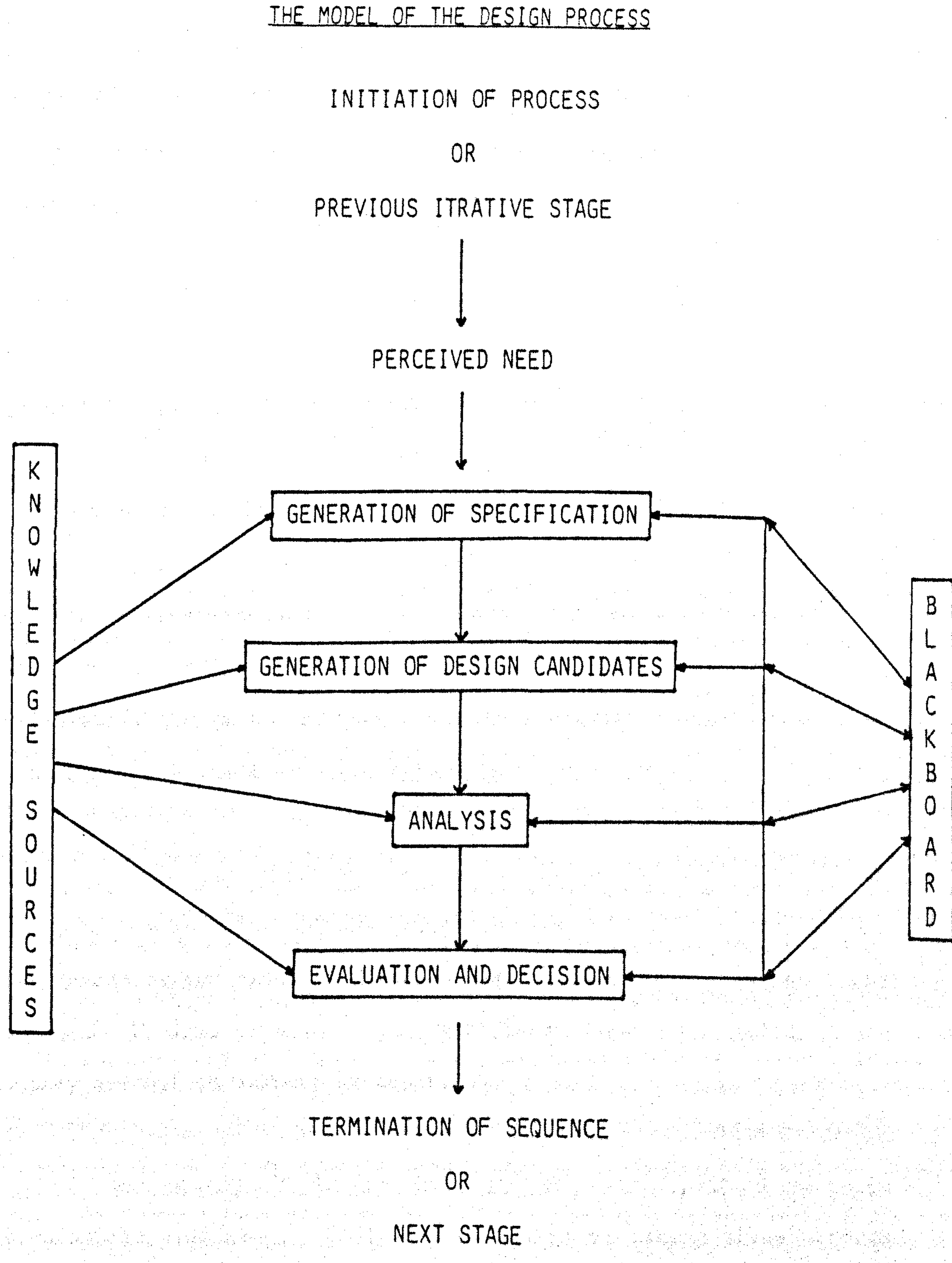
Introduction

The model of the engineering design process which is described in this section has been created by analysing the literature on design and from this producing a consensus as to how the design process takes place. An outline of the model which is to be discussed is given in figure 2a.

Any brief description of the model will be necessity leave many aspects of the model not fully explained, however before going into a more detailed accounts, a brief description would be of use.

The model attempts to synthesise a number of factors, and as such is both sequential and interactive. It is described in terms of functional stages within an informational process. The initiation of the process as a whole starts off with a perception of need of some kind and then within each of the subsequent interactive stages forms the requirement specification acquired from the previous design stage. The basic sequential stages take place both as a whole throughout the entire design activity and in terms of each of the actual design activities.

Fig. 2a


THE MODEL OF THE DESIGN PROCESS
INITIATION OF PROCESS
OR
PREVIOUS ITRATIVE STAGE
PERCEIVED NEED
KNOWLEDGE SOURCES
GENERATION OF SPECIFICATION
GENERATION OF DESIGN CANDIDATES
ANALYSIS
EVALUATION AND DECISION
BLACKBOARD
TERMINATION OF SEQUENCE
OR
NEXT STAGE

The sequential stages themselves are those of the formulation of the specification requirement, the generation of candidate designs, the analysis of candidate designs, theme evaluation and finally decision. The above terms and their meaning and significance are discussed in full a little later and presented at this time as a means of providing terms of reference. In parallel with these stages there exist two other elements. These consist of the knowledge base and the Blackboard Model. The first consists of available knowledge to which the designer has access at any given time within the design process. The second element is that of the Blackboard, or Blackboard Model. This is a mechanism by which design information about partially formed or whole design solutions are stored and added to or combined. The Blackboard concept is a major part of the design model and as such a more indepth discussion of its function and relevance is given within a separate sub-section. Before however beginning the discussion as to the actualities of the model a number of points should be addressed as to the nature of the views and perceptions of design models.

Within the field of design theory there exists two basic views as to the character of the design process. These two basic views on design can be described as design being a sequence, and design being a process. It will be argued that both these views have validity and that they are not in essence incompatible.

The notion of design as a sequence is typified by such writers as Pahl and Beitz (1982) who see design as taking place through the progression of a number of stages each characterised by a particular type of design activity each following on from the completion of the last in a linear manner from the initiation of the process to its final completion as a fully detailed set of design drawings. The above description of the sequential view of design is necessarily something of an over simplification, it does however capture the main points of this view. In something of a contrast to this those theorists who view design as a process, (Lawson 1979, Hayes-Roth 1980, Alger and Hays 1968) take the view that design is a continuous cyclic process, almost entirely, or indeed entirely, interactive in nature, where the design solution search is virtually unstructured and possible and partial solution are continuously drawn upon, modified and combined. It is important to note that this view does not in the main see the design process as being a predominantly interactive activity, rather it argues that the majority of design takes place without the use of systematic methods.

In many ways the two views of design reflect not only the differences in types of design practices based upon the size, complexity and organisational structure of the design project itself but also upon the empirical base from which the model has been drawn. The vast majority of design literature is based upon participant observation, usually an experienced designer drawing both upon that experience and also making suggestions as to methods of improvement. This in turn has lead to an unclear division within the literature concerning what is being described by the author as a model of how design actually takes place and what is being prescribed as a model of how design should take place. Often within individual works in this area this division is far from explicit.

There are however within the literature some works which do make this division clear and it would appear that there is in fact a basis for this division in terms of the method of approach towards the study of the design process. Lawson (1979) through a process of interview, observation and experimentation concluded that what designers actually did fitted the process view of design rather than that of the sequence. In a continuation of this line of research Lera (1983) similarly asserted that designers often even when believing themselves to be using a systematic design method, in fact did not. Rather the designers tended to move rapidly from one area of the design to another as possible or partial design solutions became apparent. This type of activity often meant the leaving of a particular course of design solution search, often before it had been completed and moving to another aspect of the design, either returning to this later, or often not at all. Hayes - Roth (1977, 1983) further developed this notion of the design process by attempting to incorporate it into a theoretical framework, that of the Blackboard Model. As previously mentioned a more detailed discussion of this model is undertaken later within this chapter along with the work undertaken within this area.

The view that design is sequential in nature is heavily represented within the literature. Before moving on to discuss this however it should be mentioned that the literature which represents the view does not exclude the notion of interaction as an aspect of design, but rather tends to stress the need to operate in a systematic manner returning to a previous design stage once a particular course of activity has been seen to be unsatisfactory. Asimow (1964) asserts that design does not exist in terms of a sequence of activity stages but does not exclude the returning to previous design stages to modify or change the course of a design and sees it as an important element within the process. Oakely (1984) though advocating that design benefits from structured sequences each of clearly defined objectives similarly acknowledges that a key element within design is interactive, though equally asserting that by the use of vigorous systematic method throughout the process this necessity may be minimised, which he states is desirable as it prevents wastage of time, design effort and resources. Often within the literature it is acknowledged that design combines both of the views of design. Eeckles (1986) both discusses the design process as a sequential event and in terms of a continuous interactive process, noting that any sequential divisions made within the process are never totally rigid and that exceptions to the stage order can and often do occur.

The debate amongst design theorists as to whether design occurs sequentially or as a process represents not so much a fundamental division within this area, but rather a reflection as to the way in which the theorists have chosen to study the subject and the empirical basis upon which they have chosen to base their studies. Those authors who base their work upon experience and participant observation tend to prescribe to a greater extent than authors who base their works upon more formalised empirical studies. In addition to this those authors who tend towards prescription almost entirely view design as being sequential in nature. These sequential description range from general acknowledgements that design takes place in this particular manner to comparatively rigid descriptions typified by the advocating of systematic methods.

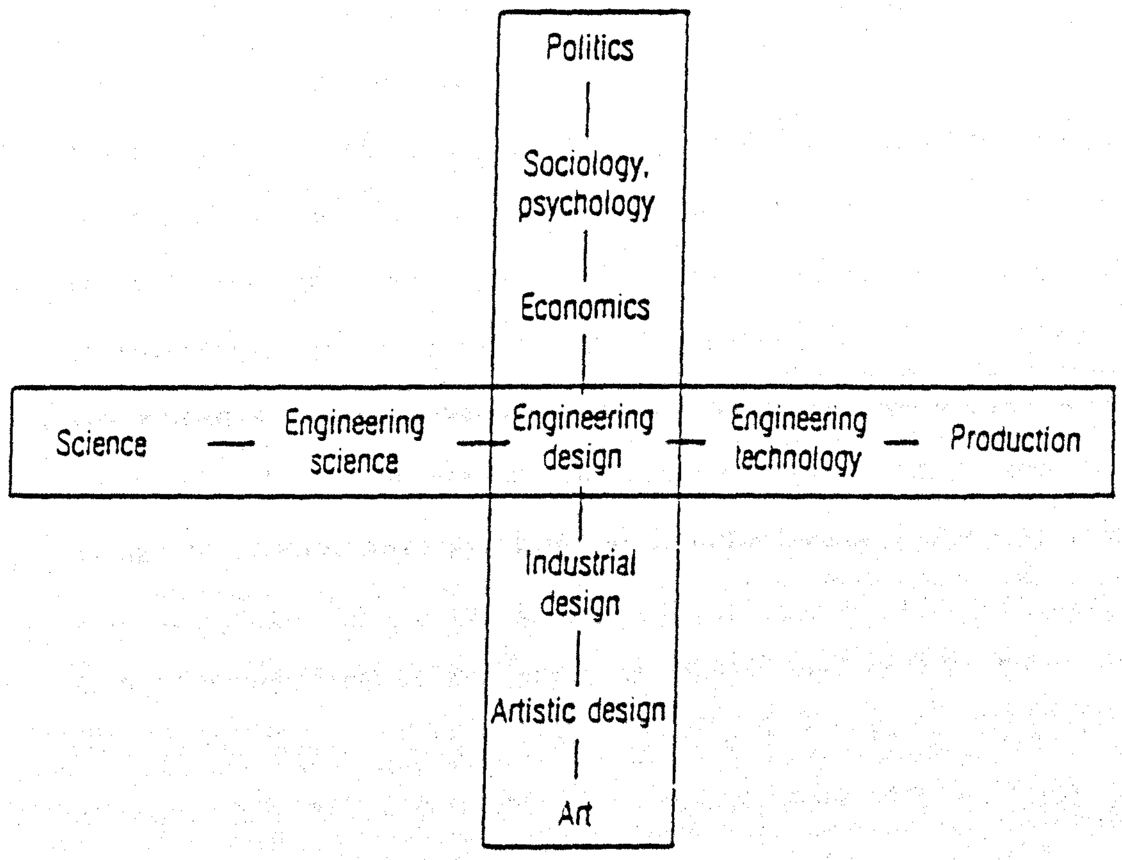
Authors who assert that design should be viewed as a process have tended to base this assertion upon research, (studies and interviews) directed towards the description of how designers actually operate. It should be noted however that though designers may not always adhere to a systematic method, or conduct their activities in an entirely sequential manner the actual design itself does develop through a progressive number of stages as it approaches its final realisation. For Eekles (1985) this development was best described as a movement from the abstract to the concrete by way of gaining greater and greater definition through constant interactions.

The above discussed division within the literature having however been noted I shall now move on to describe the model in greater depth. The form this will take is to discuss each of the aspects of the model in turn, explaining in detail their main characteristics, and offering justifications for the form they have been given.

3.1. The Initiation of Design Activity

The precise point at which design activity commences is one which in many ways is not absolutely clear. This is because the division between initial design activity and its precursors is not one which can be easily made. The perception of need is often cited as being the initial part of the design process and though this may be correct it also, unfortunately, is rather vague. It is possible to argue that the generation of the design specification is the initial stage of the design process, and indeed this view is probably correct, however the problem still remains as to what has caused this activity to take place. Dixon (1966) asserts that the origins of a design activity are embedded within the social, economic and technological context of the society within which a design takes place. By this what is meant is that at certain points in time societal demands will be made through the various agencies and organisation of that society and dependant upon the economic and technological conditions, these demands will gain form and orientation. The wider society will make various types of demands for items and the way these turn out will depend upon the skills and resources available at that time. Similarly Asimow (1964) views design as being initiated by environment. For Asimow the environment with regard to design consists of socio-economic, and socio-ecological factors. From these factors will come the initial needs which then require to be more fully identified and formulated during what he terms the initial Feasibility phase. The point at which a need suitable for the initiating of a particular design activity takes place is one which is generally not clearly defined or given any vigorous theoretical explanation or framework. An exception to this, though dealing specifically with the initiation of engineering design activity, is Penny (1970). For Penny (see page 95a) the design sequence is initiated at a point when economic and technological factors converge. Economic factors provide the impetus and technological factors channel this impetus into the type of need which is perceived which it is then the job of the specification requirement to define, clarify and quantify. Oakely (1984) takes what is essentially a very similar view to that of Penny (1970) though for Oakley a greater stress should be laid on the effects of economics when considering the factors which initiate the design process. Though Oakely is primarily concerned with the factors which affect product design much of his argument can be generalised to the whole field of design. Available resources play a critical part not only in determining the final item which is to be designed but also affect the manner in which initial need perceptions are defined. Although emphasising the way in which economics determine perceptions about design needs Oakely also stresses that design is very much a product of change. For Oakely these changes are brought about through competition, changes in fashion, tastes, styles and the law, along with political factors, diminishing natural resources and the need to gain profit. The notion of design being brought about by change or the need to change, or even merely a perceived need to change, is one which is central to the comprehension of what actually initiates the design activity. Lawson (1980) though acknowledging such factors as general change and its foundations in society, the economy and the state of technology etc., takes the view that it is possible only to acknowledge such factors rather than to produce any theoretical framework through which to more fully comprehend there workings. Lawson asserts that the

Fig. 3


Politics
Sociology, psychology
Economics
Science
Engineering science
Engineering design
Engineering technology
Production
Industrial design
Artistic design
Art

range of factors and the complexity of their relationship defies a more precise understanding. This view though not always asserted appears to be the predominant view within the literature on design as in many works a number of factors are acknowledged as exerting an influence upon the decision to start design activity but few offer any explanation as to how this influence might in fact operate.

What becomes clear from the discussion of the literature is that there is a necessity to evoke a boundary of consideration when dealing with this area. Society and the broader economic and technological conditions no doubt do exert an influence upon the initiation of design. However it becomes necessary to limit the scope of investigation when considering this matter if an indepth sociological and economic study is to be avoided. Such an investigation though no doubt of value in terms of comprehending more fully the context of design is however beyond the scope of this thesis. For the purposes of this discussion in general the initiation of the design process will be seen as commencing at the point at which there can be found a clearly articulated need. Rather than pursuing the line of causality to the ultimate ends the start of the design process will be seen as taking place at the point at which a need arises to which an attempt is made to satisfy it. This boundary of consideration serves a number of important functions. The first is practical in that it limits the sphere of discussion and thus makes the area more amenable to discussion. Also such a boundary allows the relationship between the initiator of a design and all subsequent activities to be more fully explained.

By stating that the design process is initiated when a need is clearly articulated what is meant is that the design process commences at a point at which a statement can be produced as to the desired outcome of a design sequence. In other words a rough idea as to what is required has been formed. It is taken as read that when discussing this area the term need also implies the desire to fulfil that need, or at least attempt to satisfy it in some way. The way in which the attempt to satisfy this articulated need is undertaken is the design process. Indeed in many ways the design process consists of clarifying and articulating through ever increasing definition of the original need. The initial step however in this process consists of producing a qualitative and quantitative definition of that initial need. This is done through the generation of the designs specification requirements.

3.2. Requirement Specification

The requirement specification is the final product of the initial stage of the design process. The purpose of the requirement specification is to offer a statement about what actually it is that should be designed. The way in which this is defined may vary considerably from an imprecise statement of general function, to a precise set of performance characteristics. It is from the specification that the direction of the design activity is determined and it is against it that the success or failure of the finalized design will be measured. The specification however is rarely a static set of characteristics which are required to be possessed by the final design, but rather it is usually open to modifications and change as either requirements are found to be difficult or expensive to achieve, or when greater definition is required to determine the precise nature of what it is that is to be designed. Because of this the requirement specification is an integral part of the decision making process which takes place throughout the design process. It is this aspect of the requirement specification which has led to a division within the literature as to the exact nature of a specification. This division is based upon the emphasis which it is felt should be placed upon the role of a specification and its effect upon decision. Authors such as Gosling (1959, 1962), Asimow (1964) and Cain (1969) assert that the purpose of the requirement specification is that of task clarification. This means that a designer should be able to commence his design activities with a clear idea as to that which he wishes to produce. Pahl and Bietz term this approach solution - orientated. Other writers on this subject however state that the specification should be more than this. Both Chestnut (1967) and Churchman (1986) assert that the specification should take the form of a value model or value criteria. By this what is meant is that the specification should be put in terms which make explicit the value placed upon each of the required characteristics of the design, both with regard to the final design and in terms of their relationship to each other. Implicit to this view is the notion that within any design activity trade-offs will have to be made between the possible characteristics and functional attributes of the design. To do this it is claimed the value, or importance of a particular requirement will have to be known.

The specification is the product of the initial design activity. To more fully explain its source, function and relationship to following design stages it is important to comprehend the factors which have affected the generation of the requirement specification.

The initial phase of the specification stage is that whereby information is gathered concerning the defined need. This information and the scope of the search undertaken to gain it, is itself dependent upon a number of factors. The knowledge and experience of the design team will obviously affect the orientation and often the scale of the initial search, as will such things as time and resources available. Also and of equal importance, decisions made early in the process will affect the generation of the specification requirement. The initial decisions made as to the likelihood and possible consequences of having to modify a specification will greatly affect the manner in which it is formulated. The perceived ease of making an alteration at a later stage in the overall process, usually in terms of the consequences upon any progress made within the design, will affect the vigorousness with which the generation of a specification is pursued. The main point being argued here is that the rigidity and detail of the initial specification is dependent upon early design decisions or often perceptions about the possible outcomes of the overall course of a design activity. This in turn is a product of designer knowledge and experience, as this will affect information gathering activities, or if indeed they will take place at all.

In addition to factors such as designer knowledge and experience and the way in which these affect the initial information gathering phase, organisation factors play an important part in the generation of the specification requirement. It is important to remember that design does not exist solely in isolation and as such though technological and techno-theoretical factors will very greatly affect the outcome of this stage, they will not do this entirely.

The organisational factors which set the context within which design takes place have a very substantial influence upon the way in which a specification is generated. The organisation within which a design activity is to take place sets the parameters which determine how a design solution is sought. These organisational considerations often form a large input into any specification. This happens in a number of ways. Firstly it is through the organisational structure that the initial need is articulated. The structural make-up of organisations vary considerably and it is dependent upon the emphasis of the many divisions and sub-divisions which take part in the shaping of the defined need, which will alternately determine the form of the specification. Elements such as, production engineering, marketing, accounts and the technical design team will between them define the design need, and as such the influence of each group relative to the others plays a part in determining that perception. The organisation will also influence the specification by determining the resources, human, technical and monetary which are available to a particular project. Another equally important factor which is defined by the organisation within which a design is to take place is that of time. The organisation will define for the design team the time scale through which the design process will be operated. This will affect the manner in which the search for possible design solution will take place, will often be incorporated in the initial design brief and can become part of the actual specification. Similarly the allocation of resources will greatly determine technological factors. Finally the compatibility of a finalized design with existing production methods will also form part of a specification.

It is not within the scope of the present discussion to explore all the external factors which exert an influence upon design, however certain external factors will always impose themselves upon the specification. The effects of laws for instance cannot be ignored and though to all intents and purposes they are beyond the design activities direct influence and as such external to it they are automatically part of the specification. Similarly codes of practice and national and often international standards exert an influence upon the way in which a specification requirement is generated. Industrial standards set levels of minimum acceptance and as such lay down specifications to which a design must conform right at the start of this generative process.

Codes of practice though often not legally enforced will often non - the - less exert an influence upon the generation of the specification which is external to organisational context within which the design activity is to take place. Finally non-enforced factors which exert an influence upon the generation of the specification such as environmental impact will also affect a specification.

All the above mentioned factors will determine, often prior to technological design considerations, certain aspects of the requirement specification. Before embarking upon a discussion of the ways in which technical aspects will influence the generation of the requirement specification I shall briefly recap on the points made so far. The generation of the specification requirement is influenced by perceptions of the design problem and the way in which these influence initial decisions about possible outcomes of that activity. The degree of flexibility and detail incorporated in the specification will be determined by this. The organisational context of the design activity will greatly determine the generation of the specification by the allocation of resources and by the articulation of the design problem. Finally a number of factors which could be considered to be external to the overall design activity will automatically be incorporated into the specification, i.e. appropriate legislation.

In addition to the above mentioned aspects of the specification there also exerts a component part of this stage which could be termed the production specification. Essentially the production specification can be characterised as comprising of the technical requirement of the overall specification. The production specification is basically a statement of the technical problem which is to be solved. The form and content of the problem statement will largely be determined by the method of formulation used. However though differing in style and structure most methods will produce a statement containing the same basic components. A statement of overall function will be included within this to provide the basic orientation for the activity and a preliminary outline of the main features the design must possess. In addition to this a degree of definition will also usually be given to the sub-functional structures of the design. In most cases this will consist of identifying the sub-functional areas and indicating their relationship to one another and the overall function. Again the form the sub-functional structure takes will be largely determined by the method of formulation chosen; and this choice will be in turn determined by the complexity and scale of the problem and by the evolutionary stage of development of any particular design. A further level of structural decomposition may take place with the definition of elements within each of the sub-functions. Between them these levels of functional identification will form an abstract description of the basic operational structure of the item to be designed.

The form the production specification takes will ultimately be determined by the method of formulation chosen. As such the sub-functional relationship will gain their form from the degree of abstraction, and form of synthesis used by, or inherent within the formulation method. The initial problem statement however, which forms the basis of all further activities within the process of generating specification, though again differing in precise detail of formulation will essentially be a product of the interplay of a number of basic components.

The most dominant of these components in terms of influencing the outcome of the formulation process is the value criteria. The term value criteria when used in this context refers to the way in which the required qualities and quantities are weighted in terms of desirability. Value is used in its broadest sense, to indicate not only the economic, but also the technical value of a characteristic. A value criteria will exist within all design processes for without one no form of decision is possible, and the orientation of the process so range as to be almost useless. The clarity and definition of the elements within any given value criteria are dependent upon the wide range of factors which influence its formulation, and the vigourousness within which they are pursued.

As the perceived need is initially analysed problems will start to be identified and a preliminary statement of goals and even possibly intermediate objects, will be formed. At this early stage the relationship between the criteria, the identification of problems and the stating of goals, is a fluid one. Where some form of methodology is used the relationship may become more rigid. However as Matousek (1963) points out in his examination of the morphology of specification, there exists a 'ripple effect' which he states may not always be able to be eradicated until the latter stages of a designs evolution when goals, probabilities and types of systems behaviour have received greater attention. In other words it is not until the criteria is defined that accurate and informed decisions can be attempted. The information which is required for the formulation of the criteria is however derived from, the defining of the designs parameters, the defining at even the most abstract levels of the systems inputs and outputs, and some form of projection of the types of behaviour the system is likely to exhibit. The definitions and projections are themselves in part formed by the criteria used within the process and decisions which are dependent upon it. Thus a tautology of sorts exists which is overcome by the element which receives either the greatest design effort, or strongest methodological technique becoming the driver of the formulation process.

The precise weighting given to each of the elements which influence and contribute towards the generation of the requirement specification, differs within the literature from author to author. Dieter (1983) takes the view that the generation of specification is driven primarily by the definition of the problem, which itself is generated by a rigorous examination of need. For Dieter the gathering of information as an aspect of specification generation is an activity ultimately driven by problem definition rather than a process which has a major influence upon problem definition. The definition of the problem is for Dieter derived from the formulation of the problem statement, and the analysis of the problem. These two processes, may be formally or informally undertaken (Dieter recommends the use of a systematic methodology to provide definition to the problem by forcing the designer to examine the need and re-state it with greater clarity. The point that the requirement specification is essentially about clarification of problem is one which is also noted by Matousek (1963). For Matousek (who is again working from a systematic view of design) the two elements which contribute to this clarification are a listing of the problems, or more usually types of problems, which are to be solved, and the production of some form of value model. For Matousek the value model, or criteria can only be fully defined after further knowledge about the parameters of the activity, and likely types of system behaviour are known. This he believes can only take place as a design is developed. This is not however to state that he takes the view that it is impossible to form a criteria of value in the early stages of design activity. In the early stages of the activity Matousek sees the value criteria being formed through an interplay between the perceived need and the problem statements. By the evaluation of the latter against the former an initial criteria of value is formed which is then built upon and gradually formed as greater knowledge becomes available, into a precisely defined statement of idealised value requirement.

Ostrofsky (1977) who looks indepth at this area within the design process, essentially views the whole process of generating the requirement specification, as one of producing sets of goals for the design activity, preferably with as much detail as possible. Ostrofsky views the requirement specification as being generated within what he terms the feasibility stage. This stage encompasses all the preliminary design activities from need analysis to lists of possible solutions, (candidate designs). For Ostrofsky the requirement specification is generated through a three stage process consisting of need analysis, the identification and statement of problems, and finally a statement of goals and sub-goals. Within this preliminary stage the sub-process of the production of a value criteria takes place during need analysis. Through the analysis of need Ostrofsky views it as being possible to identify the primary aspects within that need, which assert a dominant influence upon the other areas within the need. It is these which will formulate the initial criteria.

The term feasibility study is also used by Asimow (1962) with a similar meaning to that of Ostrofsky, but with different emphasis within it. Asimow makes the point that the need is perceived through economic realities and that for a need to become established as potential area for design activity it must in some way establish its economic existence. Asimow returns to this theme constantly within his work stressing the point that the economic is as important as the technical, (and ultimately more so), in determining the specification of a design.

The generation of the requirement specification is the culmination of the initial activities of the design sequence. The preliminary activities of any particular design will produce an initial specification, it is however through its interaction with the other stages of the design process during the early interaction development of a design that a fully developed requirement specification emerges. The generative process itself, though in terms of precise detail, taking differing forms, is essentially composed of a number of common elements. The relationship between these is determined by the degree of emphasis placed upon them. However it is widely acknowledged within the literature that it is the value criteria, or model which will ultimately determine the form of the output from this activity and this ultimately the finalised design.

3.3. The Generation of Candidate Designs

Introduction

The second major area of specific design activity within the model is that concerned with the generation of candidate designs. Candidate designs can be defined as possible design solutions which appear to fulfil the specification requirement. This area of activity can be broadly defined as that which takes place between the input of the specification requirement and the output of a candidate design or designs. The generation of candidate designs is the central area of the design process and is the activity most commonly associated with design.

The way in which the generative activity takes place within this area is dictated by a number of design principles. These principles are derived from a number of sources. Primarily they have been generated through an analysis and synthesis of literature concerned with the problems of design. As such they are primarily consensus based and consist of a combination of both prescriptive and descriptive material. These two types of approach tend to support each others view, with the prescriptive approach moving towards becoming a methodological aid by attempting to structure the agreed upon framework which represents the model of the design process.

In addition to the general type of activity undertaken within this stage of the design model it is also characterised by a number of specific types of activity which guide the generative process. These sub-activities are viewed as taking place within all design regardless of size or complexity.

The sub-activities which form the structure of the generative stage have been derived from the design literature of a number of areas. Systems science and systems engineering strongly advocate that design problems are described in terms of function, and that these functional descriptions should be abstracted to the greatest degree possible. Design theorists working from a systems approach also advocate the decomposition of the problem to the greatest degree possible before attempting to formulate possible solutions. This type of approach is similarly advocated by researchers investigating the problems of creativity. Notions such as the abstraction and decomposition of design problems prior to attempting to produce design solutions are also much in evidence within the design literature in general and especially so within literature concerned with systematic method. The precise way in which such literature and it accompanying conceptional models have influenced the sub-structure which will be argued for within this section is discussed within each of the appropriate sub-sections. Before arguing the theoretical soundness of this aspect of the model however a brief outline of what is to be discussed will be given.

Initially the design problem should be abstracted and described in terms of function. The abstraction of the problem should always take place to the greatest degree possible so as to allow for the broadest view of the design problem to take place. Functional description serves a similar purpose by attempting to negotiate any pre conceptions which may otherwise adversely influence the formulation of a design solution. The problem should then be decomposed to its most basic sub-components. This process serves a number of purposes the most important of which is to allow for a fully defined problem. Once a design problem has been abstracted and decomposed the generation of design concepts may take place. By the composition of the component concepts the candidate design is formed.

The above description it should be noted offers only a very basic description of the process which takes place within the generative stage of the design process. It will however be argued that this is in fact what does take place both within formal and informal design and is not, as is often argued, merely a systematic methodological aid which may on occasions assist the designer. Neither is it a systematic constraint upon the designer. The above described process it will be argued is not a systematic method which restrains design creativity, but rather is a description of what in fact takes place when design activity is undertaken within this stage of design.

3.3.1 Abstraction and functional description

The generation of candidate designs takes place through a sequential process which contains a number of stages or areas of activity each of which have their own particular characteristics. The first of these has as its main activities the abstraction and functional description of the design problem. By this what is meant is that specification is moved for any specific formulation and broadened in context through the process of abstraction. Functional description forms part of this process again as a means of both clarifying the actual need, and also broadening the scope for the recognition of possible solutions. It is asserted that this process takes place within all design processes.

The evidence to support this claim comes from a number of sources. Psychologists working in the areas of both general creativity and creativity as an aspect of design, provide evidence which supports this claim. De Bono (1972, 1974, 1976, 1977, 1980) asserts that the primary activity within all generative thinking is that of abstraction. For De Bono the greater the ability to abstract and to recognise the relationships between abstracted ideas, then the greater the potential of an individual to synthesise possible solutions. Similarly Guilford (1950) asserts that all creative thought will require synthesis and that all synthesis of ideas and concepts requires as its very first step, abstraction. Osborn (1963) asserts that the recognition of similarities between any ideals will require some degree of abstraction. From a psychological point of view it can be seen that initially in all forms of generative thought abstraction will be required as a necessity for the recognition of similarities and the synthesis of ideas.

Systems science also advocates the use of abstraction through the use of functional description. For systems thinkers (Checkland 1981) before an attempt can be made to solve any given problem the first step should be the functional description of that system or problem. The primary objective of this procedure is to produce a view of the problem which is not solution biased and thus give a more accurate understanding of the problem, (M'Pherson 1980). The benefits of such an approach are reiterated within the sub-sections which follow this. These basically consist of broadening the scope of the designer to produce better design by allowing him to view what is essential to a design system and what is not. By this method the designer is able to identify the essential elements of a system and to gain a broader view of the relationships within that system. The functional description of a design problem is the first step in allowing this to take place.

Many design theorists also advocate the abstraction and functional description of design problems as a preliminary stage in the generation of possible design solutions. Dixon (1966) asserts that the broadest possible view of a design problem should be taken prior to the commencement of any search for a design solution. To do this he advocates looking for the 'essential characteristics' of the problem. Design theorists working from the perspective of systematic design theory are more explicit in their view of the importance of abstraction and functional decomposition as the starting point of candidate design generation. Pahl and Bietz (1984) emphasise this practice as the start of a sub-process within the generative stage which ensures that the best design solutions are obtained. This view is substantiated by Machett (1981) who drawing upon the findings of a review he had undertaken asserted that abstraction was the essential initial point from which the generative stage concerned with the production of candidate designs should commence.

From an analysis of the literature discussed above it becomes evident that the term abstraction is used to convey a number of differing meanings. These meanings however can all be said to fall within one of the following categories; 1) Isolation, 2) Generalisation, 3) Idealisation. By the term isolation what is described in this context is the way in which it is possible to abstract an item or type of knowledge by attempting to identify its basic elements or characteristics by isolating these away from other more incidental features. Generalisation in the context of types of abstraction simply means that the statement, item or type of information is expressed in the broadest terms. Idealisation refers to the abstraction of an item or system by stating it in its most simplified form.

There is, as has been shown, general agreement that the processes of abstraction and functional decomposition should and in fact do form the initial phase of a search for candidate designs. Psychological research indicated that abstraction is a necessary pre-requisite for generative thought to take place, and these assertions are reinforced by literature from the areas of systems science, systems engineering, design theory and systematic design method. It shall be noted that the authors cited, though not exhaustive, are believed to be highly representative of the areas from which they were drawn.

3.3.2. Decomposition

By the processes of abstraction and functional description the design problem will have become described in generalised terms.

Before however a search can be undertaken to attempt to find design solutions the decomposition of the problem should be undertaken. The term decomposition is used here to describe the reduction of the design problem to its most basic sub-functional units. In some instances this may have taken place as part of the process of abstraction and functional description. If however this is not the case decomposition should be undertaken. This activity serves a number of purposes. By the process of decomposition the design problem will gain greater definition which will allow the designer to view the problem with greater accuracy. It will allow the relationships between the various aspects of the problem to be more clearly understood. The abstracted and decomposed design problem should reveal the precise nature of the task which has to be undertaken, as well as allowing the designer to remove any preconceived notions as to the exact nature of the design problem. The last point is one about which there has been some debate. Some design theorists (Lawson 1982, Whitefield 1985) have asserted that designers are solution orientated and as such take a holistic approach towards the generation of design solutions. In reply to this it can be asserted that the process of decomposing design problems does not necessarily mean that designers cannot draw upon previous design experiences, (for a more detailed discussion of these issues see section 5.1.). For designers to recognise the similarities between design situations some form of decomposition of a design problem will be required. The process of decomposition not only benefits designers who wish to find innovative design solutions, but also is an essential part of varied design in that through this process elements of a design which are redundant or which can be modified are revealed.

The view that decomposition is an important part of the generation of design concepts is supported by a large number of design theorists, as well as by evidence drawn from other areas.

French (1971, 1985) dealing specifically with the area of concept generation, has advocated the designer should always attempt to decompose a design problem in some formal manner. He bases this assertion upon the fact that he believes that all designers will do this, to some degree, naturally, and that as this is the case it is beneficial to the design if he is fully aware of what he is doing so as to avoid only partially implementing this process. Similarly Pahl and Bietz also advocate the use of formal methods to undertake this process, stressing the benefits to the design of decomposition, and the benefits to the designer of the use of a systematic procedure. Eeckels (1981) in his description of the morphology of design, views decomposition of design problems as being an essential aspect of the way design develop.

The notion of reducing a problem to its most basic functional sub-units can be seen to be highly compatible with work conducted in the area of systems theory. The decomposition of problems and the benefits from doing so, (outlined above), are emphasised by systems theorists, (Chestnut 1965, 1967, Checkland 1981, Churchman 1966). Similarly researchers into design looking at the problems of organising the process from the point of view of management have also recommended the decomposition of design problems. Clough (1972) and Oakely (1984) both reach the conclusion that to fully understand a design problem it is necessary to decompose it into basic units.

Simon (1969) in his work The Sciences of the Artificial devotes considerable attention to the importance of decomposition. For Simon decomposition is an essential aspect of all forms of human understanding and reason. By the synthesis of ideas from a number of disciplines, (notably, systems theory, linguistics and cognitive psychology), Simon shows that a system of any type needs to be reduced into manageable sets and category groupings. By this means it becomes possible to understand the whole by comprehending the constituent parts and their relationships. Simon extends this argument to encompass the area of human reason. For Simon problems need to be disassembled and categorised for them to be correctly identified and understood.

The degree to which decomposition should take place, and the amount of formal method that is required (if at all), will be dependent upon the nature of the design being undertaken. It will however always, in some form be required.

3.3.3. The Generation of Primitive concepts

Primitive concepts are the possible solutions which are generated to fulfil the requirements of the abstracted and decomposed design problem. As such primitive concepts are the central element in the generation of design concepts, candidate designs, and ultimately the finalised design. The term primitive concept is used in this context to indicate that in their initial form the component parts of a design are often generated as abstractions, generalised principles, or physical laws. As designs are developed through the combination of primitive concepts and the continuous iteration of the design process, the design concept will be formed and gradually gain detail, until eventually a fully detailed design is produced. Eeckels (1981) recognises this process when he refers to design as being the moving from 'the abstract to the concrete'. The aim of this section is to establish the way in which primitive concepts are generated and to discuss the way in which they contribute to the development of a finalised design.

The way in which primitive concepts are generated can vary considerably in both the formality of the process and the type of generative method which is used. These factors will vary depending upon the type of design which is being undertaken. It is asserted however that within all primitive concept generation there exist basic similarities. These similarities exist in terms of the types of approach which can be used to generate a design primitive. Regardless of the type of design which is being undertaken or the degree of formality with which a concept has been generated, it will have had to have been done through one, or a combination of, the following generative processes:-

- Convergent concept generation
- Divergent concept generation
- The systematic variation of a concept.

The above classification of types of methods by which it is possible to generate design primitives, has been produced from an analysis of the literature both from within the field of design and from that of psychology. A general discussion as to the validity and wide scale recognition of the types of search strategies mentioned above will be undertaken in this section. Here an examination will be made as to what is meant by each of the classifications and a description given of the types of activity undertaken within them.

Convergent Generation of primitive concepts.

The generation of primitive concepts by the use of convergent search methods is widely advocated throughout the literature on design. The term convergent generation is however seldom used to describe these types of methods. Types of search strategies that are referred to here are those which could be described as starting from a wide field of possible solutions and which then attempt to reduce this solution area and converge upon an appropriate solution. Typical of this type of approach is the search of types of information which are likely to have embedded within them design concepts which will be of use to the designer in the production of primitive concepts.

From an analysis of the literature concerned with design it became apparent that the informational sources which are used by this type of generative method can be categorised as follows:

- Literature
- Patents
- Catalogues of design concepts
- The study of existing equipment

The use of literature as a method of generating design primitives is widely recommended by design theorists, (for example, Asimow 1962, Alger and Hayes 1964, Pahl and Beitz 1984). Within this category are included, text books, treatise, monographs, periodicals and conference literature. The aim of this approach is to provide the designer with a broad area of information from which it will be possible for him to either, recognise solutions to similar types of problems which may be used or adapted to fulfil his present design need, or to recognise instances where differing types of basic approach have been used. From this information it is possible for the designer to either adapt existing design solutions or to use the fundamental principles as a means of devising a new solution. A search of patents will provide information in a similar manner, and is also recommended by a large number of writers, (typical of these are, Woodson 1966, and Dixon 1969).

As mentioned above it is possible for designers to obtain information useful to them in generating primitive concepts by locating solutions to similar design problems and examining the fundamental principles by which they operate. The examination of catalogues containing design concepts will assist the designer in a similar manner. The degree of abstraction with which such catalogues present design concepts varies considerably depending upon the particular area of design and the type of search method advocated for the use of the catalogue. These range from lists of physical principles and laws, for the type of catalogue recommended by Wilde (1964) and Hix and Alley (1958), to catalogues which contain listings of simple components and sub-components such as those referred to by Krick (1965) and Potts (1973). The manner in which the type of search method can affect the appropriate choice of catalogue is discussed later within this sub-section, within a general discussion of types of methodologies available to the designer.

The study of existing equipment is referred to by Pahl and Beitz (1984) as being the most common method of primitive concept generation. An analysis of the literature confirms that in almost all cases where a discussion of the generative stage of design concepts takes place, this type of search is mentioned. There appears to be no main advocate of this type of approach above others, though some authors give it greater precedence, (for example Johnson 1971).

The searches of the above mentioned types of material are primarily carried out by means of convergent strategies. The strategies may take the form of broad appraisal of appropriate material from which an attempt is made to converge towards a suitable primitive concept, or they may take a more methodological approach. The type of methodological approach which will be appropriate will depend upon the type of material which is being considered. The search of literature, patents and the less abstracted forms of design concept catalogues can be assisted by the use of morphological type techniques. Examples of these are morphological analysis (see Arnold 1959) and morphological matrices (see Ostrofsky 1977). Both these methods are fundamentally similar, providing an ordered and systematic means of cross checking concepts both against the design need, and against each other. By this means it is possible to collect all suitable ideas, and to recognise ideas which are similar but which may not initially appear to be so. Both these examples require the decomposition and functional expression of the design need.

The search of catalogues of design concepts where concepts are expressed in an abstract form may also be undertaken with the use of methodology. Such methodologies are put forward by Hix and Alley (1958) and Wilde (1964) amongst others. Primarily these types of methodologies consist of the systematic listing of physical laws and properties to determine an appropriate set of principles, and the systematic examination of a physical law to derive a design concept. The morphological types of methods previously mentioned can also be of use with regard to this type of abstracted catalogue, (Eekels 1985). In addition to this Encarnoco and Krause (1981) suggest that the computerised use of catalogues can be of use, provided appropriate storage and search strategies are used.

The study of existing types of equipment can provide the designer with useful primitive concepts. The way in which this can be done is either through recognition of similarities between the item and the design problem, which can be assisted by either attempting to recognise similar basic operating principles through abstraction or through the variation of certain aspects of the item i.e. reversal or negation of components and functions. As this method is dealt with within this section, no further elaboration will be undertaken here.

Divergent Generation of Primitive Concepts

Divergent methods of generating primitive concepts are characterised by attempting to release the designers search for possible solutions from as many restraints as possible and thus broadening the area from which such solutions might be found. In addition to this divergent methods are also characterised by the designer making maximum use of his powers of abstraction and his abilities to make connections between analogous material. The divergent generation of primitive concepts takes place either informally relying upon the designers natural skills and abilities, or through the use of divergent techniques. Although there are a great many such techniques, the majority can be described as being one, or a variation of one, of the following types of approach;

- Synectics
- Fundamental Design method
- Lateral Thinking
- Brainstorming

Synectics

Synectics comes from the Greek word meaning the joining together of apparently unconnected elements. The methods described by this term are essentially concerned with creating the conditions from which this may take place. The main characteristics of this method are basically, first to encourage the designer to withdraw his concentration from the problem, then secondly, to encourage the designer to undertake an exercise in free association, and then finally the designer returns to the original problem and hopefully will have managed to generate some new ideas. It should be noted that the term designer is used here mainly for convenience, the synectics approach towards the creative generation of ideas is in the main put forward as a team activity (Raudsepp 1969).

The methodology used is essentially similar regardless of which of the authors in this area is examined. The process commences with an in depth analysis of the design problem. What is sought here is a clarification of the problem so that its major features may be identified, and those which are only incidental ignored. A point to note here is that nearly all the writers in this area assert that the process of problem clarification will itself often provide useful potential solutions. However once a problem has been fully clarified it is then put aside for a while and ignored. The term ignored is however used advisedly, for though having clarified the problem one should explore subject areas which appear to be unconnected to that of the problem, they should at least appear to be the sort of area which could provide a solution. Gordon (1961) for instance notes that biology is the richest source of analogous material for both problems and potential solutions. Wherever the search for possible solutions takes place it is important at this stage of the process not to become too focused upon the problem, though of course it will be borne in mind. The important aspect of this part of the method is to allow the broadest analogous search to take place. This having been done the design problem is once again considered and it is hoped new solution ideas will be forthcoming.

Fundamental Design Method

Fundamental design method is the generic term given to a number of methodological approaches to the problem of concept generation all of which have in common certain fundamental similarities. The title Fundamental Design Method was first put forward by Matchett (1968) who though not the first person to conduct research in this area, was the first to recognise the similarities between the various groups described by this method. The principal characteristic which the methods and techniques described by this term have in common is introspection. The designer through the process of introspection critically examines the controls and restraining influences which he himself has imposed upon his imagination's search for possible solutions. By the identification of these controls and restraints the designer is able to largely negate their influence and thus broaden the areas of solution search. This type of approach is advocated as a systematic methodology, by the adherence to which the designer will be ensured the greatest degree of success in recognising the restraints he is imposing upon himself.

Lateral Thinking

This technique starts from the premise that there exists two modes of thinking. These are termed lateral and vertical thinking. The first type is most easily recognised when it leads to ideas which are obvious only after they have been thought of. The second type, vertical thinking, follows a more logical pathway, through which it is possible to follow the development of an idea. An additional notion put forward by DeBono (1971) is that with vertical thinking it is possible to return along the logic pathway to the starting point of the process, where as with lateral thinking it is not.

Lateral thinking is at its most useful when new and innovative ideas are required, or when a new perspective of all old problems is required. De Bono (1967, 1969, 1971, 1976) states that where as in vertical thinking logic is in control of the thought processes, in lateral thinking the thought processes are in control of logic. He further asserts that lateral thinking is for generating ideas, where as vertical thinking is for developing, selecting and implementing such ideas. A discussion of the types of techniques which assist with this method are given in DeBono (1976).

Brainstorming

Brainstorming was originally conceived as a group activity for the generation of possible solution ideas in a spontaneous manner. Though this technique may have been used for a considerable length of time, it did not receive its famous title until the 1950's (Osborn 1953). The technique has been widely written about and discussed. From these works it is possible to state that there is agreement as to the main elements of the technique. These are:-

- No criticism of any idea should be allowed until the end of the session.

- All contributions should be welcomed

- The production of the greatest number of ideas should be encouraged.

The aim of the above stated guidelines is to help create a relaxed, free thinking, adventurous atmosphere where the most creative contributions can be made. There is no ideal number of people for the group taking part, though they should neither be very small nor very large. Essentially this method is good at taking initial ideas and developing them into possible solution.

A number of variations of this technique exist, most noticeable, the Delphi method, and the 653 techniques. All however are in essence similar to the basic technique of brainstorming.

The Systematic variation of a concept

The systematic variation of a concept as a means of generating a design primitive may take place either in conjunction with convergent generative methods, or with divergent generative methods. This form of search may be used both as a way of giving the design problem greater definition, and also as a way of examining concepts which have been generated as possible design solutions to reveal features which may otherwise be missed. Most forms of design literature suggest this type of method to some extent, however notable amongst these are Biot (1970), Lanezos (1966), Schen (1963), and from the field of psychology Simon and Barenfield (1969). Advocates of this type of technique vary in detail and the degree to which a formal systematic methodology should be used; those however which do put forward a systematic approach are basically similar, their main characteristics being:

- i) Variation of the functional structure
- ii) Examination of each function to see whether there are alternative forms of realisation
- iii) Systematic regulation
    - a) Component removal
    - b) Component reversal
- iv) Analysis of attribute characteristics
    - a) enhancement of desirable characteristics
    - b) removal of limitations

The three categories of methods which can be used to generate design primitives were produced through the analysis of a large amount of design literature. The generation of a design concept may not always take place in strict accordance with just one of the discussed methods, it will however be forced to take place through at least a combination of these methods.

3.3.4. The composition of a candidate design.

A candidate design is formed by the composition of the component concepts into a whole system. By the recomposition of the decomposed design problem for which design concepts have been generated it is possible to produce a candidate design. The initial composition of a design may require modification and adjustment, and this may be undertaken through the process of iteration. It is also possible that a number of solutions have been generated for the sub-functions and components. Through the process of combining these in different ways it may be possible to produce a number of alternative design candidates.

The ways in which the composition of a candidate design takes place will vary in accordance with the degree of formality with which a design is being undertaken. In many cases it may be possible for the designer to simply conduct this activity by himself without resource to any method of aids external to himself. When however this is not the case there are a number of techniques and methodologies which can be used. These range from rough sketches or loose symbolic representations to the use of formed methods such as morphological tables and concept matrix. Zwicky (1951) is one of the earliest advocates of morphological tables as a means of producing candidate designs through the systematic combination of suitable design concepts. Similar Norris (1963) advocates the morphological approach. The use of such tables however requires that the design concepts be structured within a formal table and as such may present difficulties to the designer if he has not used such an approach throughout the design process. Alger and Hays (1964) have noted this problem and state that the use of such tables will depend upon the overall context of the activity and the methods used to generate design concepts. Hill (1968) stresses that such formalised methods may well only be of relevance to designers if used as part of a convergent search structure. Asimow (1964) makes a similar point by putting forward the notion that the production of candidate designs takes place through a process of creative synthesis of design concepts.

Though there exists within the literature differences as to the way in which design candidates can be composed there does exist general agreement that this activity does in fact take place within the generative stage, though the process may be modified through the iterative process as designs are evaluated and analysis takes place.

3.3.5. The generation of design concepts and the Blackboard model.

As attempts are made to generate candidate designs, design concepts will be produced. These will need to be stored either in some formal manner, or in the designer's memory. It will be desirable that these design concepts can be 'reviewed' throughout the generative process so that their relationship and likely effect upon the overall systems can be considered at any time during the development of a design. The aspect of the model of the design process which facilitates this is the Blackboard. Similarly when the composition of a candidate design takes place a number of combinations may be undertaken. The storage of solutions and partial solutions is conducted through the use of the Blackboard concept. A detailed discussion of the relationship of the Blackboard concept to the design process as a whole and the generation of candidate designs in particular is given in Chapter 3.6.

3.3.6. Conclusion

The generation of candidate designs takes place through a process which consists of the abstraction and functional description of the initial requirement specification, the decomposition of the problem, the search for suitable design concepts and then finally the composition of these concepts into candidate designs. The evidence for this being the case comes from a wide variety of sources both from within the field of design and from disciplines not primarily concerned with design. It is asserted that all design takes place in this manner, regardless of the type of design which is being undertaken, or whether or not formal design methods are used.

3.4. Analysis

In general usage the term analysis is defined as 'the division of a physical or abstract whole into its constituent parts to examine or determine their relationship', and as 'a statement of the result of this', (Oxford Dictionary 1988). By this definition it could be argued that analysis takes place at a number of stages within the design process, or even that it takes place to some degree throughout the entire process. However, when strictly applied this definition can be used to reveal analysis taking place in three main areas within the process. These areas consist of need analysis, taking place as an aspect of the generation of the requirement specification, economic analysis, which occurs both as part of the evaluation process and as part of the generation of specification, and, the analysis of the attributes of a design relevant to their function.

It is with the analysis of attributes relevant to function that this chapter will be primarily concerned. The other two types of analysis which occur within the design process occur as aspects of larger design stages, and as such are discussed within the chapters concerned with those stages. The aim of this chapter is to establish that there exists within the process an area of activity which can best be described as the analysis stage. This having been done the discussion will move on to examine the types of design activity which take place within the analysis stage, and to discuss their importance to the process as a whole. Before continuing any further it would be useful to outline the main characteristics of the stage which are to be discussed.

The position of the analysis stage within the design process is viewed as being between the concept generation stage, and the evaluation and decision stage. The activity within this stage is primarily that of examining the attributes of a design relevant to their function. This consists of attempting to discover what the functional performance of the constituent parts of a design are likely to be and how the design will function as a whole system. In the case of simple design the designer may well conduct the analysis heuristically with little recourse to methodological techniques. The same may also be the case in the early stages of the iterative process. With more complex or developed design problems however the designer will require the use of design aids to allow him to produce more accurate information. The analysis stage is in many ways concerned with modelling the design so that an accurate picture of it can be obtained. Indeed the use of modelling techniques are frequently referred to within the literature in connection with analysis. This point is discussed further within the section concerned with literature in this chapter. Before building up a more detailed description of the types of activity which take place within the analysis stage a discussion will be undertaken to determine whether in fact it is correct to assert that such a stage can be identified within the design process. To do this an examination of the literature will be undertaken and from this evidence drawn to show that this is in fact the case.

Analysis as an aspect of the design process is referred to widely within design literature. These references can in turn be categorised as taking two forms, those that view analysis as a general aspect of the entire process taking place throughout the development of a design, and those that identify analysis as a specific stage of design.

The discussion will deal firstly with the literature which asserts that analysis takes place during a number of stages within the design process. It will be argued that although this literature does identify analytical activity taking place within a number of areas in design, those activities other than the analysis of attributes relevant to function can be categorised as belonging to larger design stages. The aim will be to show that there is a stage within the design process where analysis takes place which itself cannot be categorised as an aspect of one of the other design stages.

Typical of those design theorists who view analysis as taking place at a number of stages during design is Simon (1975). For Simon (1975) the term analysis is used to indicate areas of design where critical examination of information takes place. However Simon (1975) recognises that there is a specific stage within design which he refers to as the analysis and testing stage. During this stage Simon views that the candidate designs are analysed essentially stating that the attributes of a design relevant to function are examined. Simon stresses the importance of this stage of design by stating that it represents 'the greatest area of design effort', (Simon 1975 pp 15). This type of view is put forward by a large number of design theorists. This point of view recognises that there exists a major area within the design process where analysis takes place, but also refers to analysis taking place during other stages. Dixon (1966) makes similar points concerning analysis and its relation to the stages of the design process. Dixon (1966) notes that analysis takes place at a number of stages during design. In addition to this however he acknowledges that there is a major stage within the design process when the dominant activity is that of analysis, and that this is aimed at attempting to gather or generate information concerned with the functional performance of a proposed design. It is important to note that not all authors use the term analysis to describe the activities of this stage. Some authors though referring to activity which is argued for within this chapter do not use the term "analysis" exclusively. Krick (1969) for example acknowledges that a critical examination of the attributes of a proposed design will always need to take place and as such has incorporated this as a part of his description of the design process. In cases within the literature where the analysis stage is in fact referred to it is often done so by referring to it as a particular type of analysis. This takes place most predominantly amongst authors who use the term to describe other specific analytical activities which take place within the process. Asimow (1962) and Woodson (1966) are two good examples of this. Both Woodson (1966) and Asimow (1962) initially link analysis to the start of the design process. The term need analysis is used by both authors to characterise the preliminary stage of the design sequence. The activity described is fundamentally that of the generation of the requirement specification. Analysis is however also used in the sense defined by this chapter, that is as an activity concerned with the attributes of a proposed design. This form of analysis is termed as, estimation and order of magnitude analysis by Woodson (1966) and, analysis and prediction (Asimow 1962).

The examples taken from the literature and discussed above illustrate that there is a recognition that there exists an analysis stage within the design process. Though such examples use the term analysis in connection with a number of stages of the design process or in some cases not at all, they all recognise that there exists within the process a major area of activity where an attempt is made to assess attributes relevant to function.

The literature which can be used to indicate the view that analysis takes place only at a specific stage during the design process will now be discussed. Due to the fact that the literature of this sort is supportive of the notion of an analysis stage within the design process, the discussion that is to follow will be some what briefer than the above. Essentially all I aim to establish at this point is an agreement to the existence of an analysis stage, and to show that broadly similar types of activity can be seen as characterising this stage.

Design theorists who approach the problems of design from the perspective of systematic method are amongst those who most firmly recognise that there exists an analysis stage within design. Pahl and Beitz (1984) refer to the analysis stage of the design process stating that the types of activity which are undertaken within this stage are primarily concerned with assessing the functional suitability of a design in terms of its performance. Performance when used in this sense it should be noted can be seen to be being used in the broadest sense. Essentially what is being expressed here is that an examination is undertaken of the candidate system, and its constituent characteristics, and an attempt made to generate its likely operational features. For Pahl and Beitz (1984) the analysis state is largely characterised by the use of techniques and methodological aids. Though this is a view consistent with their systematic approach and the nature of the type of area within which they are discussing design, that of mechanical design, it is a view expressed by many authors on this area, and as such cannot simply be dismissed as a feature of subject and style. This point is elaborated further later in the chapter when a discussion is undertaken of the nature of the activities which take place within the analysis stage. Hubka (1982) offers a similar view of the analysis stage to that of Pahl and Beitz (1984). Hubka (1982) similarly asserts that within the design process there exists a stage which is characterised by activities which examine a candidate design in terms of attributes relevant to function. In addition to this Hubka (1982) also asserts that the primary means through which analysis takes place are those of methodologies and techniques. The recognition of the existence of the analysis stage is not however solely confined to theorists working from a systematic perspective. Gibson (1968) refers to the analysis stage of the design process, as do Beakley and Chilton (1974). Both recognise that within any description of the design process it is important to give a place within it to an analysis stage. The features of this stage are similar in the way they are described by both sets of theorist. Essentially the analysis stage consists of examining the candidate design to assess the way in which it performs its function. Not all theorists who view analysis as a single stage within the design process do so purely in the terms expressed above. Alger and Hayes (1964) for example view the technical and economic analysis of a design as indivisible, and Buhl (1960) similarly views the analysis stage as being concerned with a number of aspects which will affect the final decision to implement or modify a design.

From the above discussion of the literature it is possible to see that although some design theorists refer to analysis as taking place in a number of areas within the design process, (predominantly within the areas of need analysis, economic analysis, and the analysis of attributes relevant to function), there is almost unanimous agreement that there exists a stage which matches the description given by this chapter. This stage, the analysis stage, is the area within design where analysis becomes the predominant activity. Other areas of analytical activity can be seen to be constituent parts of larger design stages and as such are dealt with within those sections. Having established that it is valid to refer to the analysis stage of design the discussion will now move on to discuss what takes place within this stage, and how.

This part of the discussion will firstly examine the literature to establish what types of activity are undertaken within the analysis stage and will then move on to discuss how these activities are undertaken. This division has been made for two reasons. Firstly to demonstrate that although there are differences in the way that the literature approaches and classifies the problems and activities of this area, there exists a fundamental similarity. The second reason is that although it is possible in some instances for analysis to take place informally and heuristically, in a great number of cases there will be a necessity that the designer uses some form of design aid.

Amongst the literature already referred to within this chapter there exists a number of good examples of the differences of approach towards the analysis stage and that which takes place within it. These then are a good place to start the discussion. Pahl and Beitz (1984) refer to the analysis stage as being concerned with three basic types of analysis. For Pahl and Beitz (1984) the analysis stage is concerned with the analysis of performance, the elimination of technical contradictions and environmental factors. This type of categorisation of the types of activities which take place in the analysis stage is one which is common amongst a great deal of literature. Whilst recognising that an analysis of a design's attributes relevant to function is an essential element of the analysis stage, Pahl and Beitz (1984) also add two other areas where analysis is used. Within the model of design being argued for in this thesis other forms of analysis are recognised but categorised differently. Environmental factors for instance are seen as being the concern of the specification and evaluation and decision stages, and the elimination of technical contradictions as taking place as a function of the composition of the design primitives and the operation of the Blackboard. The important feature of Pahl and Beitz's (1984) view of analysis is their view of the way in which analysis of performance takes place, as this is the feature of their work in this area most common to the other theorists work concerning the analysis of design. Pahl and Beitz (1984) though recognising that informed analysis may take place, strongly advocate the use of methodologies and systematic techniques. Briefly these can be described as the use of modelling techniques, finite element analysis, schematics, and graphical representations. A discussion of the most common types of analytical methods follows this section so the types of techniques advocated by any given theorist will only consist of a brief categorisation of this stage.

Another theorist amongst the literature previously discussed is Asimow (1962). This theorist also makes divisions within what can be described as the analysis stage in his model of the design process. For Asimow (1962) the way in which the attributes of a design are analysed consists firstly of discovering the way in which a design adapts to change. By this what Asimow (1962) is referring to is an analysis of the dynamics of a system. When considering the attributes of a system Asimow (1962) refers to the performance of a system which he defines as 'the pattern of correspondence between input and output variables' (pp 26). Analysis however is not just applicable to dynamic systems and Asimow (1962) recognises this by discussing another element by the analysis stage calling this stability analysis. Similarly to Pahl and Beitz (1984), Asimow (1962) also notes that the elimination of technical contradictions can be an aspect of analysis, Asimow (1962) senses the term compatibility analysis. It is however with Asimow's (1962) recognition that the predominant activity of analysis is an assessment of attributes that the importance of his work to this chapter lies. He states that the purpose of this type of analysis is to increase the designer's insight into the workings of a design, and thus providing the designer with the information necessary for the education of a design and the decisions which will be based upon this.

Mostow (1985) when discussing the analysis stage of design takes the view the primary concern of this stage is the production of an increased comprehension of the workings of a system. This he states is done by concentrating upon the functional requirements which a design is to meet and determining its success in fulfilling these. For Mostow (1985) the analysis stage is divorced from any attempt to determine the value of the design or its attributes. Detail must be produced regarding a design's characteristics, and these details may then be assigned values, and an evaluation of a design take place. Ostrofsky (1977) similarly acknowledges that analysis is a separate design stage from that of the evaluation of a design. Ostrofsky (1977) is similar to Pahl and Beitz (1984) in his views as to the types of activity which should be undertaken during the analysis. He too concentrates upon the methodology and means to producing detailed information regarding the attributes of a design. This notion of the types of activity which characterise the analysis stage is also held by Matousek (1963). This theorist views the principal activity of the analysis stage as being the analysing the attributes of a design relevant to function and that this is primarily accomplished through technical methods.

It can be seen from the above examples that there exists within the literature a consensus regarding the type of activity which takes place within the analysis stage. This consensus view regards the analysis stage as primarily being concerned with the analysis of the attribution relevant to function. The means by which this analysis is seen as taking place is through the use of analytical techniques, and it is these which will next be discussed. It is important to note however that the model does not represent analysis solely as a technically orientated stage, and this is borne out by the literature. A number of theorists who allow for the possibility of analysis taking place informally are noted above. In addition to these the works of McCory

(1963) and Paynter (1961) should be noted. These two authors are good examples of this point as they also acknowledge that analysis may in the instances of the preliminary stages of design, or in the case of simple design, take place heuristically. This point is noted by a number of other theorists notably, Lawson (1980) and Tovey (1986). Having noted this point the discussion regarding the means to design analysis will now be started.

The number of individual techniques which are available to the designer in performing the task of analysis is extremely large. Because of this, and because a discussion of the technical operation and merits of a technique is beyond the scope of this thesis, this part of the chapter will deal with means of analysis in terms of a number of categories. These categories have been produced from an analysis of the literature and are supported by work done in this area by the City University Design Theory and Methods Group. The work of the Group was undertaken as part of Alvey Project 142, a user modelling tool for interface design. The findings of the study were based upon a large scale literature review conducted in conjunction with experts in the fields of expert system and simulation, and interviews with designers.

Generally analysis takes place in two stages, approximate idealised simulation, and accurate simulation. The first of these stages corresponds to the earliest stages of the iterative process of a design's development, or in the case of the simplest forms of design. The second stage corresponds with the later iterative stages of a design's development as greater definition and detail are gained by a design.

Approximate idealised simulation takes the form of simple schematic and rough calculations. In the case of simple design it is possible that such activity is carried out heuristically by the designer. Most usually this form of analysis is conducted during the earlier stages of a design's development when general points of information are required to assist with initial evaluations and decisions.

The second stage, that of accurate simulation, is characterised by such activities as model building and accurate simulation of the design. This stage of analysis takes place in the later stages of a design's development. The aim of this type of analysis is to produce detailed and accurate information concerning a design's attributes. Accurate simulation follows on from approximate idealised simulation. The former providing the design rapidly and with a minimum commitment of design effort and time, with information in a form appropriate to the initial development of a design. The latter requiring a greater commitment of design effort takes place once a design has taken on a greater degree of detail.

Within these two stages of analysis there exists in each two categories of analytical aid. These two categories are the same within each of the stages. They consist of those types of aid which are a means of knowledge representation, and those which constitute knowledge sources. A description of the nature of knowledge sources is undertaken in the chapter concerned with the Blackboard model, (6). Briefly, knowledge sources can be described as both information and methodological techniques available to the designer during the course of any one particular design process.

Aids to design representation which are available to the designer during the analysis stage consist of drawings, schematics, block diagrams and graphs. The technical complexity of the representational aids is dependent upon the analytical stage during which they are used. Drawing for example may be rough sketches done freehand during the first stage of analysis, or they can be fully dimensioned representations during the second stage.

Knowledge source aids to analysis also exist within both the stages of analysis. These can be categorised as, calculations, model building, dimensional analysis, and performance measure. Again the technical complexity of the aid will be dependent upon the stage of analysis within which it is taking place. In this case of model building for example idealised modelling will take place during the first stage and fully detailed during the latter.

Analysis is an area in design where the use of computers has had a major impact. By the computerisation of the design aids which can be used in this area designers are now able to analyse designs with greater speed and accuracy. The prediction of the way in which complex dynamic systems will behave has been greatly enhanced as have many simpler analytical problems.

It is important to note that design aids do not consist of the only way in which analysis may take place. As with earlier stages analysis may take place heuristally with the designer drawing only upon his own skill and experience. As indicated from the discussion of the literature however, the majority of analysis takes place through some form of method, techniques or formal practice.

3.4.1. Summary of Analysis

The analysis stage of design is when the attributes of a candidate design are examined. The aim is to produce information regarding these designs so that a detailed picture of the design may be obtained. The purpose of this is twofold. Firstly through analysis a greater understanding can be obtained of the way in which a design will operate. Secondly, analysis provides the information for the final stage of the design process, that of evaluation and decision. Without the production of information concerning the attributes of a design it is impossible for the evaluation of a design to take place, and thus impossible for decisions to be made regarding the rejection, implementation or modification of a design to take place. The analysis stage then serves two purposes. To increase the designer's understanding of the features of a design, and to provide necessary information for the completion of the design sequence.

From the discussion of the literature it was established that although there is some divergence amongst design theorists as to whether analysis takes place solely in one area within the design process, there was agreement that there existed a stage where candidates designs were analysed. A consensus was found to exist in the literature regarding the type of activity which was undertaken during this stage. This consists of an analysis of attributes relevant to function.

The way in which this analysis takes place was generally agreed upon as being through the use of design aids. These aids were found to vary in sophistication depending upon the complexity of the design being analysed and the stage of development of a design.

3.5 Evaluation and Decision

Evaluation and decision are essential elements in the production of all design. Within the model of design these two processes have been linked together as the final stage of the design sequence. Whether or not they form the final stage in a design activity will be dependent upon the degree to which a design has been developed and the decision to continue with or terminate the iterative process.

The decision to place these two activities together and to regard them as belonging to part of the same design stage is based upon the highly inter-related nature of their relationship. At many times during the development of a design the division between these two activities is unclear and as such a separation of them would be artificial.

It is during this stage that the various merits of a design are calculated and a decision reached as to whether to reject, implement or modify a design. In addition this stage is also connected with the requirement specification. This connection operates in two ways. The value criteria which provides the basis of the evaluation procedure is formulated during the generation of the requirement specification. The second connection between this stage and the specification is that as a result of evaluation and decision it may become apparent that a modification of the requirement specification should take place. This takes place as an aspect of the iterative process.

The structure this chapter will take is to firstly examine the evaluative aspect of this stage, and then that of decision, and finally discuss the way they relate to the process as a whole.

Evaluation takes place when a candidate design has been analysed. Having determined the attributes of a design, values are assigned to them and from this it is possible to calculate the overall worth of a design. The concept of value is one of the most fundamental components of the design process. Falcon (1964) has defined value as that which satisfied desire. This is in many ways an applicable definition for use in the context of design. The notion of value is inherent to the design process. The value of any given aspect of a design is dependent upon its desirability, and this is determined by the way the perceived need is translated into the value criteria.

Evaluations and decisions take place constantly throughout the design process as they are an inherent part of any selection procedure. As such they may often take place in an informal and rapid manner often comparatively unnoticed by the designer. In the early development of a design, or when the item being designed is of a simple nature this may well be sufficient. As designs develop and become more complex this type of approach may well become inadequate. When this becomes the case a designer will have recourse to the use of methodologies and techniques.

There is no single dominant method of evaluating a design, but rather a wide selection of individual methods. These are primarily drawn from the areas of systems science, operational research and management science. The differing areas from which such methods are drawn reflects the broad scope of differing aspects of a design which need to be considered as part of the evaluation process. The primary features of a design which influence any evaluation are the technical and economic. The relative importance of each of these is a matter of some debate within the literature and is discussed below. In addition to these two considerations a considerable number of other factors need to be considered. These include a design's aesthetic value, its social value, and its overall utility value.

Whether evaluating a design's technical merits or its economic merits the techniques used are essentially similar. These primarily consist of value analysis and value engineering (M'Pherson 1980, 1981). With these methods value is interpreted in the widest possible sense so as to include not only the monetary cost of a design but also its ability to fulfil its required functions. It should be noted that although value analysis and value engineering are ways in which the technical and economic viability of a design may be assessed, their contribution takes place throughout the iterative process and will not always be used just once a candidate has been generated and analysed. Value analysis is of great use to the designer in that its stages of operation can be related to the design process as a whole. These stages are given various names by different authors, however a general description is given by Davis (1965):

i) Information
ii) Speculation
iii) Investigation
iv) Recommendation

v) Implementation

The information stage requires the gathering of factual information about a proposed design. This activity is basically very similar to that of the generation of specification within the model of the design process. Similar basic generations have to be answered, i.e. what are the functions which the system must perform. Speculation is the search for alternative ways of meeting the requirement. This is generally viewed as a creative activity, (Pitts, 1973, suggests the use of brainstorming). Investigation is concerned with the feasibility, both economic and technical, of the various solutions, and appears to be analogous of the evaluative stage in design. Recommendation is used to indicate the reaching of a decision or more usually a number of possible alternatives each of which offer differing merits (Simon 1975). Implementation is used to indicate that the decision to choose a particular recommendation has been taken and its accompanying implications incorporated into the overall design decision.

Falcon (1964) views the contribution made by value analysis to the production of good design as being essential. For Falcon (1964) all but the most elementary of evaluations should be undertaken by the use of this evaluative method. The use of method as a way of evaluating design is indeed advocated widely throughout the literature which concerns itself with this aspect of design. Miles (1973) in his discussion of the various techniques of value engineering reiterates this point expressing the view that all technical evaluation becomes little more than guess work and individual performance without it. Pahl and Beitz (1984) also working from the point of view of technical evaluation strongly advocate the use of method. It is however not only for technical evaluation that method is advocated. Economic factors involved in the production of a design should also be subject to value analysis. The literature in this area comes predominantly from the area of management science. Murdick (1961) views the economic evaluation as a factor which determines the outcome of a design activity to a far greater extent than technical considerations. The point is reinforced by the work of such management scientists as Oakely (1984). Oakely (1984) advocated that the likely final economic analysis should be planned for throughout any technical development. He acknowledges that to some extent this does happen and probably always has, but points out that the best method of ensuring success is through the implication of some form of systematic procedure.

In opposition to this view is the work of Lera (1981). Lera (1981) argues that the vast majority of evaluation within any design is undertaken by lone designers without recourse to any formalised system of undertaking this. Lera (1981) asserts that to impose any form of method upon a designer during the generation of a design would be disruptive to his creativity and would not benefit the activity in the long term. Lera (1981) does however acknowledge that there is a stage within the process where major evaluations take place and agrees that formal methods are appropriate here. This view does not contradict the model which takes account of the likelihood of rapid and informal evaluations taking place throughout a design's development, and allows for this through the iterative process and the operation of the Blackboard.

An additional aspect of evaluation so far not discussed is that of optimisation. Optmisation forms both an aspect of evaluation and decision. When considering a design either separately or in comparison with other designs, trade-offs and modifications will need to be determined so as to produce the best design. Most optimisation techniques are derived from the field of operations research, (Churchman 1974). Optimisation in this context consists of attempting to maximise the overall value of a design. A modification in one attribute of a design may allow for the increase in value of a second attribute. To determine whether this is desirable optimisation techniques are used. Siddal (1972) uses the example of an aeroplane wing to demonstrate this. Strength and lightness are stated as the valued characteristic. The design may have produced an extremely strong wing which is also extremely heavy. It may be possible to lighten the wing by reducing the strength without diminishing the safety of the plane. To determine whether this is possible the applications of optimisation techniques should be used. Wilde (1974) provides a good review of the most common forms of optimisation calculus. Wilde (1974) asserts that optimisation of some form takes place within all design but stresses that heuristic methods are only useful where the variables are single and costs low.

Having discussed the major features of evaluation and the techniques primarily concerned with this aspect of the last stage of the design process, it is now proposed that a brief discussion is undertaken of two of the dominant technical theories which concern both evaluation and decision. These consist of Decision theory and Utility theory.

Decision theory consists of the assignment of values to the various qualities and quantities which constitute the requirement specification, the determining of the relationships of these values with regard to possible outcomes, and the means by which these can be determined.

The decision to select and implement a technical product or system is determined by the balance between its technical and economic value against the specification's criteria of value. The most common methods of assessing this are basically similar. The ratio of technological effectiveness to cost, [E/C], or the difference between the two [E-C] forms the basis of most decision techniques. Other methods are however used. Quadratic cost is one such method. Quadratic cost is represented by the formula, $[(1-e^2)+C^2]$, where $[1-E^2]$ can be regarded as the penalty paid as technical performance deviates from the ideal or optimum and C is the cost of getting the systems performance back to that ideal, (English 1968).

Utility theory is primarily concerned with determining the overall worth or utility of a design. To do this the attributes of a design are assessed in terms of their value with regard to the value criteria established by the requirement specification. The total value of a design is determined by the combination of these individual values into a whole. By the determination of a design's value in this manner it is possible to identify ways in which the attributes of a design may be enhanced or negated to produced the maximum utility. The basic structure of the methodologies used in utility theory are as follows.

A candidate design, Ci, has a set of design characteristics, ci....cin, which are those of its attributes which are relevant to the fulfilment of the design objectives. There is generally a multiplicity of separate criteria, K, by which the design must be evaluated, i.e.: sub-objectives of the total design objective. In systematic evaluation the criteria should be formulated as utility functions of the form, $U_{iK}=U_{ik}$ (ci.... cin), which assigns a value U_{ik} to a set of design characteristics. A set of utility values is thus determined for each candidate design. The most common methods of combining the utility values of a candidate design to form a total worth are:-

$$U_i = O_p u_{ip} \quad O_p=1 \quad \text{i.e. linear combination}$$

$$P=1$$

O_p are weighting factors representing the contribution that aspect p makes to the total design worth.

There exist an infinite number of functions U; () and basically these are a subjective matter for the decision maker, and are resolved through a determination of trade-offs between objectives.

The decision aspect of this stage though closely related to evaluation is distinguished within the literature as being a number of separate characteristics.

Decisions are made throughout the development of a design, and will during the initial stages of the iterative process be taken heuristically. As a design solution develops and becomes more defined and detailed it becomes possible to apply a collection of methods which are collectively termed Decision theory. Decision theory is closely related to the techniques of evaluation with the essential difference being that decision theory contains techniques for aiding the designer to make decisions in conditions of uncertainty. That design almost always takes place with some degree of uncertainty attached to it is a point noted frequently within the literature, (for example Kaufman 1968, Siddal 1972).

Similarly to evaluation the concept of value is essential to the decision process. This is because it allows the success of a design to be judged and decided upon, and the relationship of the attributes of a design to be defined. Bross (1953) argues the relationship of design attributes in terms of value is determined by the possible outcomes of differing courses of action. The value of a design attribute is thus determined by the ability to predict a possible outcome. The ability to predict the likely outcome thus becomes a major element in the way design decisions are made. Keeney and Raiffa (1976) assert that the methods used by designers in their attempts at predictions of outcome are; by intuitive means, by the use of analogy, by drawing upon experience , by the assumption that all elements likely to affect the outcome are known and will remain constant, that any changing factors are known and will remain constant, and that some factors will be unknown or uncertain. Each of these conditions will produce differing predictions of outcome and depending upon each the relative values of the attributes of a design will change and as such the decision made within each will differ.

The techniques used by a designer to help him reach a decision will depend upon the degrees of risk and uncertainty under which he has to make them (Mack 1971). The types of possible decision which can be made however remain constant. These consist of;

i) To terminate the process and implement the design.

ii) To return to an earlier stage in the process as a means of modifying the whole design.

iii) To return to an earlier stage in the design process as a means of modifying an element of the design.

iv) To modify the specification

v) To completely re-start the process

The evaluation and decision stage of the design process comes at the end of the design sequence. It may constitute the end of a particular design activity within the iterative process or it can be where the process terminates and a design is implemented. During the initial development of a design the evaluation and decision process may take place in an informal manner. This may continue to be the case if a design is not complex and there are a very limited number of design variables. In most cases however it is apparent from the literature that as a design is developed there will be an increase in the complexity of both the relationships between a design's attributes and thus the decisions which have to be made. The amount of risk and uncertainty will further complicate the process. To overcome these problems a selection of techniques have been developed. These assist the designer by defining relationships and assisting in the prediction of likely outcomes.

The decision process is, as has been shown, a complex and multi-variete process. It is beyond the scope of this thesis to go into precise detail concerning the differing types of decision making techniques which the designer can use. Rather, what will be of relevance in the context of this thesis is a description of the decision process which has been generated through an identification of the main features common to all design decisions. It should be noted that as previously mentioned the precise division between evalutory and decision making activity is not always clear. This fact is reflected in the description given below.

The first element which is required in a discussion of the structure and relationships of the decision process is a relevant and workable definition of what is meant by the term 'a decision'. After careful consideration the following definition has been developed. A decision is a psychological event characterised by:

i) the exercise of discretion, (e.g. in selecting a course of action)

ii) prescribed non-discretionary limits, (only within these limits can discretion be exercised)

iii) a goal, (towards which the decision maker is aiming)

iv) committal, (i.e. an external event will result from a decision, a wrong decision causes waste or harm in some form or other).

In relation to the above definition it would appear that design is very much a decision making process. Set the same design problems to a number of designers and they are likely to come up with many different plans for design solutions, which suggest that there is a discretionary element in design. These same designers will invariably explain that their solution has been affected by the limits that somebody or something has prescribed. Equally design is a goal orientated activity, and the decisions which are made as an aspect of design do cause external events to take place, and the possibility exists for decisions to be wrong in a meaningful sense.

Design decisions take place within the particular context of the design environment. This context though differing in detail between any two given designs is in fundamental terms the same for all design decisions. The decision attempts to act as an interface between cause and effect. Essentially there are three types of causal relationships which exist with regard to design.

A. Uncontrollable causes which have uncontrollable effects.

B. Uncontrollable causes which have controllable effects.

C. Controllable causes which have controllable effects.

Using these terms we can now formulate a fairly concise definition of the designer's decision making task. It is to choose the controllable causes and to adjust them in such a way that, under the circumstances defined by the uncontrollable causes, desired controllable effects are obtained. These desired controllable effects constitute his goals. Through the choosing and adjusting of controllable causes he exercises discretion.

It is already evident that the designer must be aware of the existence of design parameters as well as independent and dependent variables, when making a design decision. As such three operations in the decision process can be defined immediately.

1) The identification of design parameters. Design parameters as measures of controllable causes.

2) The identification of independent variables. Independent variables as measures of the

uncontrollable causes and effects.

3) The identification of dependent variables. Dependent variables as measures of the controllable effects.

In addition the designer must be aware of cause and effect relationships, relationships involving parameters only, or parameters and dependent variables only. Hence, the decision process in design requires;

4) The identification of relationships amongst parameter and variables.

It is also known that designers need to predict the values that the independent variables will take whether directly, or in terms of the effect produced. Thus the decision process in design will also require;

5) The prediction of values of independent variables.

Dependent variables are measures of the designers goal, and to be a goal at all it must in some respects at least, have a clear definition. In practice there are many goals, which invariably arise from the attributes required. The important thing to note about these requirements is that they are mostly expressed in terms of limits, or constraints. Hence, the designers decision process will need to undertake;

6) The identification of constraints governing dependent variables.

These constraints delimit some of the designers ends rather than limit his means. Design parameters are also governed by constraints. The decision process will thus require;

7) The identification of constraints governing design parameters.

Each of these parameters will have its own unique value. This necessitates;

8) The identification of values of design parameters.

It is necessary that the designer's decision should be informed by a knowledge of the effects that any given design is likely to have. This will require;

9) The identification of expected values of dependent variables.

A designer cannot take all available information into account at once. Solutions are formulated to one or more sub-problems on the basis of some of his information. It will then need to be determined whether these solutions are consistent with each other, as well as with the as yet unused information.

10) The investigation of the consistency of values, relationships and constraints.

A design process may produce several alternative solutions to sub-problems or even to whole design problems. The designer therefore has to compare and choose between them. The criteria will be the dependent variables. The values they take, once a design is realised, will indicate how successful a design is in coping with environmental circumstances, i.e. independent variables. This element of the decision process is;

11) The comparison of, and selection from alternative sets of values.

The elements of the decision process which have been outlined above characterise the way in which the decisions are reached during the design process.

3.6 The Blackboard Concept

3.6.1. Introduction

The Blackboard Model was originally developed by software engineers as a tool for recognition of certain types of information, (Hayes - Roth 1977). The characteristics of the Blackboard Model were however such that the applicability of the model has since been considerably expanded. In the context of design the Blackboard framework provides a means by which the development of designs can take place. The structure of the Blackboard Model is such that by its incorporation into the model of the design process a framework is produced through which the generative and iterative aspects of design can be represented.

The Blackboard Model has three main components. These consist of, the Blackboard, the knowledge sources, and the control mechanism. The knowledge sources are sub-divisions of the knowledge base which exists within any particular discipline, each of which consists of a specific area of expertise or knowledge from within that discipline. The Blackboard, from which the model takes its name, is a conceptual, (or indeed actual) device which allows for the storage and display of information. By fulfilling this function the Blackboard acts as a conduit between the knowledge sources as it is through this that the knowledge sources are able to communicate. The control mechanism determines the selection for storage and combination of information generated by the knowledge sources. This storage and combination function of the model takes place upon the Blackboard.

The operation of the model is initiated by the input of a piece or set of information. This information can be defined as a 'problem' to the model in that it must attempt to generate a solution to it. The way in which this solution is generated consists of each of the knowledge sources by applying its particular area of expertise to the problem, producing a possible solution or 'hypothesis' as to what could be the complete solution. These hypotheses are displayed upon the Blackboard and it is from the Blackboard that each of the knowledge sources is able to read the partial solutions suggested by the other knowledge sources. In this way a possible solution, or a number of possible solutions are produced. The combination of these partial solutions and sets of partial solutions into complete candidate solutions and ultimately into a finalised solution is undertaken by the control mechanism. The way in which it undertakes to fulfil this task is determined by the parameters, rules and criteria of which it is composed. Before going into greater detail, and discussing the implications of the Blackboard concept for the theoretical framework of a model of the design process, a brief outline of the background and development of the Blackboard Model would probably be useful.

The framework of the Blackboard Model is derived from the Hearsay - II speech recognition program. An introduction to this is given in Erman and Lesser (1980). This program which was originally constructed in the late 1970's (see Hayes - Roth 1977) was designed to help improve the speed and accuracy of speech recognition systems.

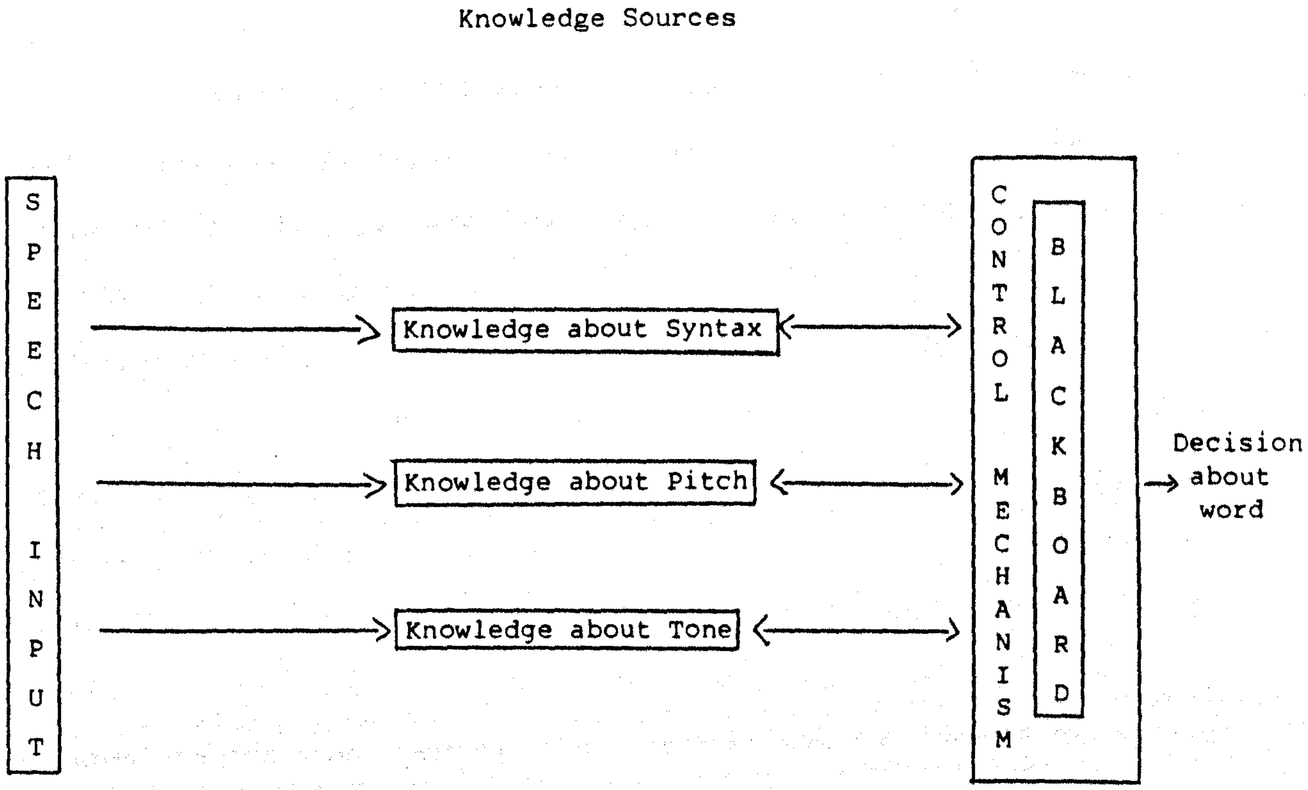
Prior to the development of the Blackboard model all speech recognition systems had operated in sequential manner through a decision - tree structure. Typically the input word or utterance would be interrogated by the system against predetermined criteria for a number of characteristics such as pitch, tone and syntax. By this means the system would be able to determine the correct identity of the input and assign to it the appropriate label, i.e. correctly identify the input word. With the Blackboard Model however the information required to determine the identity of an input word was not structured as part of a sequential process but rather was compartmentalised into independent areas of expertise known as knowledge sources. With the Blackboard Model the input to the system is examined by each of the knowledge sources individually and in a non-sequential manner. Then in accordance with the particular type of knowledge contained within a knowledge source a decision or hypothesis as to the identity of the input will be produced and displayed upon the Blackboard. Upon viewing the Blackboard it may be necessary for a knowledge source to modify or even produce an entirely new hypothesis. The decisions as to which hypothesis is accepted and which are rejected, along with how they will be combined is determined by the control mechanism. It is found to often be the case that a number of possible solutions or word identities are produced by either individual knowledge sources or the knowledge set as a whole. By the use of the Blackboard it is possible to hold these solutions, or hypotheses and for knowledge sources to re-examine their decisions. The control mechanism purpose is to co-ordinate these activities and determine the final decision of the correct or most appropriate combination (see Figure 4).

The Blackboard Model was subsequently expanded by Hayes - Roth (1983) into a general theory for problem solving by C.A.D. systems. Davis (1980) has produced similar work in the area of artificial intelligence. The work of Davis was primarily conducted in the area of Meta knowledge, that is knowledge about methods of change and adaption. Amongst the conclusions reached by Davis was that the best framework through which adaption and change of possible solutions takes place was that of a Blackboard type model.

The precise manner in which the Blackboard Model contributes towards the comprehension of design is however a matter about which there is debate. To fully explain the issues disputed within this area it is necessary to describe the differing ways in which the contribution of the Blackboard Model is perceived, and to discuss the basis upon which these points of view rest.

Fig. 4

The Blackboard Model



The Blackboard Model for a speech recognition program Erman et al (1980)

3.6.2. The contribution of the Blackboard concept to the model of the design process.

This thesis will argue that the Blackboard Model represents both a means and a framework through which it is possible for design solutions to develop, and that the Blackboard Model fulfils this function by serving as an element of the larger design model. A detailed discussion of the way in which the Blackboard Model operates within the design process is undertaken within the next section of this chapter. The discussion within this section will concentrate upon the arguments from within the field of design theory as to the precise contribution of the Blackboard Model to the understanding of the design process. The debate concerning the contribution of the Blackboard concept to the comprehension of the design process centres around two conflicting views of the way in which design takes place. These views lead in turn to a debate as to whether the Blackboard Model should be used as an element of the design process or, to represent the entire design activity.

Debate about the contribution of the Blackboard Model to design theory arises from an area of thought which asserts that the model should be used to represent the entire design process. This school of thought (see Whitefield 1986) asserts that within the design theory there exists two basic types of design model. These two model types they classify as, stage or sequential models, and process models.

The term sequential model is used to describe the traditional type of design model which asserts that design takes place by progressing through a number of stages or phases, each of which is characterised by a particular type of design activity. Authors who have advocated this type of model of the design process assert that there is a logical necessity that determines the sequence; i.e. a specification requirement must be generated before it is possible for analysis to take place. This type of design model is typified by such authors as Hubka (1982) and Pahl and Beitz (1984).

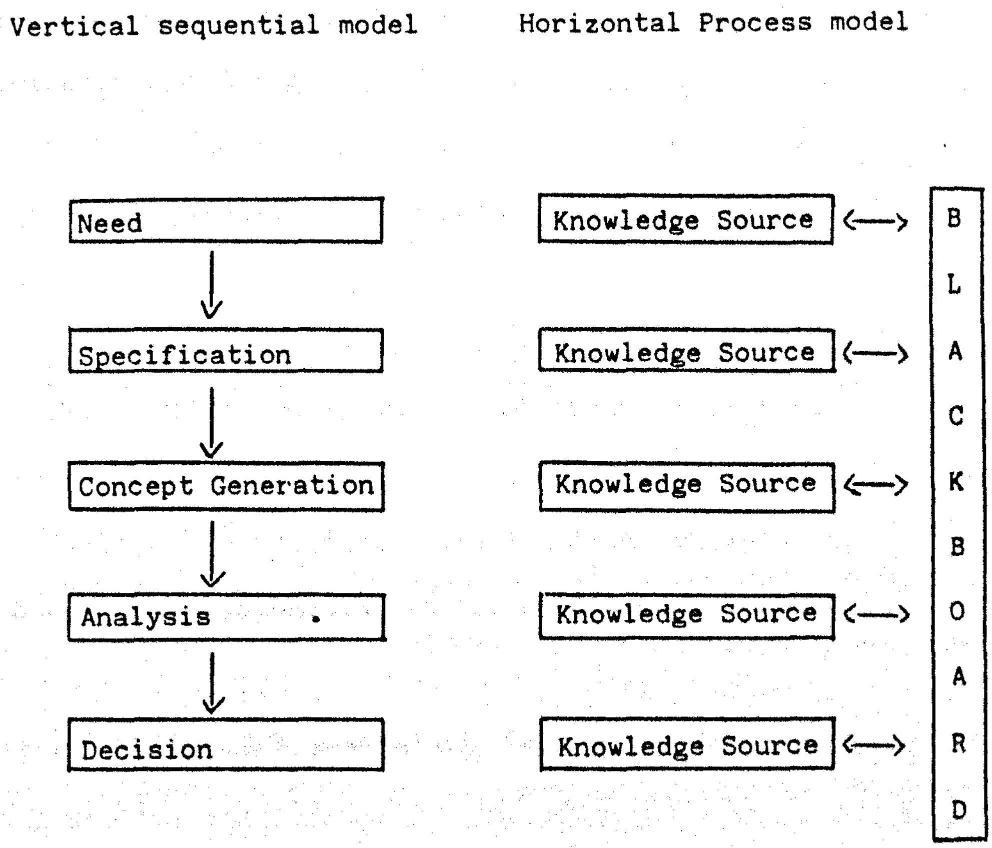
Process models of design it is argued do not present design as taking place by means of a sequential progression through a number of definable stages. Rather it is argued that design takes place non-sequentially. The basis for this assertion comes from the studies of a number of researchers who assert that when design activity is in fact described as it actually takes place, what is found is that designers do not proceed in a sequential manner. What is found is that designers tend to immediately focus their attention on possible complete solutions and then proceed by attempting to modify them so that they eventually fulfil the design need. Lawson (1980) originally put forward this notion basing his research on participant observation and later (Lawson 1981) on experimentation. Similar empirical studies were undertaken (Lera 1981, Tovey 1984) which appeared to confirm the notion of the designer as solution orientated. Attempts at modelling this view of design activity came to be known as process models. A number of researchers working from this perspective came to the view that the most accurate way to model design activity was by the use of the Blackboard Model, (Tovey 1984, Whitefield 1985, 1986). These researchers argued that with design being a solution orientated activity in which possible solutions are produced and then modified by the various activity areas which constitute design knowledge, the Blackboard Model provided an appropriate theoretical framework through which to describe design. The Blackboard Model of the design process argues that a designer uses several separate areas of design knowledge and that these can be represented by the concept of the knowledge sources used by the Blackboard Model. The designer, it is argued, uses the knowledge sources to produce hypotheses concerning what may be used as a possible design solution. By a process of each of the knowledge sources producing its own hypothesis and placing this upon the Blackboard so that it is available as an influence to all other knowledge sources, the design is gradually modified to fulfil the specification requirement.

Exponents of the Blackboard model of the design process put forward the claim that the sequential view of design is misleading and confuses rather than enhances the understanding of design. Tovey (1984) has argued that where as sequential models of design present design as being a vertical process, it should in fact be viewed as being a horizontal process, (see fig 5). By this what is meant is that rather than progressing in a sequential manner through a number of stages each characterised by a specific type of design activity, design should be viewed in terms of the continuous interaction of various areas of expertise via the storage area, the Blackboard.

Attempts to validate the Blackboard Models of design through experimental research have been made. There typically have been made as a means of gaining information to assist in the production of more supportive computer aided design systems. Whitefield (1986) is typical in his general approach. A number of experienced designers are each

Fig. 5.

Tovey (1984) - Traditional (vertical) sequential design in comparison with the Blackboard 'Process model' (horizontal) of design.



given a design problem which they must attempt to solve within a given time. They are asked to verbalise their activities during design and these are recorded both audially and visually. From these recordings, (verbal protocols) it is determined which types of knowledge source are being used, what types of hypothosis they are producing, and which of these hypotheses are being saved and which rejected or modified. By this method it is hoped to be able to produce a domain specific (specific to that particular designing activity) Blackboard Model of the design process.

This type of experimental approach is typical in that the design study concentrates upon a particular sub-function of the decomposed design. Also typically the problems presented by the design of the sub-function are familiar to the designer.

The use of the Blackboard Model as a model for the entire design process will lead to a distorted understanding of design. The Blackboard model of the design process ignores the initiation of the design sequence and the generation of the requirement specification, and instead concentrates upon generative and evaluative aspects of the production of design concepts. This research may well provide useful information about the types of search strategies used by designers, it cannot be however be generalised in such a way as to reject the notion of design being a basically sequential process. It may also be the case that designers in many instances approach a design problem with a fairly good idea as to how they will solve it. However if the Blackboard Model is generalised in such a way as to argue that it represents the activities taking place throughout the design process then by necessity the stages of design and their sequential relationship must be recognised. Equally if it is argued that designers are aware of the type of design solution which will be used from the start of the process, then it becomes impossible to explain new or innovative designs. Though the Blackboard model of the design process may be inadequate to explain and represent the whole of the design process in the manner discussed, it does however serve as an element with the design sequence.

3.6.3. The Operation of the Blackboard Model within the model of the design process.

The Blackboard Model forms an element of the design process. The context of the Blackboard Model has however been broadened, so that it is no longer viewed as being a device for the modification of existing design concepts but rather an element which exists throughout the entire process.

With the context of the model of the design process the concept of the knowledge sources is seen as being the constituent parts of a knowledge area or design knowledge base. This knowledge base consists of all the design knowledge available to the designer throughout any particular design. From the knowledge sources embedded within the knowledge area the designer will draw upon various areas of expertise and information to help solve each aspect of the larger design problem. Information gained in this manner will be stored upon the

Blackboard, where it may be modified or combined with other hypotheses drawn from different knowledge sources. This process will be determined by the control mechanism. Within the context of the model of the design process the control mechanism is seen as taking a number of forms and is comprised of several elements. In the case of simple or informed design the control mechanism may well be an aspect of the designer's skill and experience. In the case of complex design formal methods may be used. In both cases as well as either designer judgement or the use of formal methods certain elements of the control mechanism are determined by the sequential nature of the process, and the activities undertaken as part of the design process. The specific stage of development and composition of a design will determine types of knowledge used, i.e. knowledge about rules or physical principles, knowledge about types of components or the properties of certain materials. Equally the stage of development of a design will affect the control of the Blackboard process by determining the depth of analysis used, and the way in which decisions are made.

The operation of the Blackboard Model within the model of the design process takes place at two general levels of abstraction. These consist of its operation as an element of the larger sequential model and at the specific generative level in the production of basic concepts. In all design, and at every level of abstraction designers will draw upon a number of categories of knowledge. From these a number of hypotheses will be produced. These will be considered in terms of compatibility with each other and the general aims of the particular aspect of the design which is being undertaken, and also in terms of the other sources of knowledge which have been drawn upon.

When discussing the larger sequential model what is meant is that at the stage of design where complete candidate designs have been produced the Blackboard serves the purpose of allowing a theoretical framework through which it is possible to adapt or modify these designs either in terms of comparison and combination with each other, or in terms of drawing upon a specific type of design expertise to make an adaptation. When operating at the various levels of abstraction which characterise the way in which design concepts are developed into candidate designs, the Blackboard serves the purpose of providing the framework through which general principles and specific areas of expertise can operate. To fulfil this task it produces a framework which allows ideas to be produced, combined and modified.

3.6.4. Summary

The Blackboard Model provides the theoretical framework through which it is possible to explain the way in which information is drawn upon and then synthesised into design solutions. The Blackboard models the activity of conceptual synthesis within the design process at all levels of abstraction and decomposition. Its validity exists as a model of this activity when either considering the generation of a design primitive for a sub-functional element of a decomposed design problem, or when attempting to combine or modify candidate designs.

The arguments put forward by design theorists who assert that the Blackboard Model can be used to represent the entire process of design are rejected. This type of view makes the assumption that the basic solution to any given design problem is known by the designer and merely requires modification to fulfil the design need. This is viewed as only being the case with variant design. In addition by using the Blackboard Model in this way no account is taken of the way in which the decision is reached to treat a design problem as a variant of a previous design.

The research discussed confirms that design concepts are produced through a process of constant iteration through the design sequence, sometimes through the entire sequence and on other occasions from an earlier stage. This is entirely compatible with the view put forward by this thesis. The major contribution of the Blackboard Model to the model of the design process is that it provides the theoretical framework through which design synthesis takes place at all levels of abstraction and decomposition within the design sequence.

4. Summary of Chapter Three

The model of the design process which has been presented is essentially sequential and iterative in character. The process is divided into a number of stages each concerned with an aspect of the design process. By continuously passing through these stages a design is evolved. The stages have been classified in terms of the predominant activity which takes place within each. These classifications consist of

- The Generation of the Requirement specification
- The Generation of the Design Concept
- Analysis
- Evaluation and Decision

The process is initiated with the perception of a need, and terminates with the implementation of a finalised design.

The model recognises that the above noted activity stages do not characterise the way in which the entire process takes place. By incorporating the Blackboard concept within the model account is taken of the way in which solutions and partial solutions may be stored during the process. The Blackboard concept provides a theoretical framework through which it is possible to represent the way in which certain elements of the design process take place. This consists primarily of representing the way in which design knowledge, both that which existed prior to a particular design's development and that which is a product of that development, relates to the informational needs of a design throughout the process.

The model represents design as taking place in the following manner. The process is initiated by a perception of need. Once commenced the initial activities in the process are aimed towards giving the need greater definition. Essentially the types of activity which take place can be categorised as those of information gathering, and problem analysis. The aim of these activities is primarily the generation of a requirement specification. The requirement specification is a detailed statement defining the characteristics which the final design is to process. It is important to note that the production of the full specification does not take place divorced from the rest of the design process. A specification may be elaborated or modified during the course of the design process as an aspect of the iterative process. It is possible that the initial specification is quite vague and that it gains in detail through iteration. Once however some initial formulation of the requirement specification has taken place it is possible for an attempt to be made to satisfy these requirements.

The stage during which the primary activity is the generation of a solution to the defined design problem, is the concept generation stage. This stage can itself be sub-divided into a number of specific phases each of which is characterised by a particular form of activity. These phases consist of i) Abstraction and functional description, ii) Decomposition, iii) The generation of design primitives, iv) The composition of a whole system from the solutions to the decomposed problem.

At the beginning of this stage the design problem is abstracted so as to allow the broadest search of possible solution areas to take place. In addition by abstracting the problem it becomes possible to identify the essential characteristics of the problem and to ignore or remove those which are only incidental to the problem. Functional description serves a similar purpose by expressing the problem in terms of its essential features and their relationships.

The problem is then decomposed. In some instances this process may have been started or possibly even completed, as part of the previous phase. The purpose of decomposing the problem is essentially that of making the problem more amenable to comprehension and solution. By decomposing a problem into its most basic constituent parts it becomes possible to search for a design solution for each of the decomposed parts, each of which are likely to be expressed in the most simplified manner possible.

Once decomposition has taken place it is possible to start the search for solutions to each of the constituent elements of the problems. This stage of design is referred to in the model as the generation of design primitives. Design primitives are so called as they represent the most basic level of a design concept. By the composition of the constituent parts of a decomposed design problem it is possible to produce a complete system, or design concept. This can take place once a suitable design primitive has been found for each of the decomposed elements. The composition of a design concept forms the final phase of the concept generation stage. It is possible that more than one design primitive is produced for each of the sub-elements in which case it is possible for a number of design concepts to be composed. The storage and manipulation of such partial solutions is allowed for within the model by the use of the Blackboard concept. The way in which this takes place is expanded upon later in this summary when the contribution of the Blackboard concept to the model of design is discussed.

A design concept may take an initially simple form which through the process of iteration gradually becomes developed into a more defined and detailed form. The developed design concept is referred to as a candidate design. It is given this label as at this stage in the design sequence it is put forward as a possible design. The next two stages in the design sequence will determine its success, failure, or where possible modifications might need to be made.

Analysis is the next stage of the design process. During this stage an examination is made of the attributes a design possesses relevant to its function. The analysis stage then is essentially concerned with generating data about a proposed design. This may take the form of a simple assessment by the designer in the very early stages of a design, or if the design is very simple. With more complex or developed design designers will have recourse to use analytical techniques and methodologies. The purpose of using such techniques is to obtain the most accurate data possible so as to provide the designer with sufficient information to enable him to evaluate a design and thus make decisions about implication or modification.

With analysis having taken place a design enters the last stage of the process, that of evaluation and decision. During this stage the various merits and faults of a design are assessed and decisions made as to whether or not to implement or modify a design. The evaluation of a design takes place by assessing the various attributes of a design against the requirement specification. Depending upon how well a design fulfils the specification, decisions will be made as to whether to modify a design or implement it, or whether to return to an earlier design stage or possibly modify the specification.

In addition to the stages of the design process the model also incorporates the Blackboard concept. The Blackboard is seen as operating throughout the process and forms an element of each of the stages. The Blackboard concept consists of three basic elements, the knowledge base, the Blackboard, and the control mechanism. The knowledge base represents all knowledge available to a designer throughout the design process. The Blackboard element is essentially a storage area in which solutions and partial solutions are stored. The information stored in the Blackboard allows the designer to build up solution sets and to store information generated through his design activities which appear to be potentially useful. The Blackboard is envisaged as being able to take a number of forms depending upon the type and complexity of design activity which is being undertaken. These forms that the Blackboard may take include, the designer's short term memory, rough notes, methodological aids such as morphological tables, and computerised aids such as data storage. The relationships of solutions and partial solutions stored in the Blackboard, both with regard to each other and the knowledge requirements of the design process, are governed by the control mechanism. Depending upon the character of the design and its stage of iterative progression, this mechanism may take the forms of, the designer's informal or interative decision process, the systematic structure of a methodology which is being followed, or the formalised decision process which forms a stage of the design process as a whole.

The Blackboard Model contributes to the model of design by providing a means by which it is possible to explain and allow for the development of a design not only purely as a continuous sequential process but also as a process of bringing together sets of concepts which exist in differing stages of development. By the incorporation of the Blackboard concept within the model, it is possible to acknowledge that not all design knowledge is developed at the same rate, and in addition, that within any given design activity there will be a degree of redundancy amongst the design concepts which are produced by that activity.

The model of the design process which has been presented is applicable to all design. Differences in the types of design which are being undertaken may affect the speed and formality with which a design passes through the process. It will however always be the case that a design will be formed in the manner described and that the elements of the process defined by the model will always be present and comprehensive in their description of the process. It may be the case that with some forms of design the distinctions made within the model overlap considerably or even in some instances appear to combine. In such cases it is still maintained that the model will provide an accurate account of the process which is taking place. The speed with which the stages of the process are passed through may differ considerably as may the speed with which the iterative process occurs, it will however always be the case that they have in fact taken place, and ultimately in the order defined by the model.

5. Aids to Design

Introduction

The production of all technical design requires the use of design aids. The use of design forms an intrinsic part of the model of design, and as such design aids cannot be fully comprehended without relating them to their function within the design process. The aim of this chapter is to examine the use of design aids as an aspect of the design process by noting the types of aids which exist to assist the designer through the development of a design, and to assess the way in which they contribute to the design process. At this point it would perhaps be useful to offer a definition of the term design aid as it is used within the context of this discussion.

The term design aid though found to be frequently used within the literature concerned with design, is in general poorly defined. For the purposes of this discussion a suitable definition is, all that which contributes to the production of the finalised design configuration, which exists externally to the designer. This definition is intentionally broad so as to cover all aspects of design which contribute to the final production of a design which are not actually part of the theoretical model of the design process. Being highlighted here is the division within the model of the design process between the essential characteristics of design and the means by which the requirements of these characteristics can be fulfilled. For example, the abstraction and decomposition of a design problem is an essential characteristic of the process of design (see Chapter 3 sections 3.3.1.

and 3.3.2.). The means by which this activity may be undertaken are variable depending upon the type of design which is being undertaken, as well as upon the skill and experience of the designer. In some cases such as those of simple design, a designer may be able to undertake this task without recourse to design aids, i.e. he may be able to complete this task by considering the problem in an informal unstructured manner. In many other cases however the designer will require the assistance of some form of design aid such as a hardware description language or some form of graphical or schematic representation. The main point here is that design aids are aids to design, they assist the designer to fulfil tasks which must be undertaken, they are a means, they do not themselves define the design process. This point is essential to the comprehension of design, and to the role of design aids in relation to the design process.

Aids to design contribute to virtually every aspect of design and as such the information available on them is vast. To make the information amenable to discussion some form of classification is required. An analysis of the information available concerning design aids made it apparent that there exist two basic classification methods which can be used to categorise aids. One method consists of the classification of design aids in terms of type, and the others in terms of the relationship of aids to a particular stage or phase within the design process. In discussing the use of design aids and the way in which they contribute to the design process it was decided that the second method would be the most appropriate and as such is the method which will be predominately used throughout the discussion. However certain types of design aid are used throughout the entire process, so that it would be useful to acknowledge briefly the contribution to design which is made by these types of design aid. The classification of aids which is presented below is derived from the work conducted by the City University Design Theory and Methods Group. The classification took place in the context of the Alvey project 142 (the production of a user modelling tool) the aim being to produce a classification of all design aids used throughout the process.

- Methodological Aids

  These aids consist of methods, techniques and working practices etc. Such as formal specification languages, systematic design methods, evaluatory procedures etc.

- Knowledge Sources

  Aids in this class consist of the informational areas from which the designer can obtain knowledge appropriate to the design task. Included in this class are, finite element packages, catalogues design literature, expert systems etc.

- Means of representation

  The means of representation are a class of aids which allow for the representation, transfer and storage of design information. Within this class are included such items as, pencils, drawings, graphical representations etc.

- Information processing aids

  Information processing aids consist of those aids which facilitate the movement of information both throughout the design process as a whole, and from one medium to another. These aids include, such items as pencils, computers and information processing tools.

The above classification of aids is believed to include all design aids. The classes are not however mutually exclusive and are in many cases inter-related and over lapping. The relationship of the aids within the classifications to the various stages of design are not defined and aids within each of the classifications exist in each of the design stages. Because of this, the discussion of the relationship of design aids to the design process will take the form of an examination of available aids within each of the design stages.

5.1. Aids to Design and the Blackboard Model

The Blackboard concept though not itself constituting a particular design stage is an extremely important factor in relation to the use of design aids throughout the design process, and as such in determining the usefulness of a design aid to any of the stages of design. A detailed discussion of the contribution of the Blackboard concept to the design process is undertaken in section 3. It is however useful to outline its main features again here and to relate them to the use of design aids. The Blackboard concept as originally put forward by

Hayes - Roth (1977) and subsequently expanded (see Erman and Lesser 1980, and Whitfield 1987) is essentially a tool for the collection storage and elicitation of information. Possible solutions are given by the knowledge sources (areas of expert knowledge held within the knowledge area, of a person or system) in response to the design problem, and stored upon the Blackboard. This allows the possible solutions (Hayes-Roth refers to them as hypotheses) to be viewed by all areas of expertise simultaneously, and to adjust their solutions with regard to these. The use of the Blackboard takes place within each of the design stages as an integral part of the generative process, and at a higher level as a means of dealing with more developed sets of design functions and possible solutions. The Blackboard concept is in this manner the medium through which the design information generated through the use of design aids is stored and developed.

The Blackboard may take a number of actual forms all of which essentially serve the same purpose. These may range from information formally stored for later re-examination, to the designer's own short term memory (Davis 1980). Thus in most instances the Blackboard itself will constitute a design aid. The other two main components of the Blackboard model, those of knowledge sources, and the control mechanism are also of relevance when discussing design aids. Knowledge sources consist of areas of expert knowledge which can be used by the designer to generate and analyse design information. Thus within the framework of the Blackboard model the knowledge sources are the area where all design knowledge is ultimately stored. The control mechanism will in most instances take the form of a design aid, or possibly a combination of design aids. These are viewed as taking the form of a systematic methodology but will also be considerably influenced by the evaluation and decision processes.

5.2. Aids to the generation of requirement specification

The initial stage of the design process consists of giving definition to the perceived design need by the generation of an appropriate requirement specification. In this section the aids from which relevant information is obtained are described, along with the way in which they contribute to the overall activity. The design aid used at this stage contributes principally by assisting with the provision of appropriate information to the designer so as to facilitate the formulation of a clearly defined set of design objectives. The aids described below are the product of an analysis of literature which deals with this area, and a synthesis of their most common features. The most significant literature is included in the bibliography; of these it is felt important to acknowledge the influence of the work of De Marco (1979), Mullrey (1979), Esherick (1963), and Finkelstein and Potts (1986). The result of the investigation into this area revealed the following to be the most significant types of design aids.

Aids to design at the requirement specification stage consist principally of;

1. Checklists
2. Specification formats
3. Specification standards

4. Expert Systems

5. Formal methods

1. Checklists

Checklists constitute, in the case of all but the most simple or innovative forms of design, the initial point from which a designer starts to gather information about the necessary functional or performance requirements of the system, or sub-system which is to be designed.

Checklists consist of systematically ordered lists of performance and operational requirements for specific components, sub-functions of systems, and whole systems. Checklists are used to clarify the task, and task specific constraints. This is done in the main through the structured examination of the quality, quantity and inter-relationship of:-

- Geometry
- Force
- Energy
- Material
- Signals

The use of checklists is widely advocated throughout the literature on design, but especially so by authors recommending the use of systematic method; for example Pahl and Beitz (1984), Ostrorefsky

(1977), and Matousak (1963).

2. Specification formats

The specification format consists of the formalised structuring of the specifications in terms of sub-functional division, formal or implicit statement of value criteria, and including statements of effort and responsibility. A good discussion of the use and construction of this type of aid is given by Oakely (1984), and Oakeley and Van Praay (1984).

3. Specification standards

Standards exist to provide the designer with information on minimum and maximum specifications for,

- Materials
- Products
- Dimensions
- Performance
- Safety

within a system; and specifications for

- Processes
- Practices

- Systems

external to a system. Standards provide both task specific and environmental information to the designer. The rigidity of compliance to the parameters set by standards is dependent upon the body which validates them. Specification standards are drawn from the following bodies,

- International Standards
- British Standards
- Defence Standards
- Industrial Standards
- Company Standards

These standards can in turn be sub-divided into constituent sets of standards. These deal with components, sub-functions, functions, whole systems, the operation of systems, acceptable practices, safety, and their relationship to the external environment.

4. Expert Systems

Expert systems involve capturing the knowledge of experts in a given field and storing it in a computer memory from where it can be retrieved in the form of a reasoned answer to questioning. Expert systems are seen as one of the most important new aids to design.

In such systems the control system should be separate from the knowledge. This means that the knowledge can be modified without any change in the program, (Davis 1980). The system is mainly constituted by a knowledge based problem solver which contains;

(a) Knowledge about the problem domain contained in the knowledge base

(b) A data base which contains a description of the specific problem/need to be solved and serves as a working memory for system operation.

(c) Specialized problem solving programmes which use the content of the knowledge base for constructing a solution to the problem.

The desired characteristics of an expert system are:-

i) Good performance on difficult problems, taking into account that the expert systems performance is not necessarily better than that of an expert.

ii) To be implementable

iii) Good man machine interaction

iv) Good performance in terms of speed as the situation demands.

Expert systems may be used to determine the logical relationship between the inputs and outputs of systems, sub-functions and functions. Through a system data base, model structure and in most systems two valued logic structure it is possible to construct through interactive interrogation of the system an appropriate specification. The application of automation to the above noted means of specification generation indicates that the processing of information may act as an aid to design.

The information gathered in for this section was carried out through a process of interview, consultation and an analysis of design literature and appropriate systems. Literature of note in relation to the production of the above is, Abdullah and Mirza (1985), Sell (1985) and Begg (1984).

5. Formal methods

Formal methods constitute a set of systematic techniques that are available to the designer as a means of guiding his activities during the production of the requirement specification. Formal methods consist primarily of specification languages, and description languages, often used in conjunction with categorizing charts.

Formal specification languages and description languages assist the process of generation of specification by placing the designer's description of needs within tight constraints thus forcing a specification description of the need, and producing a specification which is in a form amenable to others within a design group.

The aids that exist to assist the design in the production of a specification requirement exist primarily in the form of knowledge sources, such as checklists and specification standards. Methodological aids which exist consist primarily of specification formats and formal methods. Expert systems provide the main information processing aids. Means of representation which exist at this design stage consist mainly of rough sketches and primitive schematics etc.

5.3. Concept Generation

The generation of design concepts is the area most often seen as characterising the entire process of design. At this stage candidate designs are produced to satisfy the needs of the design problem, as defined by the specification. The method by which this activity takes place is outlined in greater detail within Chapter 3. A brief outline of this activity is given below, and the types of aids used to assist with these activities are cross referenced against these activities.

The generation of design concepts takes place through the process of:

i) Abstraction/functional description
ii) Decomposition
iii) Generation of concept components
iv) Composition of a system by composition of component concepts

The kernel of design problems consists of the generation of design primitives to fulfil the requirements of the sub-functions. Design primitives are obtained from, or by a synthesis and adaption of:-

- Existing concepts
- Analogous concepts

Through the processes of

- Convergent concept generation
- Divergent concept generation
- Systematic variations of a concept

i/ii. Abstraction/Functional description and Decomposition.

Solution principles based upon traditional methods are unlikely to provide optimum designs when new technologies, procedures, materials, are available, especially when in new combinations; because of this designers should have recourse to abstraction, enabling them to ignore that which is particular or incidental and emphasise that which is general and essential. As such there should take place a broadening of the problem formulation, (Asimow 1962, Finkelstein and Finkelstein 1983).

The complexity of a problem will determine the complexity of the overall function. Technical systems can be divided into sub-systems and elements which in turn are capable of further division into sub-functions.

Aids which exist to assist these two objectives consist of:

- Hardware description languages
- Graphical/schematic representations

Description languages assist with the identification of general characteristics and the identification of essential elements such as energy, materials and signals. Graphical and schematic representations may take the form of rough or symbolic structural drawings. For examples of the use of Graphical and schematic forms of representation as a means to decomposition see, Churchman 1981, and Checkland 1981.

iii. Methods of generating design primitives

A. Convergent Methods

Convergent methods of generating design primitives primarily consist of the systematic searching for existing and analogous concepts carried out using the following sources,

- Literature

  text books, treatises, monographs, periodicals, conference literature

- Patents

- Catalogues of design concepts

- The study of existing equipment

These searches are often carried out by means of convergent search strategies based upon the i) systematic listing of physical laws and properties, to determine an appropriate set of principles; and ii) systematic examination of a physical law, to derive a design concept. Such searches require aids similar to those from the search of existing and analogous material, namely systematic methodologies and formerly search patterns such as morphological matrices, see Ostrofsky (1977). The computer implementation of catalogues with appropriate storage and search strategies provide the designer with the informational environment necessary to fulfil the needs of this type of search, Encarnocao and Krause (1981).

B. Aids to the generation of design primitives by divergent methods.

Aids to the designer which can assist him in the production of design primitives through the process of divergent search are methodological in character. The main methodologies which the designer can use as an aid are;

- Brainstorming
- Method 635
- Delphi method
- Synectics

The main characteristics of the above mentioned methods are to reduce to a minimum the constraints and preconceptions of the designer, and to encourage the exploration of the possible search area of potential solutions. Examples of the above mentioned types of method are examined in, Anderson (1959), De Bono (1970,1976,1979) and Gordon (1961).

C. The generation of primitive concepts by the systematic variation of a concept.

The systematic variation of existing design concepts to produce a suitable primitive concept may be undertaken by means of a number of systematic techniques. These basically can be characterised as follows,

i) Variation of the functional structure

ii) Examination of each function to see whether there are alternative forms of realisation

iii) Systematic regulation

   a. component removal

   b. component reversal

iv) Analysis of attribute characteristics

   a. enhancement of desirable characteristics

b. removal of limitations

The above methods of systematic variation are a synthesis of the main aspects of this type of approach. Most forms of design literature suggest this type of method to some extent, however notable amongst these are Biot (1970), Lanezos (1966), Schon (1963), and from the field of psychology Simon and Barenfield (1969). Methods of systematic variation are often used in conjunction with either convergent or divergent methods of concept generation.

5.4. Composition of a system by the composition of component concepts.

The composition of a system by the combination of realised principles, is the final stage in the production of a design candidate. The implementation of morphological tables (Zwicky 1948, Norris 1963) constitutes the most powerful aid at present available. Computer implementations of such tables provide a powerful combinative tool by which the designer may formulate candidate designs.

5.5. Analysis of candidate designs

Analysis is an important stage in the design process, it provides the link between the stage of generation of a candidate design and its evaluation and thus ultimately its selection or non-selection as a final design. It is in this stage that the designer uses those analytical aids at present available to perform as accurately as possible calculations to describe the performance of a given system or sub-system, and as such influences the decisions made by the designer as to the final selection of a design. This activity is characterised by the quantification of those attributes present in a candidate design relevant to the requirements. Aids in this area comprise of both computerised and traditional methods, by which the designer quantifies those attributes of the candidate design relevant to the requirements. The information obtained for this section of the report was gathered through an analysis of relevant literature, and interviews and consultations with experts in the field of A.I., expert systems and simulation.

Analysis takes place in two stages;

i) approximate idealised simulation

ii) accurate simulation

Within these two stages there exist in each, two types of design aid. These aids consist of:

i) Those which are means of knowledge representation.

ii) Those which constitute knowledge sources in themselves.

5.5.1. **Aids to design representation consist of:**

Drawing

Drawing may be by rough sketches which are generally freehand, or to approximate dimensions and are not bound to rules; or they constitute fully dimensional representation of a physical item.

Schematics

These consist of drawings which represent the relationships within a given functional unit or system. Schematics are used to symbolically express operations and dependencies, most often in terms of energy, matter and signals.

Block diagrams

The system is divided into sub-systems which are represented as individual blocks, and their inter-dependencies are indicated. These are indicated by the flow of energy or information.

Graphs

Another approximate modelling method can be undertaken by using graphs which are in turn divided up into different types such as linear graphs, bond graphs, etc.

5.5.2. Knowledge source aids to analysis consist of Calculations

Rough calculations using analytical formula derived from the application of physical laws are means of approximately predicting the response of a system.

Model Building

Experimental model building is an alternative approach. In this a rough physical model is built and tested to observe the response of the system and then dependent upon the data obtained from the experiment the design is improved.

Idealised modelling

This is basically an extension of calculation. Full mathematical models using such methods as electrical circuit analogy or structural graphs are used for example to determine the dynamic response of a system, accounting for all the principal variables in the system.

Full detailed modelling

In the main such modelling is based on the finite element technique. The technique is used to analyse the response of the system. These highly interactive F.E. packages are mostly used at the detailed design stage. This is a powerful numerical technique which requires powerful computers to perform the task. There are a great many of these packages available, and work is being undertaken to classify existing software approaches.

Dimensional analysis

This technique is used to generalise results so they can be used for any similar design problems. The system is described by geometric and material parameters. Then sensitivity analysis is carried out to determine the effect of these parameters on the systems performance.

Performance Curves

Using dimensional analysis technique normalised performance curves can be obtained. These curves indicate relationships between the design requirements and the design variables. Normalized performance curves can be used to investigate design of similar type without much resort to computer.

5.6. Evaluation and Decisions

The evaluation step is the determination of the degree to which the candidate design satisfies the objectives of the design.

The area of evaluation and decision is one in which a great deal of research and debate has taken place. No attempt is made here to give a comprehensive review of the work examined in this area, but it is felt that in relation to the production of this section the works of

English (1968) and McPherson (1980) should be noted.

No specific aids to this design stage as yet exist as separate entities, but rather consist of sets of evaluating techniques. These techniques consist of methods by which a candidate design which has had its performance characteristics defined through the analysis process is evaluated against the original specification requirements. A number of methods of evaluation exist, their basic structure being, in most cases, similar to that described below.

A candidate Ci, has a set of design characteristics, which are those of iK attributes which are relevant to the design objectives. There is generally a multiplicity of separate criteria, K, by which design must be evaluated. In systematic evaluation the criteria should be formulated as utility functions of the form U.k=ik (ci ...... cin), which assigns a value Uik to a set of design characteristics. A set of utility values is then determined for each candidate design.

5.7 Drawing as an aid to design

Within the design process it has been found that drawing of some degree of formality takes place at each of the design phases. Drawing is an aid to the designer as it acts as a means of visually clarifying complex concepts and inter-relationships, and in addition is the usual method of conveying information regarding the design to others involved in the design process.

Technical drawings can be classified by:-

- Type
- Method of preparation
- Context
- Purpose

With respect to the type of drawing, a distinction is made between:

- Sketches, which do not have to be strictly bound to rules, and which are generally freehand or approximately dimensional

- Drawings, which should be as fully dimensional as possible

- Plans, for example ground plans

- Simplified scale drawings

- Graphic representations, i.e. functional structures

Sketches are of particular importance during the conceptual stage, where they provide invaluable help in the search for solutions and the handling of information. Approximately and fully dimensioned drawings are particularly useful during the embodiment stage and in the preparation of production documents following the detail design stage.

With respect to the method of drawing, the distinction is made between:

- Original drawings suitable for reproduction.
- Pre-print drawings that are often not to scale.

With respect to context, it is possible to distinguish many categories of drawing. One approach is to consider how much of the overall product is represented in the drawing.

- Overall drawings (layout drawings, representations of the product as a whole.)
- Assembly drawings
- Component drawings
- Model drawings
- Schematic drawings

With respect to purpose, drawings can be seen as taking form and detail dependent upon the stage of the process at which it takes place, and the nature of the artefact which is to be designed.

The information gained for the production of this section has come from the activities undertaken as part of Alvey project 142 (the production of a user modelling tool). During this study information was obtained through an analysis of design literature, consultations and interviews with design experts and designers, and experimentation.

Conclusion

Aids form an essential part of all design activities and as such it is impossible to produce a valid model of the design process without including them as an element of that process. This chapter has aimed to discuss the way in which aids contribute to the design process, and in addition, to show the way in which they are related to the different stages of that process. A comprehensive discussion of the technical details involving the operation of the aids has not been undertaken, rather a detailed classification of aids and their relationship and contribution to the process has been presented. From this classification of relationships it is possible to see that design aids of some form contribute to all design, and it is impossible for design to take place without them.

6. Final Summary of Thesis

The thesis has been concerned with the production of a model of the engineering design process. The basic underlying assumption upon which the thesis is based is that design principles or laws exist which determine the character of all engineering design activity. The primary aim of the thesis is to identify and define these principles and then to determine their relationship with other aspects of the process and with the production of design as a whole.

The thesis was produced through a combination of interview, consultation, and an extensive review and analysis of literature (this review being completed in 1987) both from the field of design theory and areas concerned with related issues. This analysis of literature (375 sources have been used) forms the basis of the thesis in that it is largely through an identification and synthesis of design concepts, theories and approaches that the model has been produced. The model is therefore predominantly concensus based. The term predominantly is used because, as will be explained below, the model presents a reconciliation of the two main design theory paradyms. The method through which this reconciliation takes place represents one of the major achievements of the thesis.

The model of the design process which is argued for within the thesis takes the form of a description of the information flow and generative structures which form the basic constituent elements of design. It is within this context that generative methodologies and analytical techniques relevant to technical design are discussed.

Design is described as taking place by developing from a perceived need to a finalised fully detailed configuration, through a sequential and iterative set of design stages, each of which is characterised by a specific form of design activity. Within each of the design stages the generative and analytical aspects of the activity have been examined and the types of design information which characterises the stage are related to the development of the design. Through these activities it has been possible to determine that there are fundamental processess which take place during all design, and that these will be present regardless of the scale, complexity or formality of the design activity.

A detailed discussion of the informatics of the design process is also incorporated within the model. It is within this discussion that the relationships between differing mediums of information generation, transfer and storage are examined. This discussion is further expanded upon within the chapter concerned with aids to design. In relation to the means of design it is determined that these should be included within any model of design as they contribute to the form and shape of the flow of information. This relationship is defined and its influence upon design examined.

The model differs from previous work in this area in that it sythesises the two main views of design development, sequential theory and process theory, by the incorporation of the Blackboard Concept. The Blackboard Concept operates at a number of levels of complexity in terms of design information and is essentially a device for allowing the storage, continuous viewing and manipulation/transfer of solutions, partial solutions and useful design information generated by the design process. The operation of the Blackboard is therefore both analogous to the psychological processes which take place during design, (the off-loading of short term memory, analogous search, etc) and also provides a theoretical framework for the development of design, e.g. as a storage and combinotronic element in the iterative process. This is turn gives context to the means of realisation, i.e. those design aids used during the process.

The Blackboard Concept has been developed from the work conducted in the area of speech recognition systems in the late 1970's and early 1980's. This work resulted in the development of what come to be termed the Blackboard Model. The Blackboard Model was a device which provided a means through which partically developed possible solutions could be held for use either to inform other elements in the solution search or as a way in which partial solutions could be combined into full solutions. The Blackboard Model provides an analogous concept to the way in which design solutions are developed. Sequential theories of design require that the storage of partially formed design solutions are held in this manner as an element of the iterative process which characterises them. Process theories of design similarly, though primarily solution orientated, equally require an element with which to interface the knowledge sources used and the developing design. The Blackboard Concept fulfils this function.

The thesis therefore has argued for a concensus based model of the design process which includes the means to design and which reconciles both process and sequential approaches to design theory through the development and incorporation of the Blackboard Concept.

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