The Communication and Recording of Conceptual Design Information by the Inclusion of Visual Data

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Thanks are also due to Paul Kennedy for suggesting
many interesting references over the years.

This thesis is dedicated to Mum and Dad
for all of their support
and also to Ruth for her patience.

Summary

This thesis reports the results of a three year, full-time research project investigating the generation and communication of product descriptions within the conceptual phase of the engineering design process. The research pays particular attention to the role played by the designer's sketch in communicating new product ideas.

The investigation commences with a literature review of existing design process models (Chapter 2), which helps to define the area under investigation while presenting modern views of the process in relation to classic examples from established design research.

Chapter 3 presents a literature review of the methods currently used to support communication of product descriptions. These methods of Specification are assessed and particular attention is given to new computer-based recording methods such as DOORS and Cradle. Suggestions for improving the efficiency of such models are put forward and the text-only bias of such systems is identified. This comparison of the existing systems thus identifies the research questions.

Having identified the possible improvement to be gained by the incorporation of visual material in addition to the universal text description, Chapter 4 presents a literature review assessing the roles of the conceptual sketch in engineering design. As well as presenting views of drawing from philosophical, psychological and scientific standpoints, this section compares attempts made to support the engineer's sketching activity by computer means. This chapter concludes that efforts made to provide effective computer support of sketching by freehand methods are preferred to attempts made to replicate the process with current computer tools.

The resulting research experiment, the methodology of which is described in Chapter 5, uses students from the final year of the Product Design Engineering course at Glasgow School of Art and the University of Glasgow. The main aim of the experiment is to identify means of including sketches within the kind of text-based support methods discussed in Chapter 3. It also observes the volume and pattern of information produced by sketch activity throughout the conceptual stages of the design process and aims to find methods which would enable sketches to indicate the general progress of a design. The findings are detailed in Chapter 6.

From the research experiment, the use of sketches to add value to up-to-date text-based product descriptions has been assessed. A resultant model, included in Chapter 7, shows how the computer support of the sketching activity results in a database of the developing design, to and from which text and visual data can be inputted and later retrieved by query. This provides a detailed design record and a specification system which can distribute complete and up-to-date specifications instantly or issue partial specifications by query. Assessment analysis of inputted sketch material, based on methods outlined in Chapter 6, also provides an additional utility to management and/or the reflexive designer that will help to improve design efficiency through increased self-awareness.

Chapter 8 summarises the contribution to knowledge made by this study. It then suggests areas for technological research and improvement to enable the realisation of the proposed model. It also recognises how this study may be extended further to provide additional detail to the findings presented here.

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List of Symbols

c	Complexity measure of a sketch
s	Size factor of a sketch
I_{ps}	Information held in a sketch
$\overline{I}_{pw}$	Average Information total for sketches produced within one week
n_{pw}	Number of sketches produced within one week
T	Text Attribute, one unit of meaning in a specification statement
Ia	Image Associated Attribute, special text attribute from annotation to a sketch
I	General measure of information in non-annotated sketches

List of Abbreviations

B.Eng	Bachelor of Engineering
BS	British Standard
CAD	Computer-Aided Design
CBR	Case-Based Reasoning
EDSS	Engineering Design decision Support System
FSD	Fast Shape Designer
GUIDE	Glasgow Utility for the Integration of DEsign
M.Eng	Master of Engineering
PDS	Product Design Specification
PROSUS	PROcess-based SUpport System
VDI	Verein Deutscher Ingenieure
WP	Word-Processing

Chapter 1
Introduction

1.1 Introduction

The present engineering design environment is typified by shortening life cycles and growing product complexity. These two factors among many others have resulted in a cumulative increase in the amount of knowledge to be considered during design. In addition, greater accountability in terms of product liability is putting pressure on engineers to change their working practices [Hollins and Pugh 90] [Wallace 97].

The design research community has spent much of its effort in recent years developing information support systems that will capture relevant knowledge and experience needed in current product design and development. The emphasis has shifted from attempting to discover an algorithm for automated design and moved towards developing software to support designers [Fischer and Nakakoji 92]. The latter approach reaffirms the importance of the human element in design.

For several years researchers chose to ignore the earlier stages of design including the conceptual phase, in favour of developing expert systems for supporting the latter stages [Hurst and Hollins 95]. These latter embodiment and detail phases utilise an enhanced quality of information [McGown and Green 95] that is more readily amenable to computer support than that available in the ill-defined and complex conceptual stages. Work has also been carried out into improving the evaluation of conceptual design [Green 94] [Rodgers, Patterson and Wilson 95] [Cziulik and Driscoll 97] [Kuhnapfel 97] but effort is required that will develop recording mechanisms to provide conceptual synthesis input to such evaluation systems.

Knoop et al agree that computer support of the later stages of design is easier to achieve since the product description is already well known. They contend that technology push coupled with a poor understanding of the design process led to lack of support for the conceptual designer [Knoop et al 96]. Today, however, studies into the early stages of design are now an increasingly popular focus for researchers. This thesis aims to add to that growing body of work.

Up until the last few years the conceptual stages of design, typified by indeterminate knowledge and evolving priorities, have been largely excluded from the digital environment and thus any digital record of the evolving design. In essence a design record may allow for any retrospective view to unearth the long forgotten secrets of who did what and why.

If looked at in a slightly negative way such a retrospective design record can find the cause of product failures and be used to apportion blame. When the wings fall off an aircraft a professionally-kept design record can go a long way to proving that the company were as responsible as possible in their design processes and looked into every possibility of failure.

Liability aside, it is not inconceivable that the recording of decisions, personnel (sic) opinion, and the passage of information will yield the secrets of a design that eventually becomes successful. Once it is completed and ready for the market no product can reveal the many reasons for its design or how its design developed throughout the process. From [Burns and Stalker 1959]:

> 'Even though the final responsibility for taking a particular action rests with some definite person, we shall always find... that its various components can be traced through the formal and informal channels of communication to many individuals who have participated in forming its premises.'

Used in this way, auditing design appears positively beneficial and not just a useful exercise in damage limitation.

Design records made in real time provide not only a historical viewpoint but also a snapshot of the present [Bucciarelli 1988].

> 'Through it all, everything appears in flux, interwoven and turbulent. Still, the shutter must click, images must be fixed, decisions made.'

From there the design evolves and moves on, and yet more snapshots are taken. All of the important inputs to the design must be passed on to those responsible for furthering it. A design record operating in the present in this way can be seen to actively stimulate creativity and activity as well as 'play it back'.

The interactions between influences to the design can become complex and diverse and in order to combat the very finite nature of human short term memory the system should, whenever desired, provide a prompt to the designer, a reminder of 'where we are' and 'how we got here'. Enhanced quality of information enables more accurate externalisation of design ideas and improved subsequent recording of the process.

To recap, by storing distributed updates of 'current' design information a design record can be built 'while design happens'. A design record would:

- act as an aid to the designer's short term memory by prompting the designer trying to recall the reasons, decisions and sources behind the current design description;

- help to demonstrate that the firm has gone about the task in a responsible way in cases of product liability;

- help to further improve design understanding, by enabling meaningful research into the re-use of previous design project knowledge within new design projects.

1.2 Research Programme

The research presented in this thesis is based on a three-step programme broadly given as:

Research - Experiment - Generate Model

The main activities within each phase were as follows.

Research Phase

The first activity within this phase was the review of existing design process models with the aim of identifying broad research areas. Literature review of current research endeavour helped identify neglected areas of concern requiring new research or investigation using new approaches. Novel areas of study complement existing or ongoing research activities. The study presented here:

- addresses a perceived lack of research into the early stages of design;
- addresses a perceived lack of research into conceptual design by experiment into working practice, complementing a body of research gained by laboratory-based methods;
- links with work into the evaluation of conceptual design information, by aiming to improve the quality of the inputted design information.

Two areas were next researched in parallel:

- recent research into conceptual activity;
- existing methods for specification and product description.

By assessment of the shortcomings in both areas, further investigation into the *visual* aspects of communicated conceptual design activity was proposed.

Experiment

An experimental study was arranged to provide data by methods of unobtrusive measure from a non-laboratory setting. The overall methodology was influenced by ethnographic approaches. The resulting data would act as input to a model for improved information distribution. The methodology of the experiment and analysis of its results are included in Chapters 5 and 6.

Generate Model

A model for improved information distribution was constructed based on the experimental results and is shown in Chapter 7. Further work identified areas for future research on two fronts in particular:

- the need for technological improvements and research to make the model technically feasible;
- the desire for further experiments based upon similar methodology to extend the work presented here into different settings.

The final phase comprised the writing up of this thesis and in particular forming conclusions about the research results. These conclusions are discussed in Chapters 6, 7 and 8.

1.3 Project Management

Adhering to the general design of the research programme given in Figure 1.1, a work plan was constructed at the start of each calendar year. The year planners detailed the main tasks required for completion of the project and displayed them in the form of a Gantt chart. The tasks covered in each of the three years of this full-time project are given in Figure 1.2. A second experimental data set was analysed in an additional part-time fourth year.

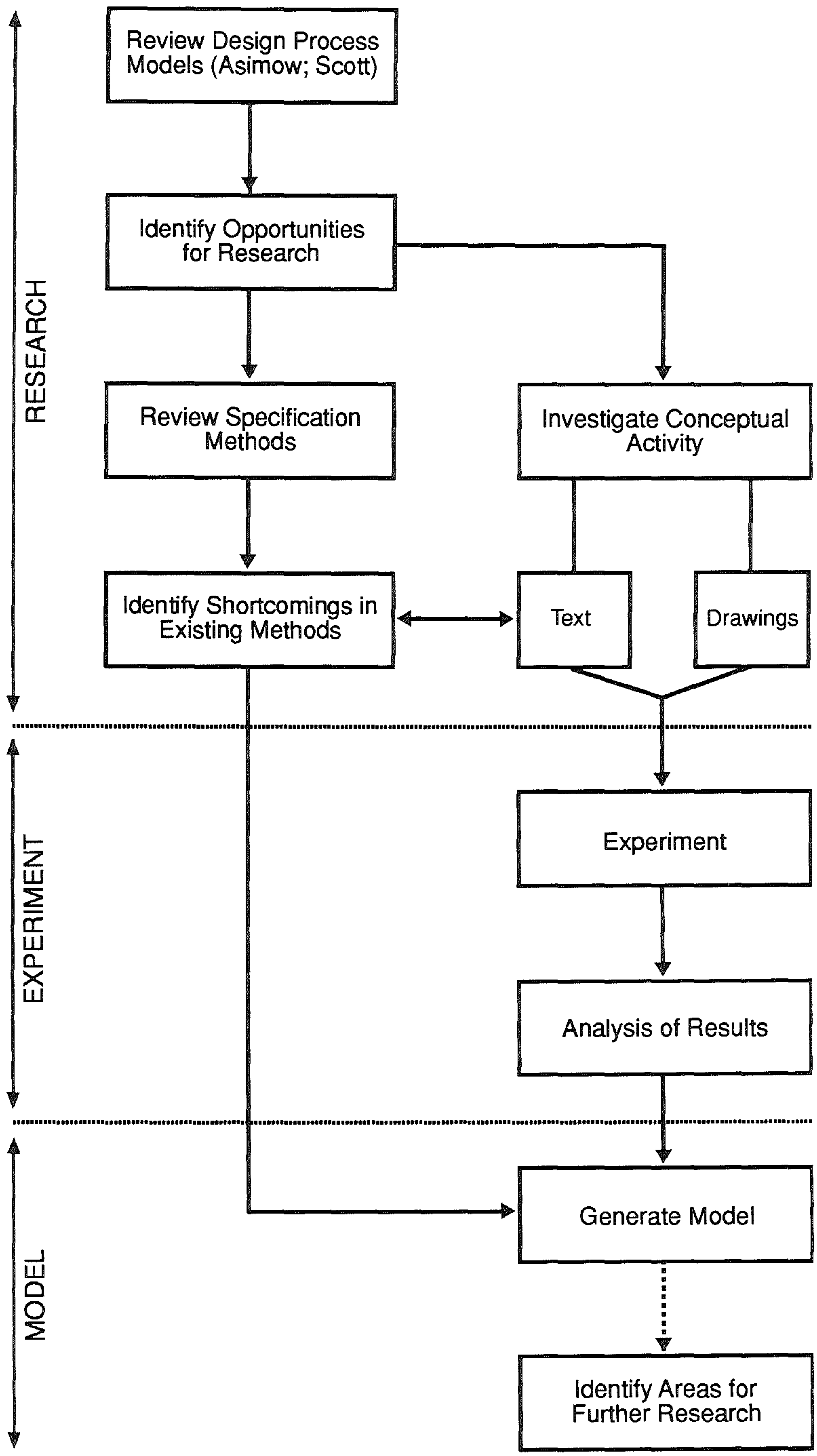


Figure 1.1 Research programme model

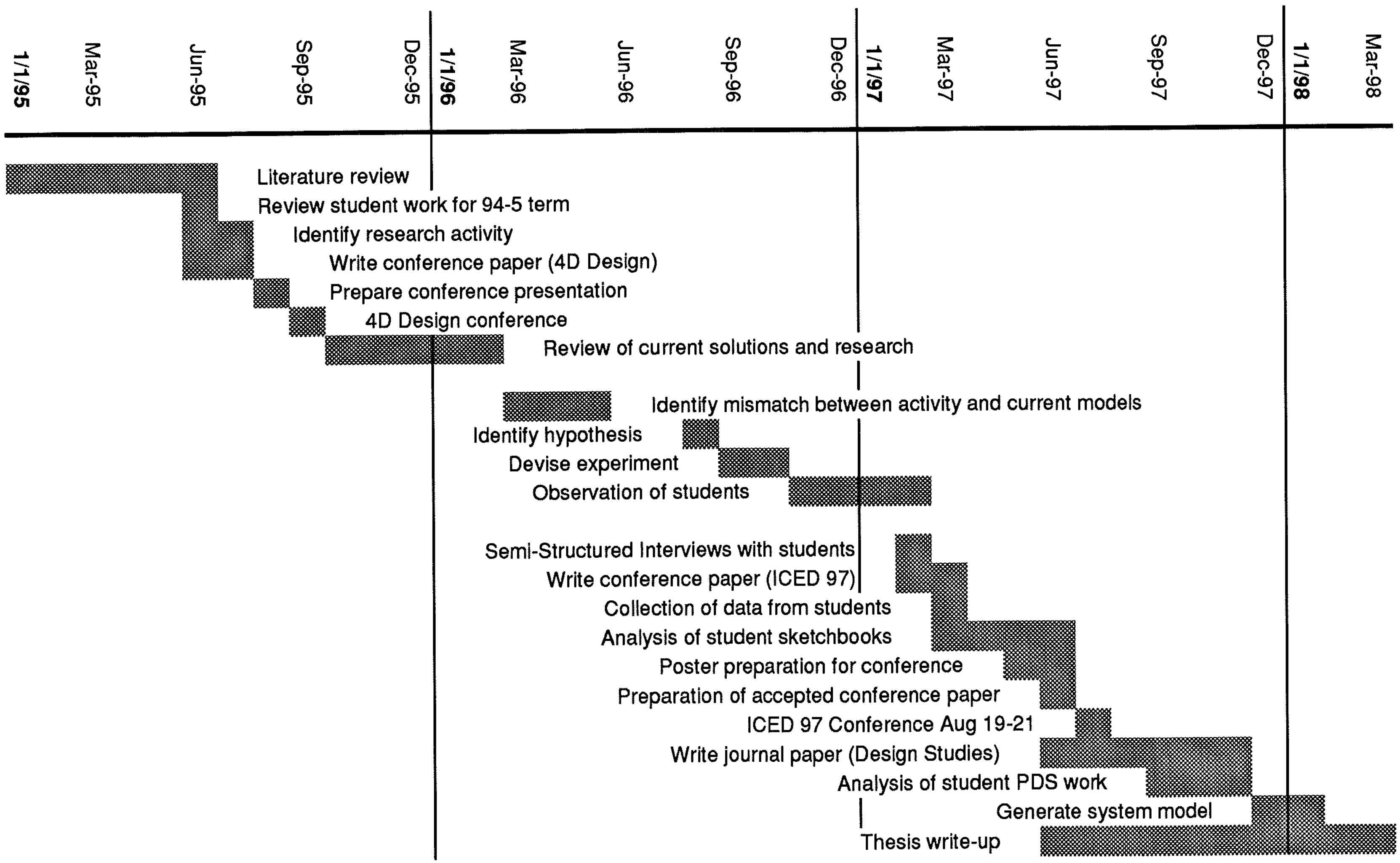


Figure 1.2 Project Management Chart

Chapter 2
An Introduction to Conceptual Design

2.1 A Phased Design Process

If this study is to focus on activities within the conceptual phase of the engineering design process, the term 'conceptual phase' and the notion of a phased design process must first be introduced.

Since the recognition of design methodology as an emerging discipline in the early 1960s, researchers and practitioners have attempted to model the design process. As early as 1924, however, Poincaré had realised what could almost be seen now as a proto-process model (described in [Lawson 1980, 1990]). Poincaré described a five stage creative process consisting of 'first insight', 'preparation', 'incubation', 'illumination' and 'verification'.

'First insight' involves recognising that a problem exists, and accepting to tackle it. 'Preparation' involves much hard work in gathering information about the problem, and Poincaré emphasised that here there is much iterative movement between this and the previous 'stage'. 'Incubation' is the stage at which the designer appears to be doing nothing, but this is the gestation period for ideas, and it is hoped that reorganising and re-examining of the salient facts brought together in the 'preparation' stage will lead to the 'sudden emergence' of an idea - the 'illumination'. The idea formed in the 'illumination' stage will then be checked for performance by calculations and the like in the 'verification' stage.

Modern methodologists have created similar models of the design process within the engineering domain as an aid to understanding how design proceeds from opportunities or ideas to a finished proposal or manufactured product. Some have done so in an attempt to describe the sequence of activities that typically occur in designing, while others have attempted to prescribe a better pattern of activities. Accordingly these two types are termed descriptive and prescriptive [Cross 94].

Most design process models are accompanied by a diagram, typically showing the steps involved as boxes linked by directional arrows. One of the earliest of the modern diagrams was very complex, showing somewhere in the region of fifty tasks, processes and outcomes involved in design [Asimow 62]. Overall, however, Asimow's model divided the design task into three discrete phases; *feasibility study*, *preliminary design* and *detailed design*. Only a few years later Krick's model for the process advocated a five step process that began with a statement of need and terminated with the specifications for a means of fulfilling that need [Krick 65] (Figure 2.1). The five stages were:

• *Problem formulation* - where the problem at hand is defined in a relatively broad manner

• *Problem analysis* - where the problem is defined in relatively detailed terms through the gathering of information

• *Search* - where alternative solutions are sought through creative thought and consultation

• *Decision* - during which alternative solutions are evaluated and screened until the best one evolves

• *Specification* - the phase which results in a complete description of the physical and performance characteristics of the product

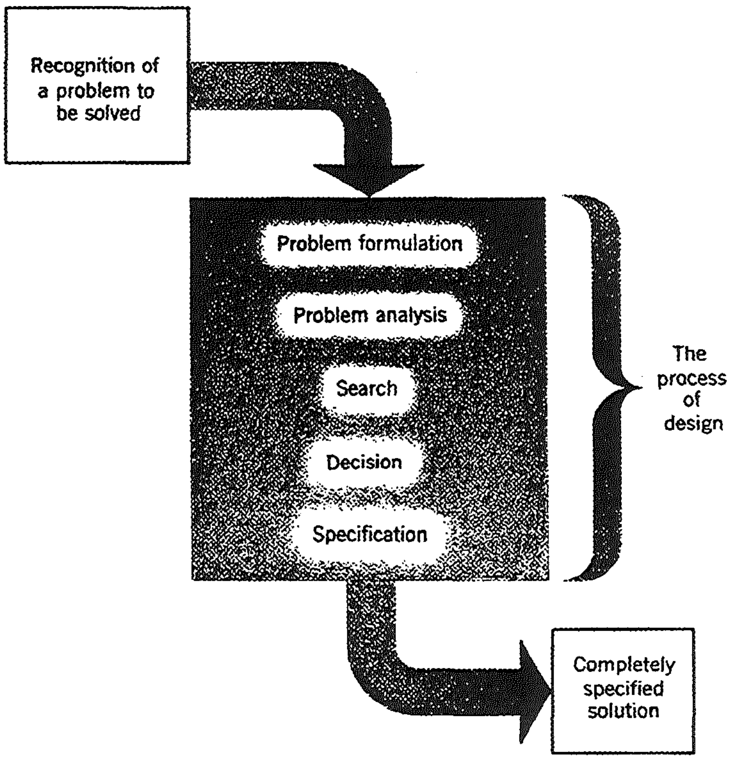


Figure 2.1 Krick's design process model

Through models such as these the notion of a sequential, linear design process became accepted. [Dixon 1966] describes the discrete stages of 'goal recognition', 'task specification', 'concept formation', 'engineering analysis', 'solution specification', 'production' and 'sales' (Figure 2.2). While different authors use different terms to name the stages of design, semantically they are largely similar. A list of terms used in some of the most well-known models and their relative position along the continuum of design from idea to manufacture is shown in Table 2.1.

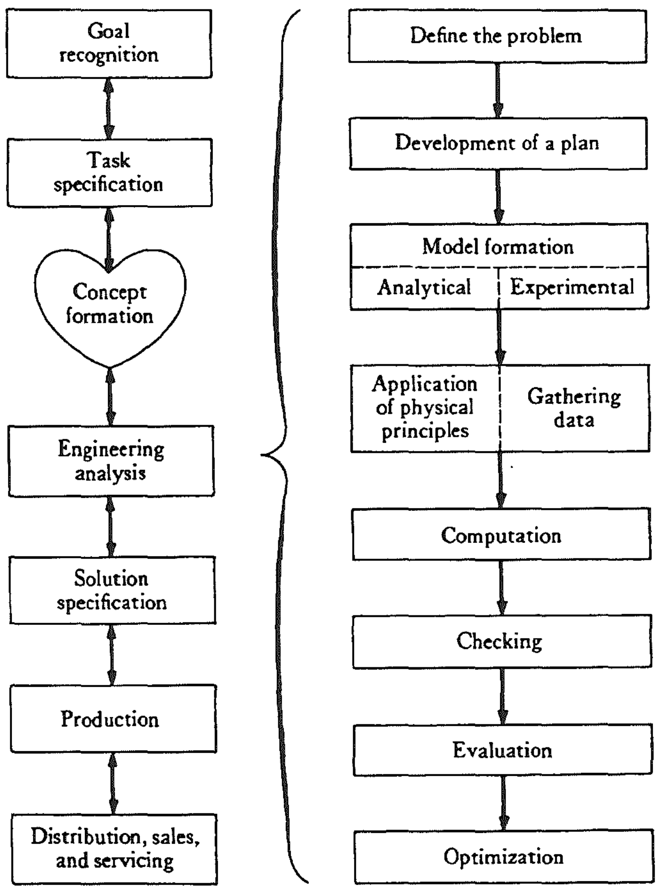


Figure 2.2 Dixon's design process model

Distinction must be made however between steps referred to as 'specification' in the various models. The early models of Krick and Dixon both speak about a 'Specification' (or 'Solution Specification') stage near the end of the process. Here this is taken to mean the finalised product description delivered to those responsible for its production - it is the end of the line as far as the engineers are

RECOGNITION OF OPPORTUNITY → MANUFACTURE OF PRODUCT

Poincaré (1928)	First Insight	Preparation Incubation	Illumination	Verification	
Asimow (62)		Feasibility Study	Preliminary Design	Detailed Design	
Krick (65)		Problem Formulation Problem Analysis	Search Decision	Specification	
Dixon (66)	Goal Recognition	Task Specification	Concept Formation Engineering Analysis	Solution Specification	Production
French (71)		Analysis of Problem	Conceptual Design	Embodiment Detailing	
Pahl & Beitz (77)		Clarification of Task - Requirements List	Conceptual Design	Embodiment Design Detail Design	
Pugh (82)	Market	Specification (dynamic>)	Concept Design	Detail Design	Manufacture Sell
Archer (84)		Analytical Phase	Creative Phase	Executive Phase	

Table 2.1 A continuum of design process models

concerned and where the job of 'making the thing' is handed over to the shop floor. Dixon distinguishes between this finalised Specification and the Specification given to (and formulated by) the designers and engineers before concepts can be created and discussed - this latter type Dixon calls the 'Task Specification' stage.

Modern models such as that of [Pugh 82] try to make engineers see the 'Specification' as dynamic; in essence Dixon's 'Task Specification' is added to and evolves to become the final 'Specification' delivered to the production people. The two documents are the same document at different points in time. So it is that modern descriptions and models of the design process may talk about Specifications being at the start *and* end of the creative process. The manufacturing industry and its shop floor still tend to think of the specification as being the final delivered description of what it is that is to be manufactured.

Another breakthrough seen in Dixon's model is the use of two-way arrows to indicate that in actual engineering practice the design process is not a straight step-by-step path. Any design solution may require a number of iterations through various parts of the process and much going back and forth [Dixon 66][Jones 70]. [Pugh 90] states that;

> 'At all stages, the design core activity is operated *iteratively*, yet upon later inspection, the stages as depicted will appear to have been gone through sequentially. So, the main design flow can, and does, often reverse at any point in the design activity and some iteration is inevitable, but operating within the design core rigorously and systematically will minimise unnecessary iteration.'

Inherent in a desire to design should be a willingness to accept that iterative activity will occur but hopefully awareness of the process made possible by such models will limit the amount of iteration required to successfully complete the cycle.

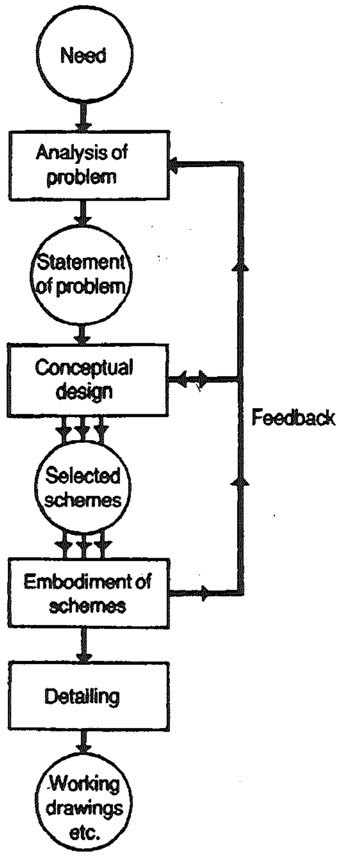


Figure 2.3 French's design process model

A slightly later model (Figure 2.3) similarly recognises the feedback loops between apparently successive stages of the process [French 71]. French has omitted relationships with other parts of the engineering purpose for reasons of clarity, but notes the importance of the inputs of information and points out that for instance there is no box labelled 'Evaluation' because he believes that it should be going on continuously in all the rectangles.

Such models are clear enough to provide a basic understanding of the progress through the design activity. As French states:

'they express only truisms and yet they have a value for all that.'

The value has been shown in design education where models such as those proposed by French and [Pugh 1982] have proved useful.

There are still limitations to thse models however. By cutting the engineers themselves out of the equation these traditional design process models may lead us to conclude that engineering design is an extra-orderly, rational process [Bucciarelli 1988] and that the conceptual, embodiment and detail phases are just simple self-contained steps to success. According to [Ferguson 92] engineering is always subject to unforeseen complications and influences, responded to by contingent strategies. To him block diagrams of process models imply a division of design into discrete segments, each of which can be 'processed' before turning to the next. Further, Ferguson feels that:

> 'Design is not, as some textbooks would have us believe, a formal, sequential process that can be summarised in a block diagram.'

More flexible, organic models respond to such criticisms and help to illustrate some of the process-related problems encountered by practising engineers [Rhodes and Smith 87][Scott 88]. Such models eschew clinical clarity in favour of complexity - illustrating the reality of the design task in industry. Rhodes and Smith illustrate the information inputs to Pugh's design core (Figure 2.4). Pugh's notion of an evolving PDS [Pugh 82], comprising information evolving dynamically through the system, is another advance in the history of design process models.

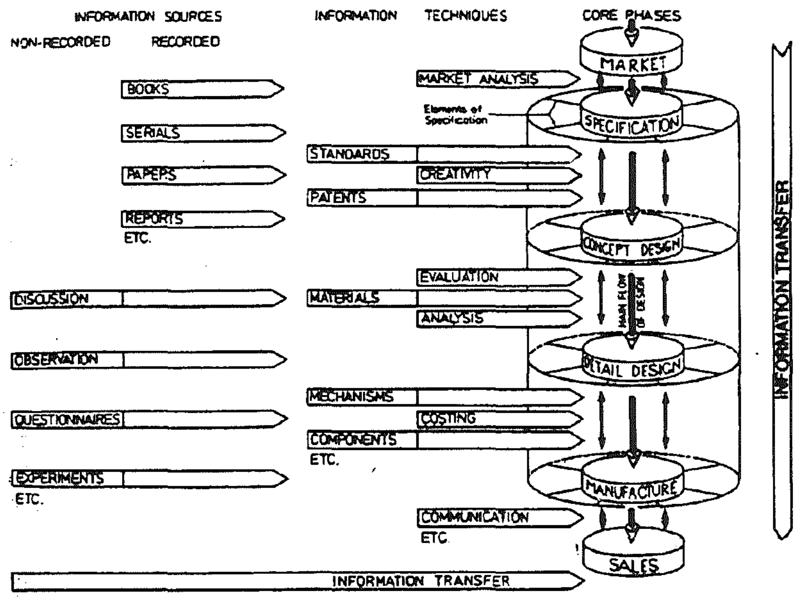


Figure 2.4 Information inputs to the design core

Scott's 'framework for design' recognises chief players and key activities in a process that is driven by the communication of 'intent' by a designer or group of designers (Figure 2.5). Thus Scott goes some way towards recognising design as a social process and so concurs with [Bucciarelli 1988] in viewing the engineering firm as subculture.

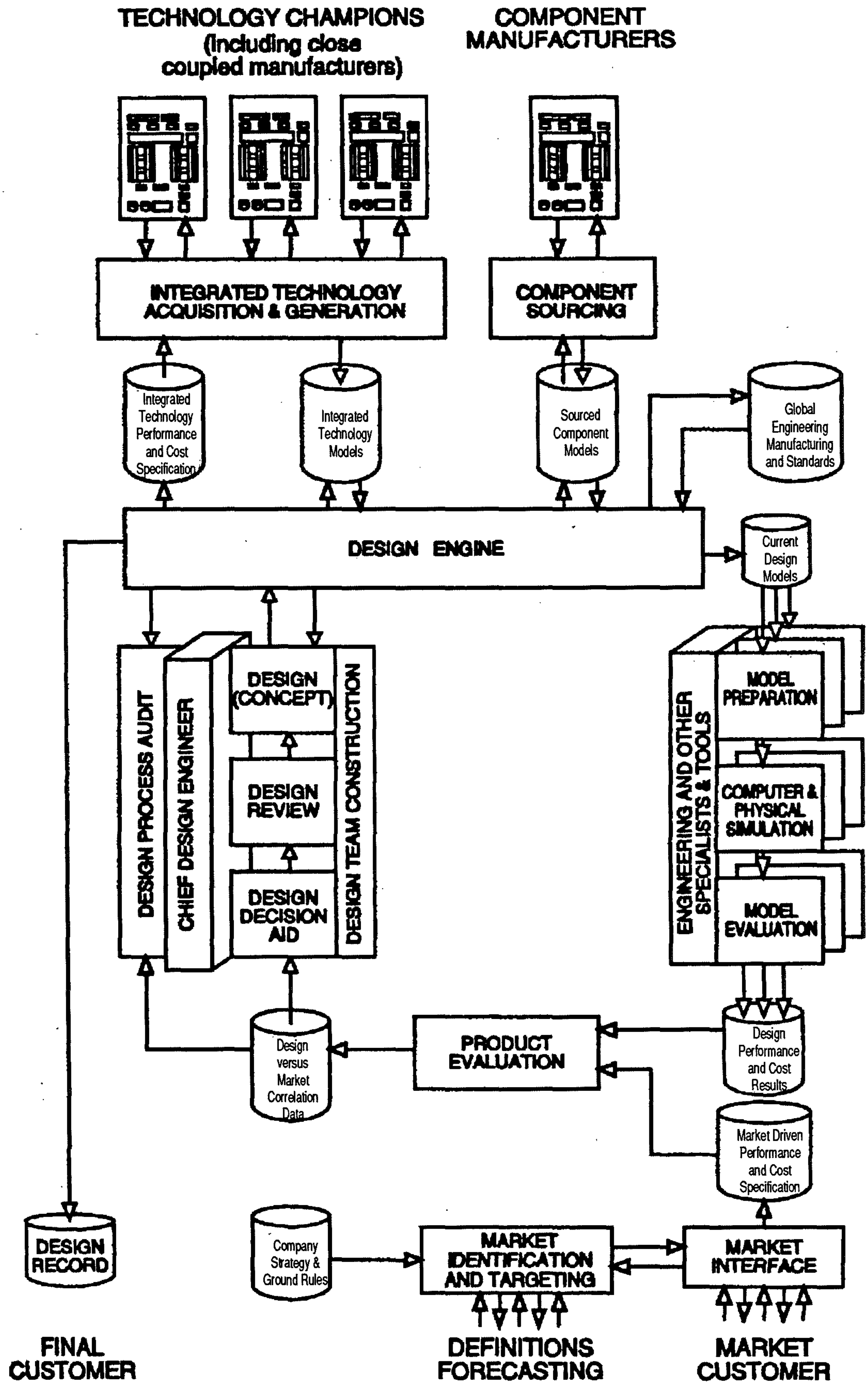


Figure 2.5 Framework for design

There are three main ideas to be taken from this discussion.

1) Recent models recognise the importance of the flow of information throughout the process, from idea to manufacture. They suggest that it is effective communication of this information that drives the activity.

2) By agreeing with Ferguson's view of engineering design as a contingent process it is recognised that the activities typically associated with the 'conceptual design phase', or any other arbitrary phase, will also occur outside of the blurred edges of the process model phase. Such activity is not truly contained within the line edges of a box in an idealised model.

3) To be exact then this thesis studies *conceptual activity within the early stages of design*, a stage where ideas are generated despite dealing sometimes in ill-defined information. The phrase 'conceptual design phase' may still be used in reference to other research.

2.2 Conceptual Activity

As was established earlier, conceptual activity within the early stages of design is an area that modern design research has only recently made concerted efforts to examine and as such is something of a 'frontier' topic. This 'phase' is one where the currency of ideas is at a premium. This activity, more usually referred to as the 'conceptual design phase' is broadly defined as a stage primarily concerned with the generation of solutions to meet the stated need [Pugh 90] and as involving a search for suitable solution principles [Pahl and Beitz 84]. Here the designer must formulate a way, a method, or a concept of how to get the task done [Dixon 66]. According to [French 85] the 'phase':

> 'Takes the statement of the problem and generates broad solutions to it in the form of schemes. It is the phase that makes the greatest demands on the designer and where there is the most scope for striking improvements. It is the phase where engineering science, practical knowledge, production methods and commercial aspects need to be brought together.'

It is odd that the area was largely ignored by researchers for many years in favour of topics of improved management and so on, since conceptual activity in the early stages of design has long been considered the stage in the design process where the most important decisions are taken [French 85]. The quality of the final product solution is determined to a large extent by the quality of the idea or concept generated at this time. It is in a sense the heart of the design process [Dixon 66]. Within all of the models reviewed by [Green 94], it is accepted that the conceptual design phase is considered:

> 'By far the most important of all in that the inherent reliability, cost, manufacturability and potential for commercial success of the product are largely established at this time.'

While conceptual activity is usually associated with ideas and creativity, the ideas considered need not necessarily be new. Conceptual activity usually requires that the engineering designer gets an idea - this can either be a new idea or an old idea applied in a new way to a particular problem. Sometimes this requires a great deal of imagination, ingenuity and inventiveness but sometimes it is quite a routine application or revision of an existing idea [Dixon 66]. Both approaches are valid, with the choice made dependent upon the context for design. Sometimes existing ideas can be applied in new and previously unrelated domains - this is known as 'displacement of concepts' [Schon 63].

From engineering case study it appears that ideas can be borrowed from other company departments or 'domains' and only become relevant or important in the correct context [Blessing 94]. This shows the importance of recording products and concepts in accessible forms.

Conceptual activity is concerned with ideas and the generation of solutions and can be seen to be made up of constituent operations; it breaks down into cyclical major components and [Pugh 90] suggests two such components.

1) the generation of solutions to meet the stated need
2) the evaluation of these solutions

It is probably more 'complete' to see the conceptual 'step' as encompassing the three dominant stages of design. Design is defined as a three step process by [Jones 80]. In general terms the process includes:

1) *Analysis* - the listing of design requirements and their reduction to a set of performance specifications
2) *Synthesis* - finding possible solutions
3) *Evaluation* - evaluating the accuracy with which alternative designs fulfil performance requirements before selection.

It is proposed that this model of the design process at a macro-level also extends to cover, in general terms, the conceptual design process at a micro-level, where it typifies each specific action:

1) *Conceptual Analysis* - information is assessed to produce requirements
2) *Conceptual Synthesis* - possible solutions are generated according to these requirements, typically as drawings and revisions and additions to the requirements presented in the previous step
3) *Conceptual Evaluation* - the alternative solutions generated are evaluated and the most promising selected for further development.

By iteration and combination of ideas, conceptual activity within the early phases should provide, by evaluation, a selected concept suitable for detailing.

This research aims to support and improve the efficiency of conceptual design activity in the early stages of design by considering each step in the three step process. It will aim to:

- improve the communication of information for assessment and analysis
- improve the efficiency of conceptual synthesis by suitable support and also enable the recording of the generated concepts
- improve the communicated outcomes of the synthesis activity and thus provide better input to the evaluation activity

2.3 Conceptual Synthesis - Creativity and Innovation

Historically, creativity and innovation are described in terms that make them seem much like black arts. A cult of 'Great Inventors' has been created, based on the largely mythological representation of such diverse historical figures as Thomas Edison, James Watt and Archimedes. This tradition is known as the 'Great Man' syndrome, a tradition which imbues talented, hard-working and creative individuals with almost magical powers [Jewkes, Sawers & Stillerman 69]. Not wishing to take away from their achievements, it is more accurate and useful to refer to men such as Leonardo da Vinci and Orville and Wilbur Wright as engineers [Ferguson 92].

Archimedes' 'Eureka' and subsequent discovery of the principles of buoyancy created an image which persists today, certainly when it comes to popular representations of working scientists, technologists and engineering designers. While the promotion of 'genius' and celebration of 'chance' may continue, the more modern view of such achievements believes more readily in the Pasteur Principle: 'Chance favours the prepared mind'. In the case of engineering design then, preparation of mind involves the bringing together of relevant and up-to-date information in a controlled manner.

The real inspiration or insight is not in instantly creating a solution, but in identifying a problem. This often forgotten but crucial act can be misrepresented as an 'inspirational moment' but this is again perhaps based on our romantic archetypes of creative acts more than it is on reality. Creativity is a talent, then, for sifting through relevant information and from it producing something both new and useful - an innovation.

More modern views also recognise the creative efforts of both individuals and individuals working in group settings. [McGrath 84] states that individuals working separately generate many more, and more creative, ideas than do groups. He suggests the coupling of creative individuals to decision-making groups in an attempt to get the best out of both approaches. [Pugh 90] agrees, believing that concepts are often best generated by individuals and that concept selection and enhancement is often best performed in groups.

It has been observed that in modern engineering practice, there are both solitary and intense periods where an individual works alone, hoping to be uninterrupted, as well as time when small groups will get together to 'struggle to set things right' [Bucciarelli 94]. Today, innovative, finished products will only be manufactured through harnessing the group efforts of many creative individuals. Rarely is one mind responsible for the entirety of a product [Bucciarelli 88].

Design teams in modern engineering must be creative almost on demand and a number of recognised techniques have been developed to promote and stimulate such open-minded thinking [Lawson 80;90][Pugh 90]. They include:

- brainstorming
- analogy
- attribute listing
- checklists
- inversion
- combination

Such techniques must be grounded in efficient gathering of relevant information and the promotion of a precise understanding of the problem that can be commonly shared - and shaped - by all members of the design team.

Some see creative synthesis and innovation as vital prerequisites for engineering success - insisting that a stream of innovative products is essential to the survival of all companies [Peters 94], and that successful ones will sustain sales over life cycles that are longer than is usual [Andrews 75]. The perfect example is the Sony Walkman, even more interesting as a success story, since it paid no heed to market research findings which wrote it off as having little consumer appeal. Interesting, because market research reports are often used as an information input within the early stages of the design process [Lorenz 86] [Morita, Reingold and Shimomura 87] especially in Japan in the 1970s as witnessed in the QFD method, discussed in the next chapter. As global recession takes hold right now, it may be that more extreme views - such as those that call for 'focus-group-driven' design approaches to be abandoned [Glancey 98] - will be accepted into mainstream industrial practice even if seen as desperate measures.

The term 'creativity' is perhaps just a value judgment on the quality of the conceptual synthesis act - 'creativity' is *good* conceptual synthesis. This study aims to better understand how conceptual synthesis in engineering manifests itself. The history books that tell the stories of the great engineers often use drawings to illustrate the moment of 'illumination', from da Vinci's scribbled early sketches of his 'helicopter' onwards. In Thomas Edison's early sketches we are apparently witness to the very moment that he devised the basic idea for his cylinder phonograph (Figure 2.6). Also we can see a discarded idea for a turntable phonograph (Figure 2.7), an idea which would be taken up and popularised many years later as the record player.

From more recent times a modern great man was Alec Issigonis, the man credited with the development of the revolutionary Mini motor car which first appeared in 1959. In these two small but extremely significant sketches from 1957 we can see the first germ of the idea of the transverse-mounted engine that gave the Mini its

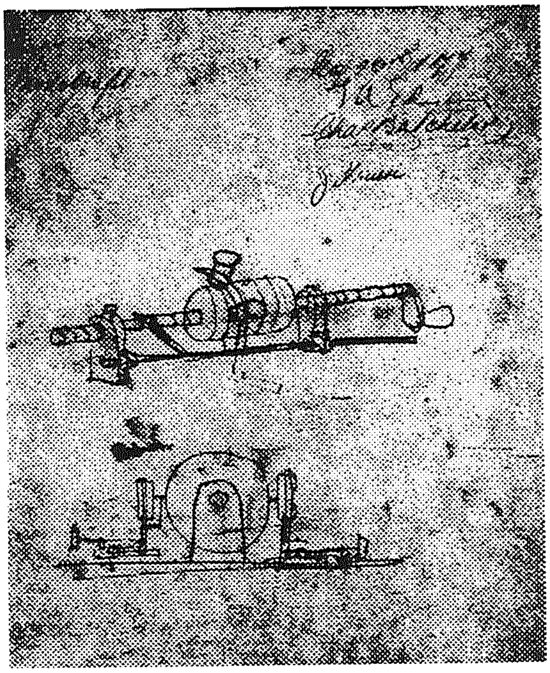


Figure 2.6 Early sketch of cylinder phonograph by Thomas Edison

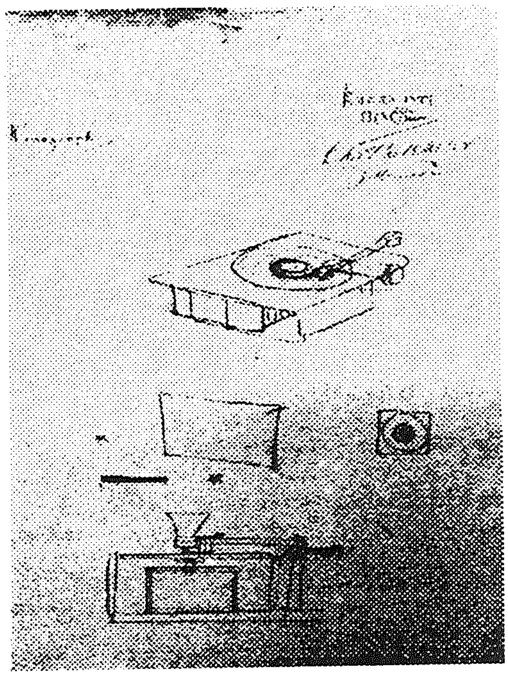
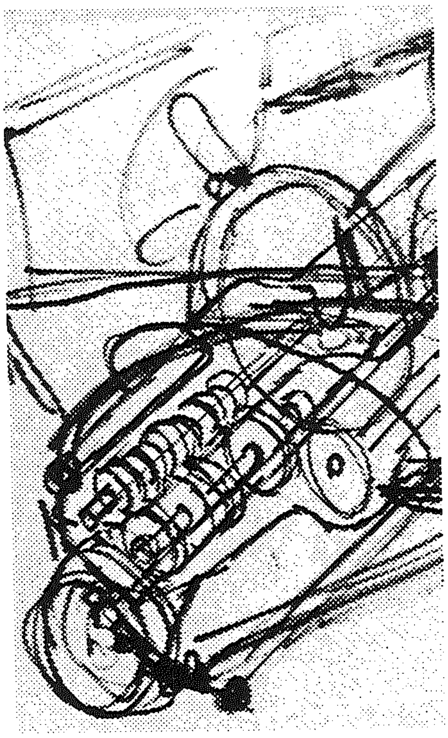


Figure 2.7 Early sketch of turntable phonograph by Thomas Edison c. 1877



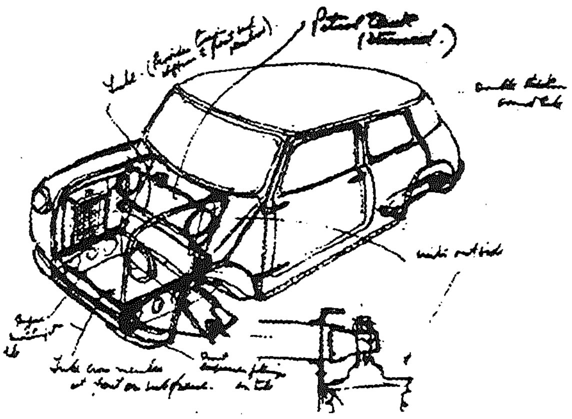


Figure 2.8 (left) Early sketch of transverse-mounted engine by Alec Issigonis
c. 1957

Figure 2.9 (above) Early sketch of Mini motor car and front engine arrangement by Alec Issigonis
c. 1957

reduced dimensions (Figure 2.8), and also the famous 'cheeky' look taking shape as Issigonis tries to configure the front engine space (Figure 2.9). It is reasonable to suggest that the conceptual sketch may similarly reveal the development of the ideas of today's engineers in a similar way.

This thesis will pay particular attention to the drawings used by engineers, regarding them as a visible manifestation of conceptual synthesis activity and as a communicator of ideas in the early stages of design. The research aims to develop support that will, if suitable, record the engineer's drawings and so improve the drawing's capacity for communication of ideas .

Chapter 3
Methods of Recording & Communicating Conceptual Design

3.1 Information Flow in the Design Process

Modern views of engineering see the design process as being enabled by effective distribution of information among all involved parties [Scott 88]. Working engineers must communicate on a daily basis, both in writing and through speech. Rough estimates of the engineer's time taken up in communicating with others range from 20 to 50 percent [Beer 92]. Written communication 'tasks' in engineering include the preparation of:

- memos
- inspection reports
- procedures
- proposals
- manuals
- drawing might also be included as a special case of 'written', non-textual communication that happens on paper.

Spoken communication includes the myriad situations where conversational communication is important, whether it takes place over the water fountain or in a meeting [Beer 92][Bucciarelli 94]. New technologies being used to handle the increasing amount of engineering information include (written) e-mail and voice mail.

One long-standing source of information is the individual designer's informal notebook, something familiar to anyone with experience in the field of engineering design and design education. Ideally, such notebooks would contain every written or drawn artifact relating to a design, from concept to blueprint, with each entry numbered and dated [Kuffner and Ullman 91].

The reality is somewhat less complete and thus incoherent, even when complemented by artifacts such as specification drawings (typically produced at a stage later than the conceptual phase and so outwith the scope of this research). Sketches are made on the back of envelopes, groups work out ideas with marker pens and wipe boards, ideas can come anywhere and at any time, decisions are made on the shop floor in response to previously unforeseen circumstances.

Notes made by one designer in an 'individualised' format like this are sometimes unintelligible to another, particularly where handwritten notes have been made; the handwriting is not good enough or notes have been written in a personal form of 'shorthand'. Such notes may appear jumbled even to the original designer months later. The misrepresentation and misunderstanding caused in this way is sometimes referred to as mechanical 'noise'; adversely affecting the communication 'signal' [Buck 66].

From the above it is clear that within day to day practice in industry there is great need for methods which enable the distribution and recording of engineering communication.

As the design process proceeds so the information about the product being designed increases. The design process may therefore be viewed as progressing from an information poor condition to one that is information rich. The richness of information relates not only to the quantity of information but also to the quality of understanding of the relationship between the elements of information [McGown & Green 95].

Enhanced quality of information enables more accurate externalisation of design ideas and subsequent recording of the process. At present this is evident during the embodiment and detail phases of the engineering design process where externalisations such as performance calculations, detailed manufacturing drawings, simulations and prototypes are made available.

The early stages of design require the analysis, synthesis, evaluation and communication of ideas within an information poor environment. Design tools and methods are being made available to enhance conceptual design performance and to aid recording of the design process within the evaluation activity [Green 94] but less has been done to provide methods that enable the recording of creative synthesis activity. The foremost work in this field is presented in this chapter.

As discussed in earlier chapters, an ideal record of the design activity made 'as it happens' can provide useful, even essential support in making design decisions, be used in cases disputing patent claims or liability and also form the basis for subsequent similar design situations [McGown & Green 95] [Kuffner & Ullman 91].

3.2 Available Requirements-Handling Methods

In essence, a *Design Requirements List* is intended as the basic communal reference to the current state of a product (also known as the 'product description') at any point in the process. As design progresses towards manufacture the List grows and is refined to form the final Specification given to the production staff. It is used to communicate the needs or intentions of one party or another [Hales 90].

[Blessing 94] uses the term 'requirement' to refer to all given and introduced constraints on the design, as is consistent with most prescriptive literature. [Ullman 95] identifies three types of constraints; those given to the designer, those introduced by the designer from knowledge sources and those constraints introduced in the course of solving the problem as a result of design decisions. While acknowledging the rather negative connotations of the word 'constraint' - these constraints on the problem will nonetheless help to *generate* product solutions - this thesis shall adhere to this terminology. Among the methods of listing requirements discussed in this and subsequent chapters, the method of Pahl

Systems and models	Used in Industry	Research Model	Paper-Based	Computer Based	Text Use	Checklist Classification Scheme	Max no. of Elements in Scheme	Knowledge-Base Expert Systems	Visual Content
Yran (72)	●		●		●	●	n/k		None
QFD (c.72)	●		●	Transitional	●	●	hundreds	Transitional	Not addressed
Pahl & Beitz (77)	●		●		●	●	90		Some schematics
Pugh (82)	●		●		●	●	35		Engineering drawings
BS 7373 (91)	●		●		●	●	35 +		schematics, eng drawings
Culverhouse (92)		●		●	●			●	Electrical components
Blessing (94)		●		●	●	●	**n/k**	●	**Capture of freehand sketches**
Tsiotsias (95)		●		●	●			●	Linked to CAD packages
Ullman (95)		●		●	●			●	Lack of visual content
Cradle (c.94-5)	●			●	●	●	variable	●	Links to software templates
DOORS (c.94-5)	●			●	●	●	variable & programmable	●	Links to software templates
Recognised Ideal	●			●	●	●	variable	●	**Freehand conceptual sketches**

Table 3.1 Specification systems and models for use in engineering design

and Beitz is known as the *Requirements List*. The term *requirements list* (lower case) in this dissertation will refer to any general method used to capture product descriptions and design decisions rather than this one specific method.

Several of these models for making explicit the requirements of products have been proposed over the years, originating both in industry and from research (Table 3.1). Attempts have been made recently to record the design process by means of computer-based requirements-handlers - Table 3.1 illustrates the predominant paper-bias of models in industry, the prevailing expert systems/ computer support approach taken by present research and also the breakthroughs promised by commercial solutions like DOORS.

The inadequacy of methods used currently to compile requirements in industry has been noted; the situation is reportedly endemic [Hurst and Hollins 95]. There is little development of the initial requirements list once a project commences and almost no formal documentation of any changes takes place. One study found that 17% of companies still rely on at least part of their product requirements and specifications being verbal (and thus going unrecorded) [Reidel 94].

At least three methods of capturing product requirements *have* found a degree of acceptance in industry.

- Quality Function Deployment (QFD)
- the Requirements List [Pahl and Beitz 77;84]
- the Product Design Specification or PDS [Pugh 82].

These three methods will be among those examined in the following sections.

3.2.1 Yran's project brief

Perhaps the earliest instance of a method intended to list product requirements and thus record design intent was instigated by Knut Yran at Philips, Eindhoven in 1972. A formalised, printed four-page document known as the 'Project Brief' was

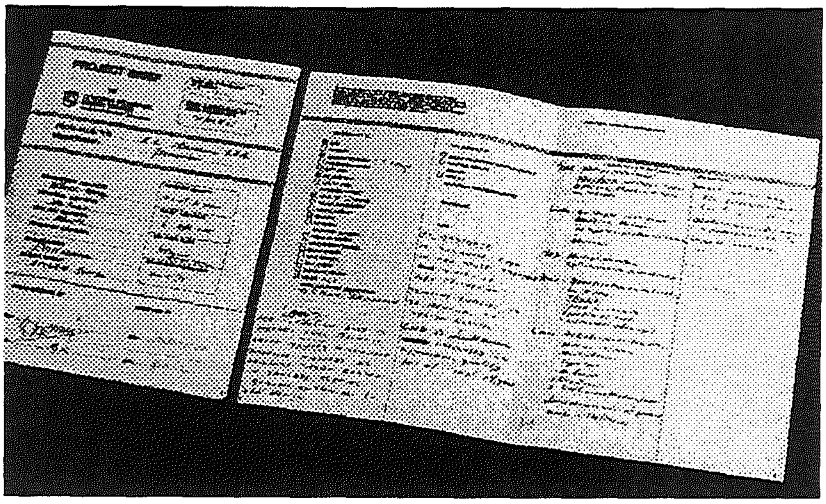


Figure 3.1 Yran's 'Project Brief' c.1972

used to capture designers' written intentions, Yran realising that verbal (i.e. spoken) briefings had made it easy for varying interpretations to be put forward [Heskett 89] (Figure 3.1).

A completed Project Brief comprised a range of both formal requests (from management) and individual responses (from designers). Most of the information was used by management to aid planning and time-keeping strategies. To further formalise this paper-based recording system Yran demanded that each designer keep the brief in a specially provided pocket on his or her drawing board. This was a great step forward in thinking, though the paper-based nature of the system did not lend itself to easy access, nor to furthering communication between the designers in a team.

3.2.2 Axiomatic methods

By the end of the 1970s so-called *Axiomatic* methods were formulated that were intended to enable concurrent engineering techniques. This prescriptive technique illustrates the progress of design and the transformations of information through it.

The axiomatic approach [Suh, Bell & Gossard 78] attempts to bring order to human creativity by the application of a set of rules. This set of simple guidelines;

> 'offers a way to proceed from the very general to the very specific, rather than beginning with the details.'

The method is based on the following hypothesis;

> 'There exists a small set of global principles, or axioms, which can be applied to decisions made throughout the synthesis of a manufacturing system. These axioms constitute guidelines or decision rules which lead to 'correct' decisions, i.e. those which maximise the productivity of the total manufacturing system, in all cases.'

An axiom is a proposition which is assumed to be true without proof, for the sake of studying the consequences that follow from its application. Suh's axioms are intended to optimise products and manufacturing systems, with particular attention focused upon their manufacture.

There are three general steps to the axiomatic method. The first step is to specify the *Functional Requirements* of the product. These are defined by Suh et al as 'a minimum set of independent specifications that completely define the problem'. Examples of this might include; load requirements, expected life, efficiency, input power. These Functional Requirements should then, according to the method, be ordered in a hierarchical structure from an identified primary Functional Requirement to the Requirement of least importance.

The second step is to specify *Constraints*. These are defined as 'those factors which establish the boundaries on acceptable solutions', for example; acceptable cost, adaptability to existing systems. While Functional Requirements are negotiable final characteristics of a product, according to this method Constraints are not negotiable.

The third step involves undertaking conceptual design, with the specified Functional Requirements and Constraints acting as a guide and with the axioms used to make decisions as design progresses.

The axioms can be seen then as criteria for the evaluation of design decisions [Green 94]. There are seven hypothetical axioms that guide the design process and these are stated as directives rather than as observations. For example, Axiom 1 is given thus; 'Minimise the number of functional requirements and constraints'

This axiomatic approach is intended to help designers deal with issues involved in optimising manufacturing productivity - its main intention would seem to be the improvement of a product's manufacture although it is also claimed that axiomatic methods will help to improve the product's overall design.

By following the step process of applying axiomatic techniques, design can be seen as a set of progressive transformations of information; information that is continuously processed between and within four distinct domains (Figure 3.2) [Albano and Suh 94].

1) The needs of the customer are established in the *Consumer Domain*
2) Needs formalised as Functional Requirements (FRs) within the *Functional Domain*
3) Functional Requirements (FRs) are then mapped to corresponding Design Parameters (DPs) in the *Physical Domain* as part of the creative synthesis phase
4) The Design Parameters (DPs) must be satisfied by mapping the DPs to a set of Process Variables (PVs) within the *Process Domain*, which generally governs manufacturing issues

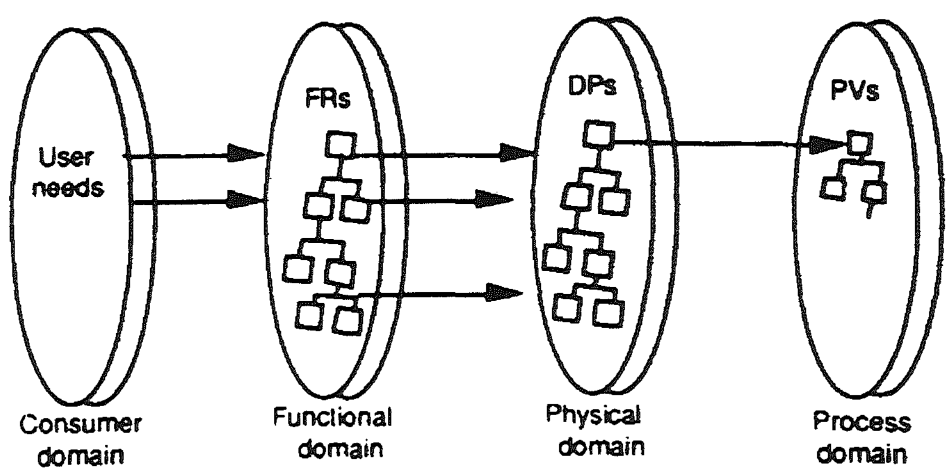


Figure 3.2 The four domains of the design world [Albano & Suh 94]

More recently efforts have been made to embody axiomatic techniques within a computational environment. This consists of a Thinking Design Machine for applying axioms and also a graphical display which illustrates FR, DP and PV hierarchies on screen. [Albano and Suh 94] recognised the need for these central concepts to be tested in industrial environments.

3.2.3 Quality function deployment

The three main aims of the *Quality Function Deployment* method are indicated in its name: 'Quality' refers to the need to meet customer requirements; 'Function' to addressing 'what needs to be done' and focusing efforts toward achieving customer satisfaction; while 'Deployment' refers to a 'broadening of activities' and thus aims to ascertain when and how improvements will be brought about and by whom. The 'Quality' statements give some sort of product description, in user terms, while 'Function' and 'Deployment' are more about calling into action the players necessary for the product's development. QFD is a system for designing a product (or service) based on documented customer demands - it is 'all about finding out what your customers want and assuring that features are built into the end product' [Coopers and Lybrand Ltd c.93].

QFD theory first started in 1972 at the Kobe Shipyards in Japan and has remained a popular design tool in that country. Nissan, Toyota and Honda have all embraced QFD concepts. QFD was introduced to the West in the mid-80s and USA users have included Ford, General Motors, Chrysler, AT&T, Bell Labs and Xerox. The method uses a succession of matrix techniques with, most crucially, customer demands on the vertical axis and the means by which the needs will be met placed on the horizontal axis. The roof-like shape at the top of the first Overall Customer Requirements matrix has led to the nickname 'The House of Quality' (Figure 3.3).

QFD is intended then as a technique for translating customer requirements into a product design. Customer needs, likes and dislikes are gathered via a number of established research methods that produce data in 'the customer's own language'.

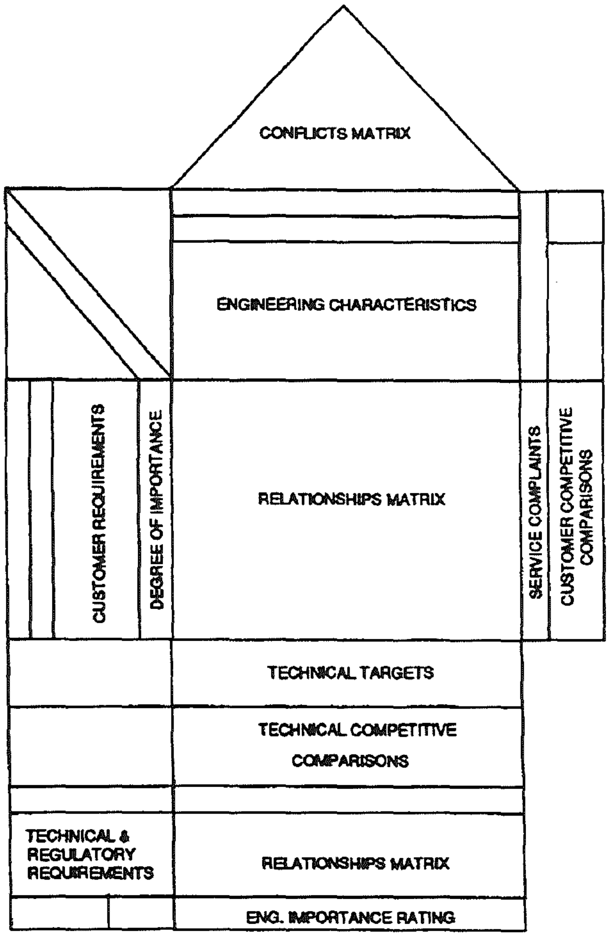


Figure 3.3 The domains of the QFD Overall Requirements Matrix

Simpler methods used include questionnaires and interviews conducted by phone or face-to-face. More involved discussion techniques are preferred: clinics bring customers together to view a product or mock up and its competition and to discuss and compare them; focus groups bring together a cross section of possible users selected at random to discuss product use issues.

The customer requirements derived from the surveys are then grouped in hierarchical categories at Primary, Secondary and Tertiary levels also sometimes known, respectively, as Strategic needs, Tactical needs and Operational needs. Most of the initial customer requirements are found at the Tertiary level, with the manufacturer thought generally to have identified his own Primary requirements. Generally-similar requirements will be grouped under convenient headings and then entered on the left hand side of the Quality matrix (Figure 3.4).

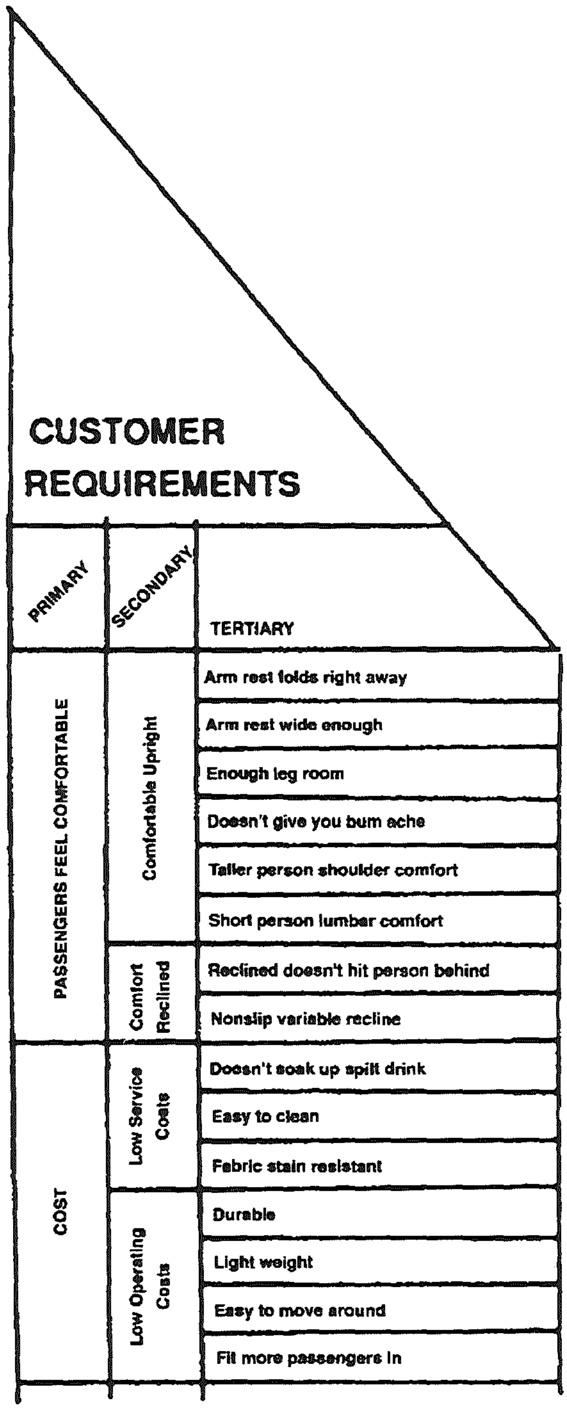


Figure 3.4 Customer requirements are mapped on the left hand side of the QFD chart

The example given in Figure 3.4 charts the customer requirements for an aircraft seat. The customers here are considered to be the *flyers* who actually sit in the chair, the *airline* and the *seat manufacturers*. The chart is intended to encompass the requirements of all three. The requirements are shown considered at their Primary, Secondary and Tertiary levels.

The main aim of the chart is to match customer requirements to engineering characteristics and determine whether the links are strong or weak - here the marketing domain, including customer-driven data, tells the company *what* to do while the engineering domain tells them *how* to do it. Relationships and conflicts can be recognised in this way and this identifies areas for improvement. It is within the rules of the QFD that each engineering characteristic must be measurable so that it can be optimised.

Within the full QFD method there are four stages of charts (with Stage 1 the *Overall Customer Requirements* matrix). The process has been criticised for lacking clarity as it progresses downwards to stages two, three and four [Sivaloganathan & Evbuomwan 97].

The QFD is about recognising a product's areas of poor performance as identified by customers and deploying resources in certain areas to change, improve, modify and refine the product. It should be noted that the QFD can really only deliver small, incremental changes suited to evolutionary rather than revolutionary product lines. This is due to a number of premises contained within the method. The discussion groups for example require competitors' products for comparative purposes - innovative new products without competitors cannot be evaluated in this way. Most requirements gained by the discussion group techniques are very much based on current expectation. Similarly, within the marketing domains of the matrix the derived target values and importance ratings can only be based on comparison with competitors' product performance.

In short QFD is 'best suited to conceptually static products for which the design elements, target values and target directions can be established directly' [Sivaloganathan & Evbuomwan 97]. This is not intended as a criticism of the QFD method, but it is perhaps worth commenting that a policy of incremental product improvement may not be enough in a climate where some believe that companies must 'innovate or die'. More radical observers like [Peters 94] assert that we are in an 'Age of Innovation' where 'the order of the day is perpetual reinvention and revolution, constant recreation, continuous curiosity'.

[Clausing and Pugh 91] among others identified this inability of QFD to handle conceptually dynamic situations. They developed EQFD - Enhanced QFD - which added more design methods to the matrix. Five enhancements were added in an attempt to improve it, including the integration of Pugh's concept selection method, means for supporting Multi-Level Deployment for complex products and static/dynamic product status checks.

Companies using the QFD and other market-research focused methods should be wary of the way in which they can aggregate customer viewpoints to produce a 'middle of the road' product solution that fails to stand out in the marketplace. [Peters 94] recalls the example of the Renault Twingo car which in pre-launch market research tests was 'actively disliked' by 40 per cent of would-be buyers and 'loved' by 10 per cent. The car's designers pressed Renault executives to listen to the 10 per cent, ignore the 40 per cent and launch. The car went on to become the second-best-selling in that French market.

One of the main differences between design specifications or requirement lists and the QFD method is that while design requirements 'reflect the engineering judgement and knowledge of prior problems... engineering targets on the other hand only reflect what is needed to assure customer satisfaction' [Coopers & Lybrand Ltd c.93]. Considering the reservations discussed above, the QFD is not thought at present to be an ideal model for recording product data.

3.2.4 Comparing the PDS and the Requirements List

The *Requirements List* is central to the VDI 2221 guideline for industry in Germany, 'Systematic Approach to the Design of Technical Systems and Products'. The aims of the *PDS* have been adopted and thus promoted by the SEED (Sharing Experience in Engineering Design) organisation and many of the PDS' main tenets have been incorporated within [British Standard 7373; 91] for integration into industry.

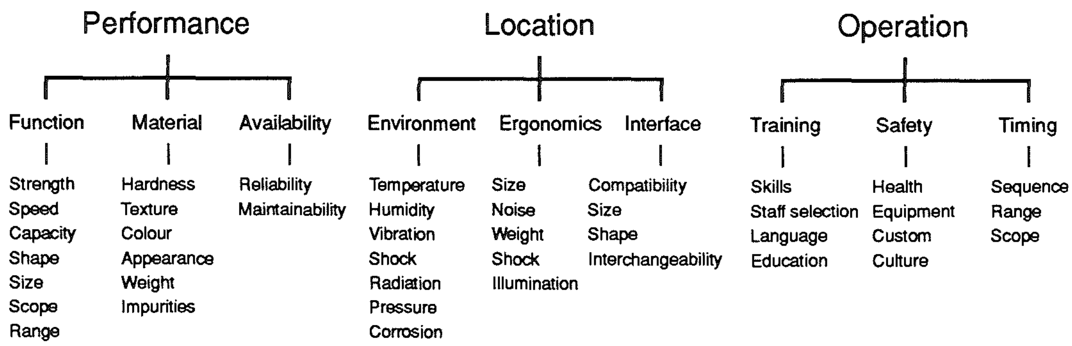


Figure 3.5 Classification headings within BS 7373

BS 7373 uses a hierarchical classification scheme to arrange up to 36 elements within various assemblages of nine sub-headings. Selections drawn from the pool of nine sub-headings create different kinds of requirements documents intended for different purposes and audiences (Figure 3.5).

The methods proposed by Pugh and Pahl and Beitz share similar objectives and perform several similar functions. Some important aims which they have in common are as follows:

- If updated during the course of the project they provide an accurate working record of the design. Both are intended to accept changes and additions which will later reflect the progress of a design project at any one time.
- Both can record the source of a particular idea in terms of its author. This makes it possible to go back to the 'proposer' and enquire his or her actual motives.
- Any updates are intended to be circulated among all involved persons and departments.
- Both make use of easily memorised checklist headings which are intended to help the designer ask the essential questions of the evolving product. The PDS utilises around 35 headings. Pahl and Beitz's method offers a choice of 90 optional element headings grouped within 16 main headings.

The main difference is seen in the more systematic approach of the Pahl and Beitz method. Their approach advocates that the requirements of the product be stated in clear order, with the product split into identifiable sub-systems, functions and assemblies and this is intended to clarify the problem.

Pahl and Beitz also give the following directions for the use of this method:

> 'Once the task has been adequately clarified and the relevant departments are satisfied that the listed requirements are technically and economically attainable, the way is clear for the conceptual design phase.'

If, as we have stated in earlier chapters, design is a contingent process, which happens despite (or perhaps because of) change and uncertainty then how can design happen if the Requirements List demands completeness before conceptual design?

This systematic approach is also implicit in the request that all individual items added to the List be defined as *Demands* or *Wishes*. *Demands* are defined as 'requirements that must be met under all circumstances' while *Wishes* are 'requirements that should be considered where possible'.

As design progresses it is common for the focus of the investigation to change, and for constraints to the design to tighten up or slacken. Thus a *Demand* in this case could be relaxed to a *Wish* - the *conscious* alteration of the status is instrumental in applying this approach correctly. In addition to this it would perhaps be useful to record the source of the original constraint and then in case of query, return to that source and ask for his or her actual intentions.

The procedures of the Pahl & Beitz method have been criticised in the design world for using a problem-focused rather than a solution-focused approach. This is thought to run counter to the designer's traditional ways of thinking [Cross 87;94] but is intended to improve upon them by avoiding fixation on one particular solution.

Observation of the Pahl and Beitz system in industry [Hales 90] best illustrates this method. In designing a gas specifier test rig, the Requirements List method initially produced a 20 page document containing 217 Demands and 91 Wishes. Once circulated among those closely involved in the project and 'corrected', 72 Demands and 20 Wishes were modified. With the specification 'agreed' before conceptual design could begin only *two* items were changed throughout the rest of the process. This is not intended to overtly constrict design but to make it more efficient. Certainly it is not the case that no concepts were created in the above example.

Whether or not to reformulate the problem and requirements throughout the process is a controversial issue [Blessing 94]. Descriptive studies show that reformulation is inherent in design but application of approaches suggested in prescriptive literature may help to improve the process and limit the number of reiterations by methodically checking that all issues have been discussed.

If the strictures of the Demands and Wishes approach can be overcome and the Demands are allowed to be relaxed, replacing a policy of 'All Demands must be met under all circumstances' with one of 'everything is negotiable' [Minneman 91], then the Requirements List becomes a more attractive proposition for designers. Used correctly both this and the Pugh method provide flexible means of avoiding early fixation on a solution, recognising the ill-defined nature of design particularly evident within its early stages.

Instead of starting bipartisan arguments over the respective merits of the Pugh and Pahl & Beitz methods it should be recognised instead that both encourage a systematic approach that reduces the load on memory of the designer by providing better access to design information. This avoids fixation on one particular solution and frees up mental effort to be devoted to creating solutions.

Both might be improved by adopting capabilities of computer processing. The capture of design information is presently less than dynamic and still predominantly paper-based, despite the huge advances in processing power and availability of computing tools that have occurred in the last twenty-five years or so. Word Processing packages have certainly had an impact but have been less than revolutionary in this field. WP packages have improved the appearance of documents and allowed comments to be changed very quickly without the need for laborious re-typing. The mechanical process of reproduction on paper however still only provides changes as large, discrete chunks rather than distributing them 'on-the-fly' as they are made.

A well-known manufacturer of hi-fi products follows the Pugh method to record the evolution of a design. Written requirements documents are updated 'at the end' of each recognised phase of the design process, to produce four intermediate documents and a final specification 'an inch thick'. The size of this final report seemed a source of pride to the managing director. Accessing specific information from a pile of paper of any size up to an inch thick will inevitably be problematic and slow. Access could perhaps be improved by computer methods. Some attempts made to offer computer support to the listing of requirements and thus the recording of the design process are discussed in the following section.

3.3 Computer-Based Requirements-Handling Methods

Most of the experiments with computer systems for use in preliminary design have been a limited success [Jakobsen *et al* 91]. The following discusses work carried out into supporting the building of specifications and the recording of the inputs to the design process. Particular note is made of their suitability in supporting the early stages of design where ill-defined problems must form the shaky foundations for a strong project.

In the domains of artificial intelligence and information technology, recent work has followed different paths. AI approaches have centred around attempts to create a problem-solver [Navinchandra 91], while others have expanded on frame-based knowledge representation to create relational databases recording inputs to the design process [Tsiotsias 95]. [Ullman 95] has proposed a decision support mechanism that captures subjective opinions expressed within group design activity.

DESMATE is a computer-based design environment developed using Apple's Hypercard software [Culverhouse, Ball and Burton 92]. Intended to remove much of the drudgery associated with the analysis of design protocols, this prototype system sets out to provide an automatic means for collecting and analysing design data. The authors claim it to be a rich and varied database of useful information relating to the design of electronic circuit networks with added facilities enabling rapid access and manipulation of this information.

The building block nature of electronic design tasks, dealing in hard and fast certainties and parameters, is of limited scope when compared to the capture of more nebulous and subjective data and ideas which this project addresses.

The GUIDE system is an almost fully functional computer tool developed through industrial consultation [Tsiotsias 95]. The system - whose acronym stands for Glasgow Utility for the Integration of Design - aims to build multi-dimensional product models which also enable traceability and audit of the design. It improves communication between proprietary computer systems and other software tools.

GUIDE understands information expressed as stereotypes - structured pieces of knowledge about entities, processes and functions. These can be used to describe such engineering features as, for example, 'a hole', which has a certain geometry, diameter, depth, position and so on. Ideally GUIDE can create accurate, generic definitions such as these from any instances of data provided. These generic representations can easily be adapted or changed as the process progresses, thus providing a dynamic model.

At earlier stages in the design activity product definition will be weak, and GUIDE aims to support this by allowing the specification of relaxable constraints, bounding values and performance criteria. GUIDE does not seem geared to defining the problem as opposed to defining the product. GUIDE's primary utility is the way in which it adds value to CAD models of the product. While it demonstrates an affinity with dimensionally-defined CAD models, GUIDE shows no real possibility of linking to requirements lists at the conceptual stage and as such is more suited to dealing with reasonably well-defined representations of component assemblies and geometric solid models such as are found within the embodiment and detailing stages of design. This is of limited use with reference to the earliest stages of design and the handling of raw ideas and opinion without physical form and parametric data which, most important of all, is happening outside of the CAD workspace.

While it is easy to imagine systems that are amenable to the capture of numerical data, it is more difficult to find a system that sets out to capture subjective, textual descriptions and data that contain uncertainty and may produce conflict. EDSS software (Engineering design Decision Support System), an interface and database constructed in a PC Windows platform, recognises that design groups will often encounter problems which require subjective interpretation in the absence of hard information, especially in the early stages of a project [Ullman 95].

Interface windows allow a group of designers to enter their feelings on each particular problem. Their suggested alternative solutions can then be discussed within the computer environment. Criteria for evaluation can be entered by the designers but, most innovatively, each designer can also admit their particular 'knowledge' on the subject and their relative 'confidence' in their own solution.

The criteria are given relative weights by the design group and probability techniques are then used by the computer to operate on the input provided. Though this may seem rather convenient in its reducing a complex problem to numbers, the system 'does not tell the team what decision to make'.

Each change made is recorded in the developing database, thus providing a complete record of the evolution of the device; each entry is 'time stamped' for later historical use in a design history or design intent system. Ullman recognises the need to extend this research to tackle the following issues:

- The system currently works only on single issue design problems: it will need to be extended further in order to link inter-dependent problems. If this were possible decisions could be made by recourse to linked requirements list data.
- The inputs made by the designers is exclusively textual at present (i.e. information is represented by word strings) and Ullman recognises the need to extend EDSS to capture design sketches and graphical work. This is an important issue which this thesis discusses at length.

Ullman's system, now running in its early testing stages on a laptop computer in industrial design situations, is one of the most obviously useful prototypes intended to support the conceptual stage of the design process.

PROSUS (PROcess-Based SUpport System) is another computer-based system, which is intended to document both the design process (design rationale) *and* the product by combining the two approaches in a design matrix [Blessing 94]. The Design Matrix maps activities to issues and so represents the design process as a structured set of problem-oriented issues and activities. The Design Matrix is the workspace for the designer and suggests possible avenues for design by structuring and documenting their activities. The structure of the matrix and the steps it suggests are expected to increase awareness of the process and encourage the various steps to be addressed.

The system comprises of the Design Matrix, a Strategy Matrix (the control level) and a Procedure Matrix (support level). PROSUS claims to be able to document any type of project data anywhere in the system - this includes text, calculations and sketches. In recognising the importance of sketches and attempting to include them within the system, PROSUS is unique among the sample discussed here.

PROSUS captures sketches using an ingenious low-tech hardware solution. A ballpoint pen is connected to an electronic tablet drawing system and so works both as an ink pen and as an electronic stylus. The designer sketches onto a sheet of paper placed over the tablet surface and in this way the designer can sketch as normal, while the PROSUS system retains the impression as a rough digital copy. If possible this thesis aims to give added value to sketches inputted to digital systems in similar ways.

It is important to note how these and other computer-based support tools largely reflect the software designer's underlying understanding of the design activity. A model like the EDSS system (a so-called *descriptive* model), based on protocol studies, seems more plausible than those which are merely prescriptive and operate on stereotypical representations of design. As [Dorst 95] commented:

> 'A better insight into the cognitive behaviour of designers is widely seen as a prerequisite for developing effective and efficient design support tools.'

The following section examines protocol research into the apparent structure of the design task and assesses the bearing this research may have upon the structure of a computer-based method or model intended to improve design communication and enable the recording of the process.

3.4 Structuring the Specification and the Design Task

A design specification and recording system based within a computer will require some kind of structure, since computers work in logical ways. [Kuffner & Ullman 91] propose an intelligent system be developed to capture, structure and re-play information inputted to the design specification and record. They suggest that such a system could *automatically store* relevant design information and, furthermore, *structure it* in a useful manner.

This structure must be subservient, however, to the structure of the activities performed by designers, rather than imposing an unrealistic, inflexible structure upon them. The genuine structure is best found through studies made of designers at work solving problems. [Davies 95] and [Dwarakanath & Wallace 95] have carried out research into the initial approach used to tackle a set engineering design problem.

[Owen 92] believes that a problem is understood via the collection of detailed information and the success with which the problem is tackled can be gauged by how thoroughly it seeks out the functions which the solution will perform. Thus a top-down analysis is performed, establishing a function structure and breaking down the solution into three hierarchical levels of operation (Figure 3.6). At the highest level are *modes* of operation and Owen considers typical modes to be; *production, distribution, specification, transport, sale, use, storage, maintenance, repair, adaptation, retirement*. If each of these could be clearly defined and understood then this would act as a classification scheme - a stereotypical way of categorising something in order to make it easier to store compartmentally. Unlike the system of [Pugh 90], which allows entries to be made within horizontally distributed element fields, Owen's system also deals in vertical decomposition. Do such top-down decompositions of the problem match the way in which designers tackle a problem?

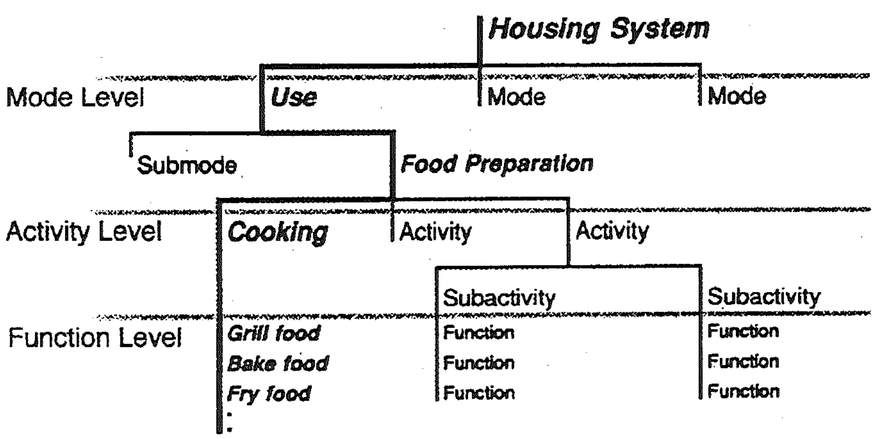


Figure 3.6 Design as a three-level process [Owen 92]

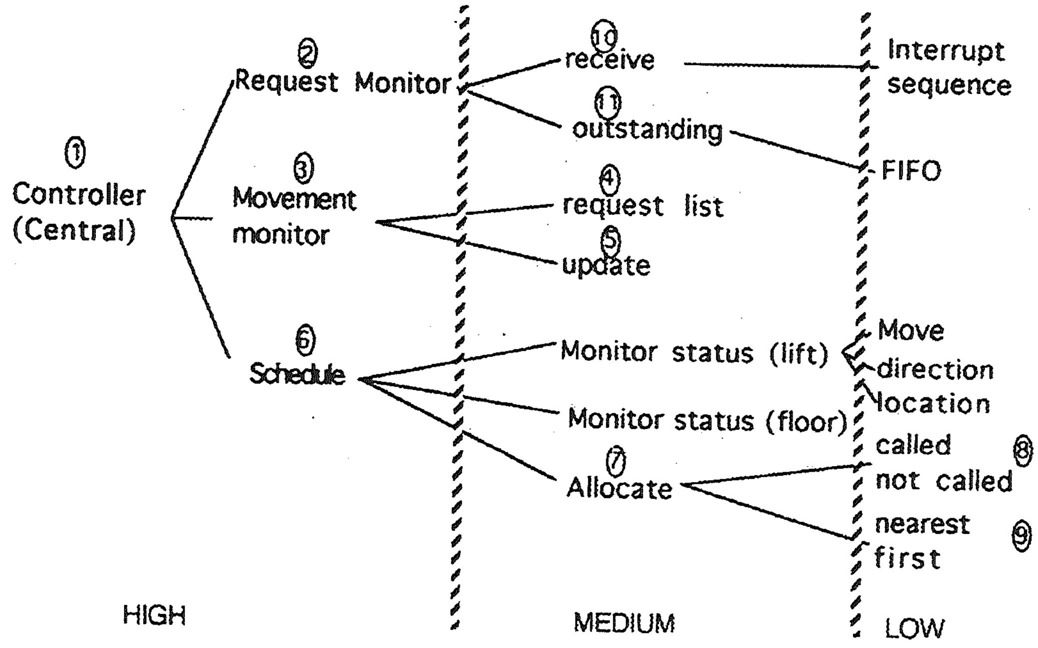


Figure 3.7 A schematic representation of opportunistic design decomposition (Davies 95)

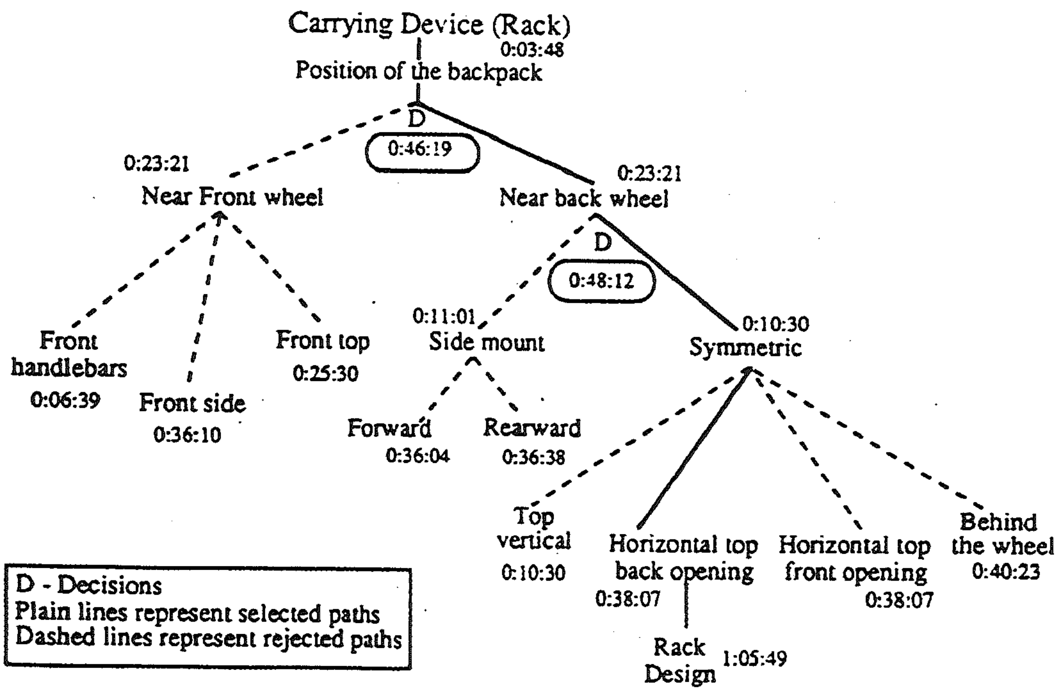


Figure 3.8 Design approach adopted by an individual designer (Dwarakanath & Wallace 95)

The description of [Davies 95] discusses decomposition of a design problem, and, like Owen, sees the problem as being tackled and thus understood at different hierarchical levels. Figure 3.7 illustrates the sequence of thinking for an observed individual designer: the circled numbers represent the temporal sequence in which the design was 'decomposed'. The fact that the high level segment 'Schedule' is numbered (6) demonstrates an opportunistic mode of thinking - the designer has felt that he can go to a lower level of abstraction (further decomposing (3) the 'Movement of the Monitor') before returning to (6) at a higher level of abstraction. Thus Davies disagrees with any simplistic notion that designers tackle problems using a strictly top-down approach. If the top-down decomposed structure of the problem is seen as a tree, then perhaps the metaphor could be extended to let us think of the designer as a monkey playing in that tree, swinging and leaping from one 'branch' to another?

[Dwarakanath & Wallace 95] make use of protocol studies to illustrate such a hierarchical approach. Their examples deal with the same problem - that of designing a carrying rack for mountain bikes - tackled by both an individual designer and by a three person group. The authors believe that the designers will first identify the *issues* involved, select the issue that they consider most important, generate *alternatives* for its solution and then develop and evaluate them through *argument* and *discussion*, either with themselves or with the other members of the group.

In utilising the breakthrough concept of recording the activity in real time, the decision path can be followed directly (Figure 3.8). The example of the single designer working on the problem shows again how in several instances he or she will jump from certain issues without resolving them and address other issues before returning to 'where they left off'. In addition Dwarakanath and Wallace make explicit the 'decision points' in the activity (marked 'D' in Figure 3.8). Like the work of Davies, the research shows how designers tackle problems in an opportunistic manner which is never truly top-down. [Nanard & Nanard 95] also view the design process as an opportunistic activity with 'erratic' switching between top-down and bottom-up thinking processes. Dwarakanath and Wallace, from their studies of design in groups, believe that groups are more systematic and less opportunistic than individuals.

Groups then can follow the problem-oriented approach better while individuals tend to be more solution focused. A top-down problem system structured using hierarchical, linked principles should not be imposed upon the designer, but if *suggested* could help guide the designer away from fixating on solutions.

Because of this apparent mismatch, a free problem space is proposed. The structure which the computer uses to capture, store and 'play back' inputted information should be *suggested to* the user, who is nevertheless free to use any 'entry point' to the problem that they wish while being reminded of important linked issues that may affect the part of the problem which they are currently working on. The PDS of [Pugh 90], with its horizontally-distributed, non-decomposed and open classification scheme provides a visible memory aid to the designer which may, if suitably adapted to a computer-based model, prove useful to a designer wishing to input problem insight and design information. Thus we have a structured problem that the designer can be made aware of if need be, operating behind the open problem interface which the designer uses to access the problem.

If it is true that the Requirements List is problem-focused and the PDS product-focused then it may be that the former is required to undergo a transition or mapping to the latter. That is to say that the design record evolves from the Requirements List at the earliest stages to the PDS at a later phase.

Contrary to this Pugh always intended, however, that the PDS could be used to enshrine the problem *and* the product: his belief that 'in total design terms design must never be started without a PDS' [Pugh 90] illustrates the intended utility of the PDS at all phases of design. Among a variety of alternative titles the PDS has been known as the 'Statement of Requirements' [Hollins and Pugh 90] and this demonstrates the similar intentions between this and the Requirements List.

It may be that in practice both carry virtually the same kind of information - that the product is an answer mapped exactly and seamlessly to the problem. If not then an ideal solution may involve matrices for each superimposed to map problem-focused to product-focused information. In summary, the important fact is that both methods have the potential to enable the recording of design intent and this is what matters most within the context of this thesis.

3.5 Use of Requirements-Handling Systems in Industry Today

3.5.1. Paper-based systems

The onus for formal information delivery during engineering design has, to date, fallen upon the PDS [Pugh 91]. Now common practice in industry, the PDS and its variations [British Standard 7373; 91] evolve in discrete stages with revisions distributed as the design progresses [McGown & Green 95]. BS 7373 describes the ideal specification as including numerical statements, algebraic equations, drawings, graphics, charts, tables or methods of computation.

In practice most companies using the PDS method will use a paper-based PDS which may on completion include a few illustrations of the proposed final arrangement of a product and some tables of quantitative data targets besides plain text material. However the mechanical methods of PDS compilation currently employed render it too static to allow for change. This lack of dynamism may be acceptable to firms which deal largely with incrementally-changing products rather than innovative products and open-ended problems. Nevertheless, the document is still complex and laborious to assemble and the onus of editorship is often placed upon one Product Manager. (Figures 3.9 - 3.11) are examples of pages from a PDS used by a vacuum cleaner manufacturer. Note that these are from the near finished Specification document presented to the manufacturing facility, rather than from the earlier stages of the project.

Figures 3.9 & 3.10 Examples of pages from a PDS document produced by a UK vacuum cleaner manufacturer

PRODUCT DESIGN SPECIFICATION - ORCHID

Doc No: PDS-001
Revision: 01
Date: 23-12-94
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8] MANUFACTURABILITY

8.1 GENERAL ASSEMBLY

Using 2-off Paced Assembly Lines with minimum off line printing or sub assembly work.

Material supply to Paced Lines will be Kanban location controlled with lineside delivery arranged where possible.

8.1.1 Manning Levels

Manning Comparison for a 10,000 Per Week Schedule

OPERATION	T/POWER 3	ORCHID
GENERAL ASSEMBLY TEST & PACK	88	80
HOOD PRINT & ASSEMBLY	5	-
CHASSIS PRINT & ASSEMBLY	-	3
DOOR PRINT & ASSEMBLY	5	3
TOP COVER PRINT	1	-
INSPECTION COVER ASSEMBLY	1	-
HANDLE ASSEMBLY	5	5
NOZZLE HEIGHT KNOB	1	-
AGITATOR BODY LACING	3	3
END BRUSH LACING	-	
AGITATOR ASSEMBLY	6	4
NOZZLE PLATE & CARRIER WHEEL	2	2
MOTOR ASSEMBLY	42	42
TOTAL	159	142

The above figures are direct operators only and do not include material handling, repairs or absence cover.

PRODUCT DESIGN SPECIFICATION - ORCHID

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3] PERFORMANCE

3.1 1000 WATTS CLEANERS

3.1.1 Air Performance Data - Through Nozzle - IEC.312
Maximum Airflow : 24dm³ /sec.
Maximum Suction : 900mm. H_2O
Maximum Suction Power: 45 Watts
Agit.Speed on IEC Carpet-Hgt.Setting No.1-3500rpm.Nom.

3.1.2 Air Performance Data - Through Hose - IEC.312
Maximum Airflow : 30 dm³/sec.
Maximum Suction : 1700mm. H_2O
Maximum Suction Power: 170 Watts

3.1.3 Pick Up Performance from Carpets Data - Through Nozzle - IEC.312
Dust Removal Performance : TBA
Difficult Litter - Strokes to Clean : Kapok - 3 ; Rayon Tow-2
Fibre Removal : Swept Width - 265mm; No. of Strokes 2.2; Fibre Removal Ability - 120
Dust Removal Along Walls - Left Unclean : Front - 25mm; Left Side - 0; Right Side - 0
Thread Removal : % Removed-100%; No.on Nozzle-None
Motion Resistance - Forward/Return - 10/16 Newtons

3.1.4 Dust Receptacle Capacity - IEC.312
Paper Bag - 4.5 Litres
Permabag - 2.5 Litres

3.1.5 Dust Emission - DIN E44956 Part 2A
Models C & E - Good+ 0.11 to 0.20 mg/m³
Model D - Very Good++ 0 to 0.10 mg/m³
Filtration to be a suitable combination of materials for dust receptacle, pre motor filter and exhaust filters to achieve stated dust emission criteria.

3.1.6 Noise Level - IEC.704-1
Overall Noise Level : Sound Power LwA
Maximum Speed - 85dB(A)
Medium Speed - 83dB(A)
Low Speed - 81 dB(A)

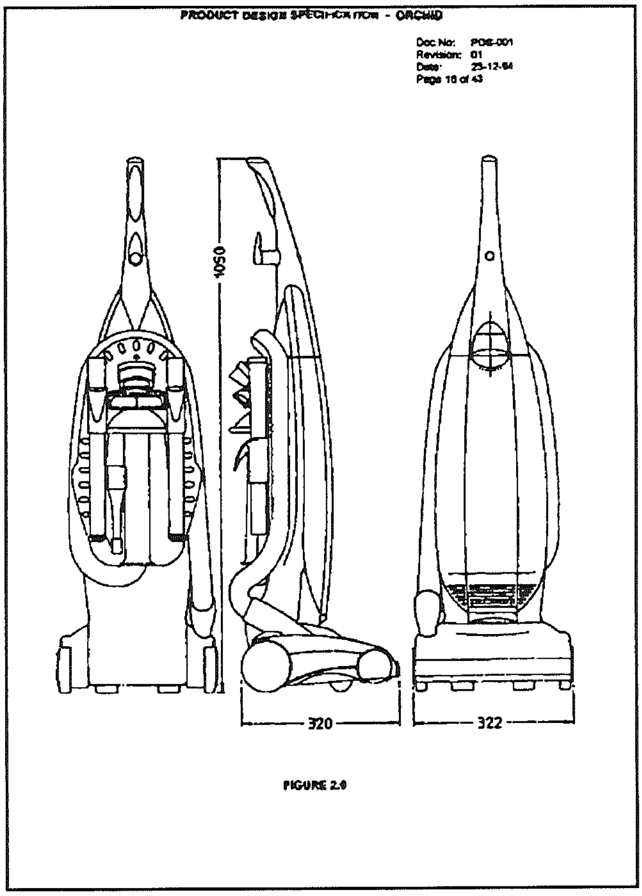


Figure 3.11
Example of a PDS document produced by a UK vacuum cleaner manufacturer

3.5.2. Commercial software systems

Commercial software solutions made available in the last few years may at last offer a replacement for paper-based systems and could signal the end of these attendant problems. The two front-runners at present are;

- DOORS (Dynamic Object Oriented Requirements System) by Quality Systems & Software
- Cradle by 3SL

DOORS is described by its makers as a requirements management and information traceability tool and aims to keep requirements simple by expressing the information as a hierarchically-organised set of text and tables [Quality Systems & Software 98]. DOORS is based on 'object-oriented' organisational polymorphism, re-use, association, relationships and inheritance. This approach is thought to offer an improvement on relational database approaches.

DOORS does not impose a set design methodology but instead comes with a choice of many structured specification systems and standards, such as the software engineering standard PSS-05. While there are many templates, any company can reprogramme and replace them with their own method using the DXL scripting language on which DOORS is based.

The functionality of DOORS is based on the following identified needs of a modern requirements handling system;

- Creation of individual structured requirements
- Linkages between structured requirements
- Publishing of requirements documents
- Connectivity to tools for design, development and testing
- Linkages to descriptive documents

The first three of these are possibly the most important aspects of requirements handling. DOORS is intended to fulfil these needs by providing for document management, handling requirements, handling traceability and providing design histories, linking to other computer tools and providing input to decision-making situations. There are, then, five main functional aspects to the DOORS tool;

- *Document Manager*: DOORS aims to present requirements as objects in documents, rather than as records in a database. Requirements can be changed as if typing into a word processor and the system is geared to producing published versions for distributing to team members. Published versions can be tailored to different audiences, producing shorter or longer documents from a consistent data set.

• *Handling Requirements*: Users can navigate through requirements documents by way of a graphical view which illustrates the document's structure of links and associations. DOORS also claims to be able to create links to unstructured documents such as letters and descriptive text written in a word processor. It does this via automatic parsing routines intended to extract all requirements.

• *Handling Traceability*: DOORS provides complete history back up of every change to every object; any set can be selected by date or any other of the system attributes.

• *Links to other computer tools*: DOORS can handle input from many other applications, particularly WP programs like Word. The add-on product DOORSNet allows DOORS documents to be accessed over the World Wide Web.

• *Decision-Making facilities*: Teams of designers can view each others work and suggestions and the system allows for the management of complex, structured decision nets via a hierarchical network of decisions stored as DOORS data. The graphical visualisation tool allows decision-making designers to quickly assess the impact of certain choices.

3SL's Cradle tool likewise aims to provide a 'clear and simple means of gathering and refining requirements' within an all-encompassing systems engineering environment [3SL 98]. Designed to suit the needs of the software development process it handles requirements through the use of five main functional aspects:

• *Requirements Management tool*: dealing with source documents this facility can identify differences between versions of documents and automatically produce impact analysis reports. With its links to other applications Cradle can store graphs, spreadsheets, tables and diagrams within requirements lists.

• *Systems Modelling tool*: By object-oriented methods Cradle can produce requirements in terms of function block diagrams and behaviour diagrams; methods used are switchable at different points in the process.

• *Document Management tool*: Cradle includes two thousand report formats while templating tools allow replication of company standard formats if preferred. Cradle can be linked to DTP packages such as Word and FrameMaker.

• *Core Linkage*: Cradle brings together externally-generated information such as is contained in CAD, spreadsheet and DTP files.

• *Software Engineering tools*: These domain-specific tools support vital software engineering operations, supporting code generation and handling C, C++ and other programming languages.

Initially-designed for use within the software engineering industries, the benefits that Cradle and DOORS promise will prove hard for those involved in the product and manufacturing industries to resist. Research efforts will hopefully soon assess the effectiveness of such commercially-available packages within the engineering design domain.

3.5.3 Shortfalls of current systems

According to a recent study [Nijhuis and Roozenburg 97] design engineers recognise the PDS as having five main functions in the following order of importance:

1) It is a tool for communication between design group members as well as with third parties;
2) It is a means for delineating ideas, helping to demarcate the boundaries of the solution space;
3) It provides guidance for the design process, determining whether the project is still on the right track;
4) It acts as a contract - either an internal agreement or occasionally a legally binding document between consultancy and client;
5) It provides criteria for evaluation and decision making - the PDS is the basis for determining the value or quality of design proposals.

The importance levels imply that the PDS is used as a catalyst for design change and is too inflexible to be used as a recording device to allow evaluation. Ideally it should allow designers to perform both roles equally well, leading to as complete a final document as possible.

[Hurst and Hollins 95] contend that the main reasons for failure of product in the market are inadequate market research and inadequate specifications. Their case study contends that commonly there is little development of any form of requirements or specifications once the project commences and that there is no formal documentation of any changes made.

The same study also contends that the two main reasons for a poor specification are *omissions* and *misleading requirements*. If a specification is considered complete only when it includes comprehensive requirements for all areas of concern then the use of checklists of relevant criteria has been shown to prevent the overlooking of important aspects. Pugh's method and BS 7373 both use checklist-type ontologies. BS 7373 gives some common sense guidance on the layout and preparation of specifications. It tries to ensure that all aspects of design are covered via a suggested ontology consisting of three major headings, nine sub-headings and thirty-five or so elements under one-word titles.

Misleading requirements are common - each person involved in the design process must have a clear and unequivocal understanding of each statement so it is important that the properties prescribed have the same meaning to all [Bucciarelli 94]. BS 7373 can only suggest that 'double meanings should be eliminated' and stresses that 'clarity is essential'. The ambiguity of natural language is widely recognised [Goel 95].

Additionally, 'non-entries' are commonly made under element headings. Agreement on performance requirements is easily reached if participants focus on self-evident, easily accomplished features rather than specifications of substantive content requiring more serious negotiation [Bucciarelli 1994].

Such bad practice should not be confused with the exploratory nature of conceptual design. Iterative processes are often founded by necessity on 'weak' information and while BS 7373 asks that attributes should be defined in purely objective or quantitative terms, it should be recognised that conceptual design often deals in qualitatively expressed ideas and information.

At least two of the drawbacks inherent in current specifications - misleading requirements and ambiguous statements - stem from the almost exclusive use of text-based information. Bearing in mind the experimental finding that 67% of the marks made on paper during conceptual activity are sketches [Hwang and Ullman 90] then the PDS and other methods of collecting design information could be improved by more readily accommodating visual material in addition to textual information.

Long-standing problems in capture and reproduction compared with that of written and typed material seems to have led to a belief that only text can be used in compiling design records. If, as the old saying goes, 'a picture could be worth a thousand words' then new technologies may now make it possible to handle both visual as well as written work and the use of drawings could help to alleviate some of the problems caused by text omissions.

3.6 Discussion

This chapter has studied the methods used to list product requirements for communicating and recording design information and makes the following conclusions.

• The need for improved communication of information within industry has been identified. A lack of robust recording methods has also been noted.

• The dynamic nature of Pugh's PDS or Pahl and Beitz's Requirements List and their inherent provision for updating will allow for the distribution of up-to-date product descriptions and also build to provide a record of the evolving design.

• The paper-based nature of compiling requirements lists has so far reduced their dynamic potential and made retrieval of historical information time-consuming. New computer-based requirements-handling systems developed for software engineering may, however, solve many of the problems associated with paper-based systems.

• From the literature, protocol studies have identified the opportunistic behaviour of the designer with regard to problem-solving tasks. A decomposed problem structure can help guide away from fixation on narrow product solutions. The horizontal distribution of the classification scheme in Pugh's PDS has been identified as a possible method for recording the designer's thinking on the product. Its checklist of requirements is thought to guard against omission and in addition a Requirements List reminds the designer of aspects of the problem. Both methods offer systematic frameworks within which design information can be recorded.

• The limitations of text-only information have been identified and it is suggested that a specification system will be improved by the inclusion of visual design data in addition to written data. New digital technologies may now make visual material easier to handle than in the past.

In response to the final conclusion given above, the following chapter examines the use of visual descriptions in engineering design, and in particular the conceptual sketch.

CHAPTER 4
THE ROLES OF SKETCHING IN CONCEPTUAL DESIGN

The designer's sketch is an integral part of the early phases of product design engineering. The majority of designers appear to have adopted freehand sketching as an invaluable part of the process [Lawson 94] [Pipes 90]. Drawings are still lost and thrown away without much care or thought for future use however [Pipes 90] [Bucciarelli 94]. In recent years attempts have been made to support aspects of the sketching process using computer methods [Lakin 89] [Hwang and Ullman 90] [van Dijk 95] [Gross 96] [Tovey 97].

4.1 Functions and Types of Sketching Activity

Visual representations are omnipresent throughout the design process, from early sketches to CAD-rendered general arrangement drawings. Cross uses drawings from each stage to illustrate the type of work that goes on as a design progresses [Cross 87;94]. The example concerns the design of a small cement mixer. In the order shown these drawings illustrate increasing degrees of concretisation and detailing [Andreasen 94] (Figures 4.1 - 4.3).

Within the earliest stages of design the sketchpad is used to express ideas and has been referred to as the medium of reflection-in-action [Schon 83]. Schon suggests that through drawing, designers construct a 'virtual world' where the drawing reveals qualities and relations unimagined beforehand. Sketches are representations which will often allow the designer to 'try out' a new idea on paper, quickly and cheaply. Schon also notes that while drawing can be rapid and spontaneous, its residual traces are stable and can be subsequently examined by the designer at his or her leisure.

Despite its importance in the design process, the sketch has a perceived low status, its true value hidden by the modesty of the designers [Lawson 94] [Pipes 90]. Though it is one of the most tangible artifacts produced directly by conceptual activity [McGown and Green 97], Schon's 'stable traces' may not be kept for subsequent use. When a project is over, early exploratory drawings are often destroyed and cleared away to make room for the next job [Pipes 90] [Bucciarelli

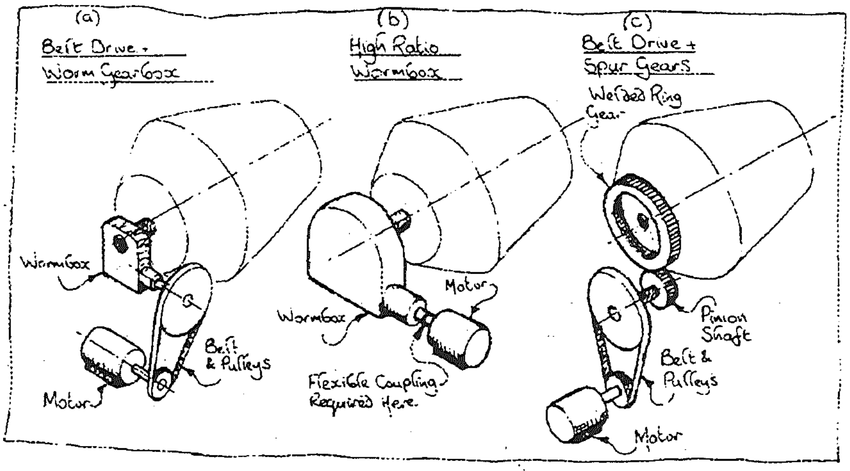


Figure 4.1 Drawings from the conceptual design phase, of three alternative solutions (Hawkes and Abinett 84)

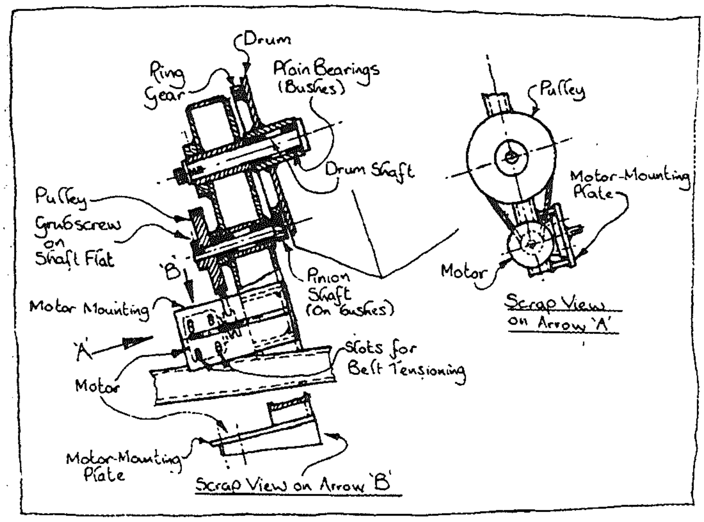


Figure 4.2 Drawing from the embodiment phase (Hawkes and Abinett 84)

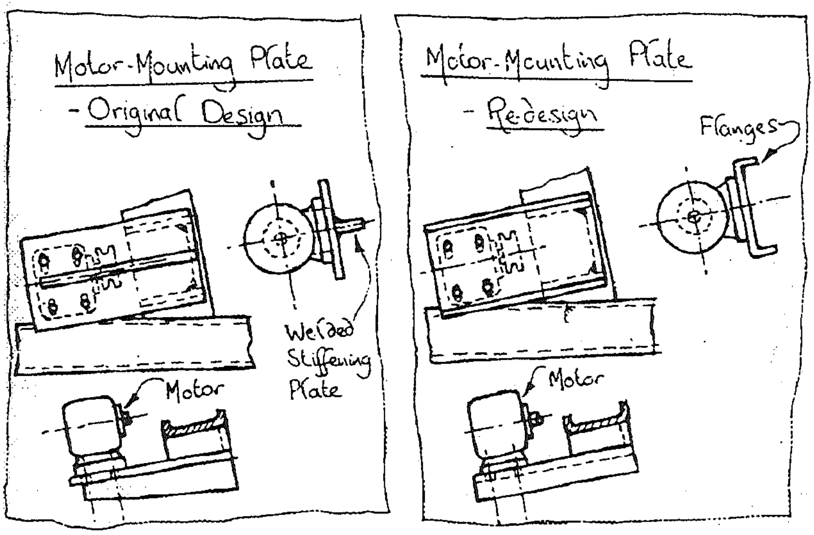


Figure 4.3 Two drawings from the detail design phase (Hawkes and Abinett 84)

94]. The permanence of the sketch has perhaps been overlooked in favour of its spontaneity. The sketch may possess the potential to act as both facilitator *and* recorder of creative acts [Temple 94] presenting opportunities for improved evaluation and the re-stating of problems.

The flexibility of freehand methods mean that there are many different types of sketch, even within the conceptual phase. Some are of particular interest within the scope of this paper, others less so.

[Ferguson 92] sees the designer as using sketches to try out new ideas, to compare alternatives and - most importantly to his mind - to capture 'fleeting ideas' on paper. He identifies three kinds of sketch:

1) The *thinking sketch* which engineers use to focus and guide nonverbal thinking;
2) The *prescriptive sketch* made by an engineer to direct a draftsman in making a finished drawing;
3) The *talking sketch*, produced during exchanges between technical people in order to clarify complex and possibly confusing parts of the drawing. Ferguson recounts how a sociologist of his acquaintance observed designers actually taking the pencil from one another as they talked and drawing together on the same sketches. The talking sketch is a shared graphical setting which enables discussion.

The second kind of sketch does not concern us here as it is used almost exclusively within the latter detailing (pre-manufacture) phases of the design process.

Furthermore, a sketch is likely to be made for one of three reasons [Temple 94] and from one of three sources:

1) To communicate the physical nature of an entity conceived in the imagination;
2) To visually recall the physical nature of objects or environments from memory;
3) To make a quick visual representation of entities or environments exposed to the naked eye.

The ability of the sketch to somehow make real an imagined object is of prime importance. The ability to communicate remembered objects is also of interest. In engineering this utility can often help to explain mechanisms like cams and gears to oneself or to another. This function is broadly similar to that of Ferguson's 'talking sketch'.

Figures 4.4 and 4.5 are from a speculative futures project carried out by professional designers and illustrate what a conceptual sketch may look like. The lines are crude and hasty, the hurried and indefinite quality expressing what is perhaps a necessary indecision.

4.2 The Cognitive Psychology of Sketching

A number of studies in the field of psychology have explored the possible workings of the mind with respect to processing and understanding visual information. A few have attempted to explain the production of visual representations from the 'mind's eye'. From this body of work there is some consensus between theories of the processing of visual information in the human mind and the underlying processes behind creating visual representations of ideas on paper.

First we must understand that seeing is not the same as understanding. Understanding, or the *visual percept*, is something above and beyond the more mechanical recording of the 'patterns of light' viewed by the eyes and projected onto the retina. The perception of qualities such as shape is the grasping of structural features found in, or imposed upon, the stimulus material [Arnheim 69].

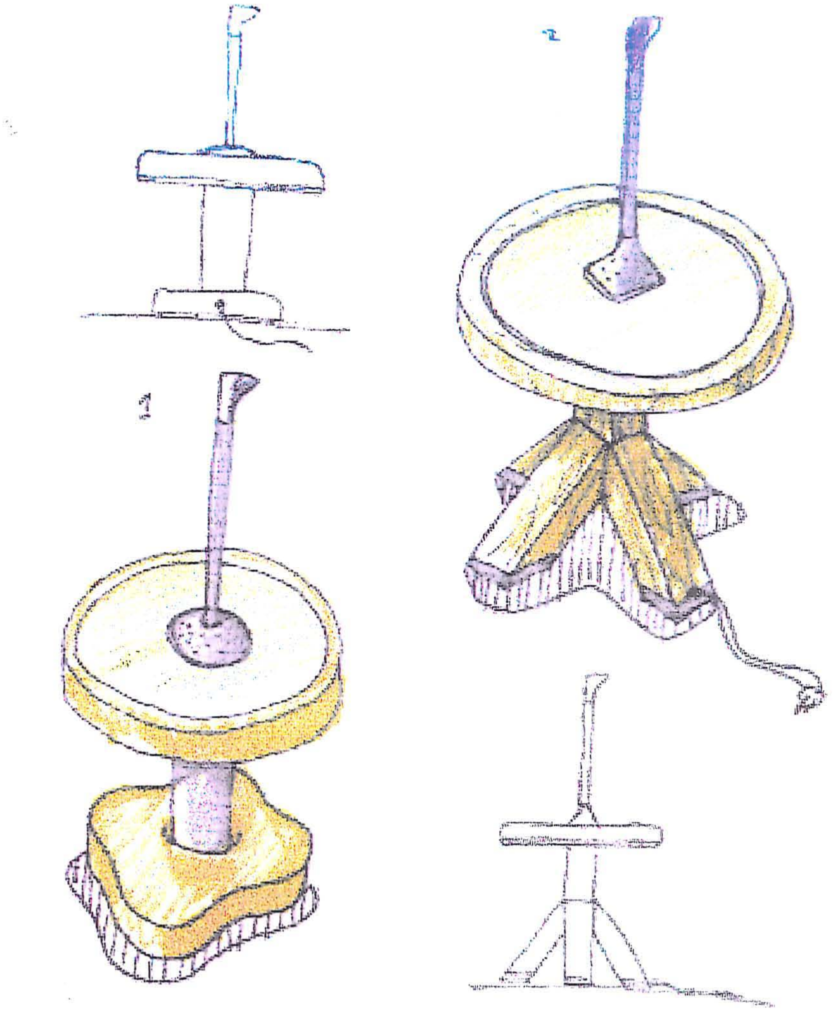


Figure 4.4 Internet table: sketch from speculative futures project in industry
(sketch courtesy of Philips, Eindhoven)

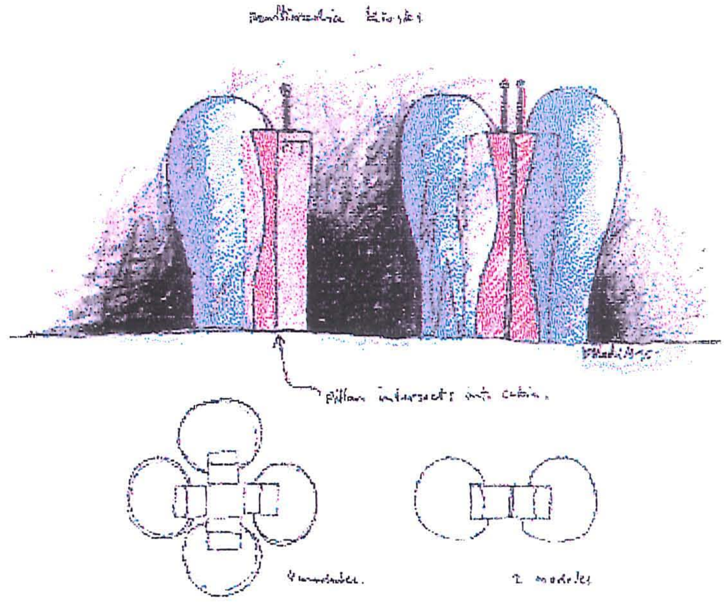


Figure 4.5 Multimedia kiosk: sketch from speculative futures project in industry
(sketch courtesy of Philips, Eindhoven)

Arnheim's is one of the earliest studies into the psychology of producing visual images, in this particular case paintings and other such 'works of art'. He acknowledges the difficulties in studying the processes that allow the unseen to become the seen, suggesting that such processes may even occur below the level of conscious thought. Seventeenth Century artist and intellectual Frederico Zuccari distinguished between inner design, the *disegno interno* seen in the mind and the *disegno esterno* rendered on the canvas. Of drawings Arnheim says;

> 'At best mental images are hard to describe and easily disturbed. Therefore, drawings that can be expected to relate to such images are welcome material.'

Arnheim also suggests that;

> '[Drawings]... cannot be faithful replicas of mental images but are likely to share some of their properties.'

Arnheim adds that drawings, unlike mental imagery, are mediated and determined by material conditions (the availability of drawing tools) and also tempered by some sort of aptitude or ability on the part of the 'artist'.

Arnheim's early study focuses on the visualising of *emotional* content in painting and other fields of artistic endeavour and while it borrows from the sciences is not a truly scientific study. It does however make some interesting observations. One such observation is that;

> '...there [is] much evidence that truly productive thinking in whatever area of cognition takes place in the realm of imagery.'

By the mid-1980s studies of cognition were based on scientific approaches and computational theories of mind. The study of visual cognition was divided by this time into two subtopics; *visual recognition* and *visual imagery*. The first studies 'the representation of information concerning the visual world currently before a person' [Pinker 84]. Visual recognition is the process which allows us to determine, on the basis of retinal input, that particular objects and scenes are in front of us. The second subtopic of visual imagery is what concerns us here. This is the process of;

> '...remembering or reasoning about shapes or objects that are not currently before us but must be retrieved from memory or constructed from a description.'

Pinker concedes that imagery is a more difficult topic to study than recognition and consensus is more rare. The scientific study of imagery is mostly concerned with the 'more pedestrian' spatial abilities such as memory for literal appearance and matching of images against visual stimuli. Nonetheless the study of these areas is hoped to contribute towards greater understanding of how imagery is, in Pinker's words, 'tied to scientific and literary creativity, mathematical insight and relations between cognition and emotion'. There is consensus on some imagery-related issues. Presented here are some of the more popular coinciding theories.

Many writers in the field posit types of operations that take as input array-like data structures created by sensory receptors (eyes and retina) and it may be possible to extend this to claim that the same processes could access such data structures generated from memory rather than from the eyes.

Perhaps the major scientific discussion centres on the following question: does imagery consist of the processing of pixels in an array with properties similar to the 2-and-a-half Dimensional sketch or does it consist of the processing of structural descriptions? Some theories have attempted to answer this.

Some definitions are required for the above question. In an 'array-like' formation images are patterns of activation in a structure consisting of units or cells that represent, by being on or off, the presence or absence of a part of a surface of an object at a particular disposition in space [Pinker 84]. For a technological analogy one need only think of a CCD chip in a video camera, placed behind the lens.

The 2-and-a-half dimensional sketch (despite the given terminology of 'sketch' do not confuse this with anything produced on paper) is one of three levels of imagery postulated by [Marr and Nishihara 78]. The first representation is called the 'primal sketch' and is a two-dimensional array that makes explicit the intensity changes and two-dimensional properties of the retinal image, in line with that described in the previous paragraph. The second level of representation is the '2 $^{1/2}$ D sketch' and this represents the depths and orientations of each point on the visible surfaces of objects relative to the viewer's vantage point. Their third level representation is called the '3-D sketch' and in this format objects are represented as a set of volumetric shape primitives within a three-dimensional co-ordinate system.

For a number of given reasons Pinker disagrees with these three representations in favour of more flexible systems [Pinker 80]. The 2 $^{1/2}$ D sketch is discounted since Pinker believes that people can form images that display two-dimensional distances as they would appear from a different vantage point, not actually seen by the viewer.

The main tenet of these more flexible theories is that;

> '...the long term memory representations of objects' shapes and surface properties... are assumed to have the format of a structural description augmented with whatever information is necessary to reconstruct the appearance of the surfaces of the object.' [Kosslyn 80;83]

If it could be permissable to add 'construct the appearance from the imagination' as well as 'reconstruct [from memory]' then we could clearly see the relevance of this theory to the design of products/objects.

Kosslyn's theory is illustrated schematically in Figure 4.6. Figure 4.7 illustrates the theory of [Hinton 79a;79b]. Like Kosslyn, Hinton's model suggests that imagery consists of information appended to a structural description of the object's shape although in his diagram the information attached is not provided via

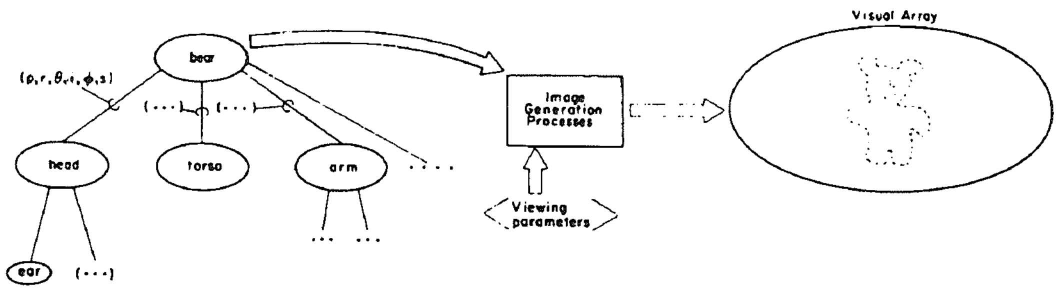


Figure 4.6 Kosslyn's model of the image generation process [Kosslyn 80;83]

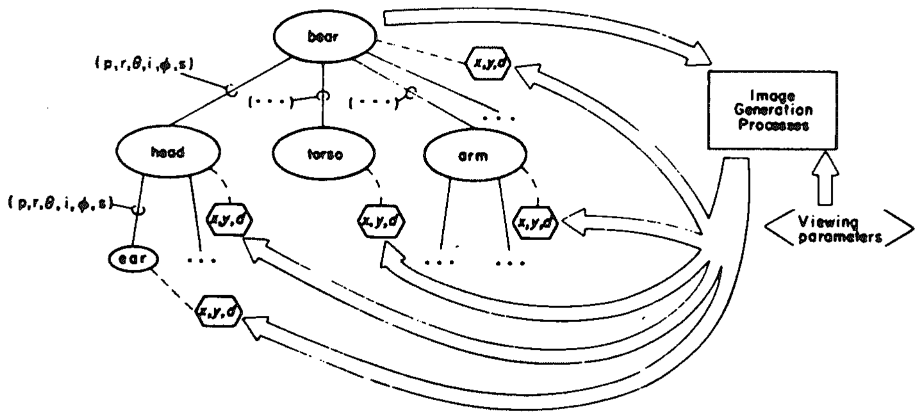


Figure 4.7 Hinton's model of the image generation process [Hinton 79]

by a system rather more like that of Marr and Nishihara's '3-D sketch'.
Broadly speaking [Seymour 79] is also in agreement with these representational models saying that;

> '...it is reasonable to distinguish between a level of picture processing which is broadly perceptual... being concerned with the construction of a two or three dimensional description of an object and a [second] level which is more obviously semantic, involving isolation of attributes of objects [and] their assignment to classes.'

The difference between these different levels of mental representation is illustrated by the following example: to answer the question 'does a bee have a dark coloured head?' requires recourse to the use of imagery but the question 'does a bee have a stinger?' or 'does a bee have wheels?' would instead be answered by accessing the mind's store of structural knowledge about bees [Kosslyn 80].

If mental imagery, by way of this combination of pictorial and structural description, can be subjected to transformations such as rotation and scaling then imagery can be used to solve problems that involve objects and spatial relations. [Pinker 84] illustrates how mental imagery is used in such problem-solving activities;

> '...certain abstract problems could best be solved by translating their entities into imagined objects, transforming them using available image transformations, detecting the resulting spatial relations and properties and translating those relations and properties back to the problem domain.'

[Shepard and Cooper 82] note how imagery, thus used, is effective in the solving of mathematical and scientific problems. This use of mental imagery to produce tentative solutions to abstract problems for further subsequent operations ought easily, from Pinker's above description, extend to include problem-solving within the engineering design domain. In problem-solving situations;

> 'imagining a concrete analogue of an entity, transforming it, and then translating it back to the original domain could make explicit certain properties and equivalences in that domain that were only implicit beforehand [Shepard and Cooper 82].'

The theory of Shepard and Cooper suggests how drawing might enable design, particularly conceptual design, at a psychological level; by acting as a *concrete analogue*. Through the relevant motor programmes controlling hand and eye, drawing allows us to transform in many ways the mind's store of semantic attributes.

[Fish 90] notes the incompletion, distortion and ambiguity visible within artists' sketches. He proposes that such drawings exploit mental processes which evolved in early man. Sketches today are 'visual stimuli [used] to improve and stabilise mental imagery'. Fish concludes that;

> 'skilfully used, ambiguous or incomplete sketch attributes may amplify imagination by stimulating the visual system to generate a stream of spatially superimposed mental imagery.'

To summarise, from the work conducted in the field of psychology we find that there is a generally agreed set of theories which propose that the mind attaches structural descriptions to 'flat' visual imagery and is thus able to transform and operate upon the images in many ways within three-dimensional space. Drawings on paper, though mediated by the ability of the person drawing them, are fair representations of such mental images and when made provide concrete feedback which allows the artist and viewer to further manipulate the mental image.

4.3 Scientific Study of Sketching

One of the most detailed studies of the act of sketching was conducted by [Goel 95]. He identifies two types of operation occurring between successive sketches in the problem-solving phases; *lateral* transformations and *vertical* transformations. In a lateral transformation, movement is from one idea to a slightly different idea. In a vertical transformation, movement is from one idea to a more detailed and exacting version of the same idea. Like the experiment and subsequent description of [Dwarakanath and Wallace 95] this theory illustrates the opportunistic nature of designers. Designers will solve specific problems progressing downwards to more exacting levels of detail for a while but may suddenly switch to a different problem, sometimes with the previous problem left unsolved to any level of completion.

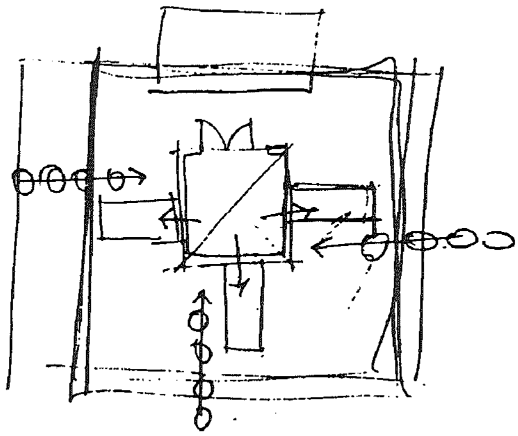


Figure 4.8

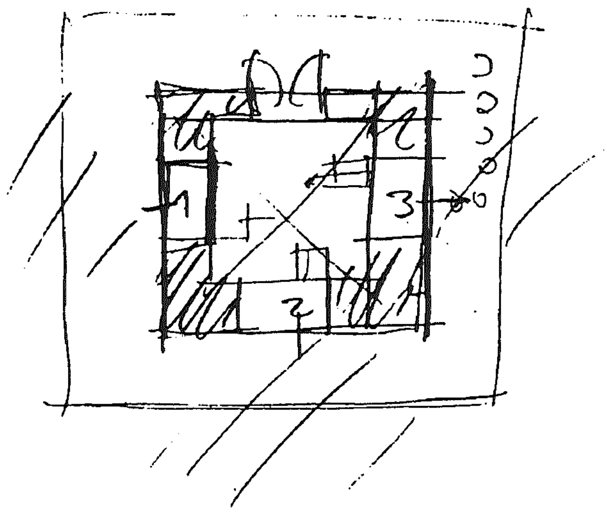


Figure 4.9

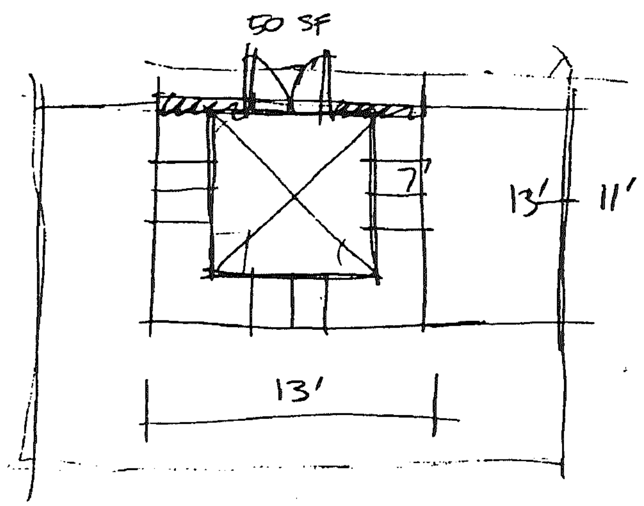


Figure 4.10

Figures 4.8 - 4.10 Sketches of a plan for a post office counter [Goel 95]

Figures 4.8 - 4.10 are sketches made as part of the architectural design of a post office counter. Figure 4.9 is a lateral transformation from Figure 4.8; three booths retain their location but have been internalised into the main core square. Figure 4.10 however is a vertical transformation from Figure 4.9. There is no modification of the idea of the booths in the central core; there is only the clarification of neater lines and the addition of dimension detail.

Goel concludes that freehand sketches - by virtue of being syntactically and/or semantically dense and/or ambiguous - play an important role in the creative, explorative, open-ended phase of problem solving. He believes that the properties of the freehand sketch facilitate lateral transformations and prevent early fixations.

Lawson [Lawson 97] supports the above, maintaining that the computational theory of mind which underpins much of cognitive science falls some way short of being able to communicate the richness and diversity of thinking implied by freehand sketching activity.

4.4 Attempts to Support Sketching Activity

Warburton assesses the use of available digital design tools during the design process, with particular attention paid to their appropriateness in modelling activities as compared with 'traditional' methods like sketching and modelmaking from card and foam [Warburton 96]. She concludes that at present:

• there are no apparent reasons why digitally-based communication media should be used for their own sake during the conceptual activity;
• digital and non-digital methods are equally appropriate in the development stages;
• computer support becomes more important during the latter stages.

Efforts have been made to affect the transition from paper-based, conceptual stage sketching to a digital environment. In the main these follow two main schools of thought. Firstly there are those that transform selected freehand-sketched concepts to digital input, via scanning or other methods. Secondly, there are those that attempt to mimic the natural sketching activity with computer-based methods.

4.4.1 Bridging paper and digital domains

The Fast Shape Designer (FSD) system [van Dijk 95] is used for making quick 3D sketch models from, and in addition to, 2D sketches. It does not try to replace traditional sketching. The system produces 'three-dimensional' sketch models from 2D sketches. The resultant model can then be milled to obtain a physical hard copy.

Tovey's prototype system [Tovey 97] attempts to link freehand sketches to CAD models and is intended as a quick and convenient way of moving from concept sketches to a computer model. The system concentrates on the stage in the process that Tovey believes overlaps engineering design and CAE. He feels that CAD has much more application at this stage of the process than in attempting to support sketch activity directly.

Blessing's PROSUS support tool facilitates the capture and storage of early sketches [Blessing 94]. It utilises a tablet/stylus interface to input freehand sketches to the system. Most notably, the stylus in use is an adapted nib-type pen. A thin sheet of paper can be placed between stylus and tablet and allows the user to see marks on paper, as in true freehand sketching. The output (on paper) is not one step removed from the input, via a monitor device for example, and it is this immediate response that is psychologically important to the designer. The secondary, electronic input is saved via the tablet as a bitmap image and entered to PROSUS' design matrices (this system is also discussed in Section 3.3).

These systems demonstrate some of the utility of adapting paper-based sketches to computerised forms. A fully working system would mean that even early concepts could be linked to proprietary computer tools.

4.4.2 Sketching in a digital environment

Possibly the first study into drawing freehand on computer was published as far back as 1963 [Sutherland 63]. More recently Lakin's [Lakin 89] VMACS system helps provide recognition routines which identify graphic 'pieces' as expressions in notational symbol systems. VMACS recognises such diagrammatic representations as rigid body diagrams, bar charts and finite state automata to allow for more meaningful processing. Hwang and Ullman's Design Capture System (DCS) [Hwang and Ullman 90] is similar in that it is a draw-to-computer set up that does not use paper and pen.

The Electronic Cocktail Napkin system [Gross 96] adopts a 'paper and pen'-like interface. The Electronic Cocktail Napkin has capabilities for recognition and parsing of visual expressions and this is probably its most outstanding feature. Parsed diagrams are compared with diagrams already stored in the index and those that match can be pulled from the database and displayed. The system is intended to augment the architectural, case-based design aid ARCHIE [Domeshek & Kolodner 92]. Case-Based Reasoning (CBR) systems apply experience stored in computerised form to solve similar problems in slightly different contexts. The electronic cocktail napkin's ability to query by diagram is added to ARCHIE's concept-related and keyword processing capabilities.

Recently there has been an apparent shift from the established Artificial Intelligence approach towards one supporting directed exploration through the design case base. This reflects a shift from *automating* design towards *supporting* design through better access to knowledge and information [Wood & Agogino 96].

[Hwang and Ullman 90] have talked of 'back-of-the-envelope' sketches while Gross talks of his 'cocktail napkin'. Both invoke the immediacy of such 'whatever is to hand' media, an immediacy which current methods of computer capture are unlikely to offer. The systems of Lakin, Gross and Hwang and Ullman all offer optional support to designers and their freehand methods. None really intend to completely replace freehand sketching at the conceptual stage.

4.5 Attitudes to Computer-Aided Drawing

[Tovey 97] suggests that there is little point in mimicking the sketch activity by computer methods unless the designer gains something over the traditional method. Sketching by conventional means is extremely quick and effective.

Research indicates that the poor response and 'feel' of current computer tools are a source of annoyance and frustration for designers [Temple 94] [van Dijk 95]. In an investigation by Temple, all of the designers involved stated that to interact with mouse and screen at an early stage would be 'inhibiting and unproductive'. As part of an experiment by van Dijk, subjects commented that sketching with a mouse is slow, 'unwieldy and inaccurate' with 'unpredictable' results. The cognitive processes will be limited by the poor response and 'feel' given by a computer mouse. Approaches which instead use stylus input may yield better results as they are improved via research and as designers grow accustomed to commercial solutions like Alias Studio.

Goel recognises the expressive properties within early and intermediate sketches. He explains that they:

> 'not only denote but also exemplify such labels (properties) as 'shape', 'relative size', 'relative location', 'fluid', 'rigid', 'elegant' and so on. They also express such labels as 'bold', 'uncertain', 'hurried' and the like.'

Only freehand media can express that much in a language understood by those involved in design. The response of the marks made on paper to the varying weight and pressure put by the hand onto the pen, pencil, marker (or whatever is 'to hand') is instantaneous. A mouse will always lag. One only has to think how infuriating it can be if you are forced to sketch with a 3H pencil when what you really want is a soft B.

The production of sketches has been described as free-flowing, involving a kind of visual stream of consciousness which depends for its effectiveness on complete freedom [Temple 94].

Freehand sketches are thought to possess the following advantages over computer sketch systems:

- greater speed
- greater ease of use
- greater immediacy
- better quality of response
- more expressive qualities
- they are constrained only by the designer's imagination

A new generation of computer-based drawing tools are however finding acceptance in leading design companies around the world. Packages such as those produced by Alias Wavefront - a division of Silicon Graphics - are making inroads into the motor industry for example. Their *Studiopaint 3D* tool is intended to allow intuitive sketching via pressure sensitive light pen and board input and gives additional value by allowing drawn shapes to be 'converted' from 2D to 3D.

Despite this, even Alias Wavefront's own publicity material shows how designers at Nissan Design International Inc will take *freehand* sketches of a part such as a car seat and *then* work them up into 3D computer files in the *Studio* package. Files from Studiopaint 3D can be sent 'over the wall' into Studio and similarly Studio files can be linked to 'hard-engineering' packages such as Pro-Engineer, to enable manufacturing and production or the creation of rapid prototyping models.

There follows a quote made in 1997 by a designer at a internationally-known, London-based electronics firm:

> 'But the only thing you will never replace is sketching. We still do that, get the pads out in a meeting and sketch out ideas. I don't know if it's cultural or psychological. Some people can't handle that because all they know is the computer. But you will never replace paper sketching.'

Lawson's accounts from practising designers provide typical reactions. One senior architect is personally unenthusiastic about the idea of computer-aided design, of which he makes no use himself. He considers that the directness with which he can alter a drawing is missing when mediated by a computer and something which he calls the 'feeling' is lost. The same architect recognises however the advantages of computer-aided *drafting* systems, widely used in his company. The use of *computer based* drafting demonstrates that designers are not anti-technology for its own sake and will use suitable technology when it is considered appropriate.

Traditional CAD systems only allow for specific geometry entities of exact dimensions and these are specified through textual menus or icon selects. Such precision features, coupled with the need to break the train of thought for the menu interface, work against early stage design capture [Hwang and Ullman 90] [van Dijk 95].

The recognisable frameworks of CAD systems lead to a situation where the tail is wagging the dog - there is a tendency for users to design only what the system allows them to. Computational interfaces not only provide tools and a medium for drawing but also help reinforce a symbol system. They facilitate certain marks and operations and discourage or even disallow others [Goel 95].

Thus, at present, there seems little reason to attempt to replicate freehand sketching by computer methods. Conversely, computer support of sketching activity can provide desirable features not offered by traditional 'paper-based' methods:

- storage facilities
- faster search for material held in storage, via meaningful processing techniques
- durability and permanence; sketches held on computer are not easily lost
- direct links to proprietary computer tools and networks

4.6 Discussion

This chapter has attempted to demonstrate the all-pervasive influence and general importance of drawing to design. The designer's sketch has been described as a medium allowing ideas to be investigated quickly and cheaply on paper, as seen both from descriptive study and supported by evidence gathered by cognitive psychology approaches. Sketches allow ideas to be made concrete on paper and this in itself further stimulates exploration of those ideas or helps generate new ideas.

A discrepancy has been noted between the importance of drawing at the conceptual stages as recognised by designers and the actual retention of those drawings. With freehand sketching at present excluded from the computer revolution, computer methods of capture would improve the storage and re-use of drawings and various attempts have been made to effect this by research. The conclusion here is that those approaches which attempt to capture freehand sketching by digital means are more likely to be adopted by designers within the earliest stages of design, in preference to those that try to make the designer sketch within digital environments and constructs.

The research experiment described in the next section observes a period of sketching within the early stages of design projects and from the observation aims to find areas that will enable freehand sketch activity to be included within computer support models which intend to encompass and record the entire design process. The research also aims to find whether sketches are indicative of the general progress of the design project and tries to determine the volume and pattern of information produced by sketch activity throughout the conceptual stages of the design process.

Chapter 5
Experimental Work

5.1 Methodological Approaches for Design Research

If researchers wish to support design activity with improved techniques and computer tools, then it stands to reason that first some research must be carried out to determine and define what design activity actually is.

In the past few years some work has been done in providing computer-based tools to support engineering and design at the conceptual phase [Hennessey 94] [Ullman 95] [Scrivener *et al* 93], with the most credible of these based on descriptive research rather than set prescriptive notions of design. It is difficult to predict the validity of developed tools without a firm basis in descriptive research methods. Tools developed using prescriptive models that do not match designers' working practices and expectations may fail to gain their confidence and this will only serve to discredit the design research community.

[Scrivener *et al* 93] attempted to conduct conceptual design meetings between Australia and England using electronic conferencing technologies which utilised many promising advances in design hardware. Though the team then gathered many items of subjective and positive feedback from subjects testing the hardware prototype it remains difficult to predict the system's validity and acceptance in practice.

The need for more detailed knowledge of design activity has led to the adoption and development of various research techniques and methods. Close study of the designer's actions will, it is hoped, lay bare the thought processes underlying intellectual activities such as cognition, problem-solving and creative thinking.

5.1.1 Protocol Studies

Engineering design research has often placed credence in data taken from observation of designers working in laboratory conditions on set tasks. The number of so-called *protocol studies* has grown steadily since the beginning of the 1980s, but such programmes have tended to happen in scattered pockets of activity so that protocol analysis is some way off being recognised as a coherent discipline [Dorst 95]. Protocols involve observation of designers at work. Almost all of these studies are based on what we might call 'experimental data', gleaned from a 'laboratory' set up: a designer or group of designers will be put into a room, with given tools and a given problem. While there is no reason for the designer to be dishonest in such an experiment, responses from a designer may be, for whatever reason, what the designer thinks the examiner wants to hear. Ad-hoc rationalisation of the activity, whether spoken aloud in lab settings or given in retrospective interviews, is probably the most pernicious aspect of conducting such research.

Much design protocol research is concerned with constraining or equalising 'variables of the research equation' [Dorst 95]. When designers work 'for real' such rational constructs do not apply. [Dwarakanath & Wallace 95] recognise the shortcomings of such experiments in saying that it is 'less representative for analyses of how design actually takes place in practice'. Acknowledgement of this caveat helps to bolster the credibility of their protocol studies, and their claim that a laboratory environment '*usefully* restricts the influences on the design process' [my italics].

Christiaans' and Cross' protocol analysis workshop at the Delft University of Technology in September 1994 represented the first coming together of leading researchers in this field [Dorst 95]. All of the analysts worked from the same set of source data; each group of researchers were given the same two sets of videotapes, one recording an individual designer at work and another observing a three-person team of designers.

The resulting range of papers reveals that even though they might be based on evidence gained in 'controlled laboratory environments', there are still many ways of seeing. Some papers focused on analysing the verbalisations of the subjects, taking them to be a more or less faithful reflection of their thoughts. Others concentrated on drawings made by the designers and one even studied their gestures.

Research gathered by protocol methods could be greatly devalued however by a failure to acknowledge the 'influences on the design process'. Dorst admits that the experimental set-up heavily influences the protocol data, but goes on to say that;

> 'conclusions and generalisations drawn on the basis of protocol research will only be valid if and when we have a coherent picture of the influence of the experimental technique and situation.'

Such protocols feel they are observing a true central activity by creating an 'artificial' environment devoid of distractions, social and otherwise. One participant in the Delft workshop exercises caution, making the observation that protocol tapes 'work like Rorschach blots' in which case 'we have been looking at ourselves the whole time'.

5.1.2 Ethnographic observation

The protocol method, with a seemingly scientific basis, has been readily accepted as a way of studying engineering design activity. More recently, and with the growing recognition of engineering as essentially a human activity, it has been proposed that the field research techniques developed in the social sciences could prove useful in helping to understand how and why design happens [Wallace and Hales 89] [Kennedy 97].

One such social science technique is ethnographic observation. The ethnographic approach seeks to provide a written description of the implicit rules, traditions and behavioural patterns of a group. The intention is to provide a rich or 'thick' description which interprets the experiences of the group observed [Robson 93]. It differs from a protocol approach, most obviously, by observing an activity without having 'created' that activity.

The researcher can take various observational stances. The participant observer enters the culture they are observing; becomes a part of the community under observation. In an engineering context, participant observation would involve researchers gaining access to companies and working as designers or with designers to get an inside view of their activities. Observation can be more or less-structured; the study can become more structured as hypotheses emerge from the investigation [Kennedy 98].

In the design research field [Bucciarelli 94] has carried out a non-participant ethnographic study of an engineering firm making photo-voltaic cells. It demonstrates how the resource, time and budget constraints within the firm and the social interaction between designers and management have a bearing upon the activity in real life situations.

5.1.3 Multiple Method Approaches

Quantitative data deals in numbers and statistics obtained by enumerative induction while qualitative data expresses concepts and ideas. Protocol studies deal in reducing qualitative source data to quantifiable data while an ethnographic approach yields purely qualitative results. The two approaches, then, have their associated data analysis methods.

The divide illustrates the two main traditions within research. These occasionally 'warring' factions are labelled as positivist, natural-science based, quantitative or 'scientific' on one hand and interpretive, ethnographic or qualitative on the other. Some see the differences as purely technical however and while recognising the differences between approaches also play down those differences [Bryman 92] [Robson 93].

Research that produces essentially qualitative results or essentially quantitative results need not be seen as opposing, incompatible disciplines. Indeed [Cross and Cross 95] and [Bucciarelli 94] both reach the same conclusion - that design is a social process - by taking, respectively, protocol and ethnographic approaches.

Some advocate a *multiple methods* approach. Multiple methods can be used in a complementary fashion to enhance interpretability. In a primarily quantitative study for example, the interpretation of statistical analyses may be enhanced by a qualitative narrative account [Robson 93]. This could explain trends and contradictions in the statistical data. Protocol studies can be seen as plausible explorations of designers' thought processes, but it must be realised that rarely are they complemented by studies of environment and social context. A mixture of the two approaches may form a reliable trace of the design activity.

The use of multiple methods in the study of the same phenomena is known as *triangulation*, a phrase first used by [Denzin 89] meaning 'getting a fix from two or more places', and is intended to neutralise bias in any one approach [Cresswell 94] [Kennedy 98]. Denzin formulated that it was possible to triangulate in terms of multiple and different sources (e.g. informants), methods, investigators or theories.

'Method triangulation' is simply the use of multiple methods. Method triangulation is described as being either between-methods or within-methods. A within-method approach involves the same method being used on different occasions (repeating the same experiment at different times of year for example) and a between-method approach uses different methods in relation to the same object of study.

5.2 Methods Used

From the discussions and conclusions made in the previous three chapters, the experiment aims are defined as follows:

1) To find areas that will enable freehand sketch activity to be included within computer support models which intend to encompass and record the entire design process.
2a) To find whether sketches can in any way be indicative of the general progress of the design project and as a corollary to this
2b) To determine the volume and pattern of information produced by sketch activity throughout the conceptual stages of the design process.

In order to answer these research questions this study focuses on the act of drawing in particular as a means of describing the design process. The research studies these visual artifacts of the design process and uses quantitative encoding methods of analysis to interpret the act of designing. Observation made of the design tasks being performed is added to this data to build a comprehensive picture of conceptual design activity.

This study is interested in the use of visible surface externalisations used by the designer, not in attempting to deduce the cognitive activities underlying the design task. It attempts to find out what is produced, how, when and in what quantity and most important of all what there might be within these prevalent externalisations that will enable a design record to usefully capture and store them. By studying the resulting artifacts of design, the experiment can be said to utilise the *unobtrusive measure* method. Such methods are given this name due to their unobtrusive and non-reactive relationship with the activity under scrutiny. The enquirer does not have to be in direct contact with the subjects as they produce these observable traces.

Difficulties can arise in linking cause and effect - it is assumed here and from our literature review that the visual traces under analysis are almost direct traces of the proceeding design activity. It must be appreciated that there are serious drawbacks to the unobtrusive measure method if used as the sole method of investigation. Unobtrusive measures can have great usefulness as a complement to other methods and here they are considered part of a multiple method investigation.

In the first iteration of the experiment the researcher is placed in the *participant-as-observer* role. This form of participant observation makes clear to the subjects that the observer *is* an observer and the researcher performs the dual role of observer and participator to establish close relationships with the group subjects [Robson 93]. In this case the observer is perceived by a wider classful of 'subjects' as fulfilling a 'tutor' role. As to the nature of the observer's investigation, the four subjects selected are only informed that the study focuses 'on how they go about their work'. One additional request to the subjects was that they keep their sketchbooks in 'good order' and try and keep all of their 'working'. This was not thought to give any specific hints that the study was most interested in the subjects' conceptual sketches.

5.3 The Observational Experiment

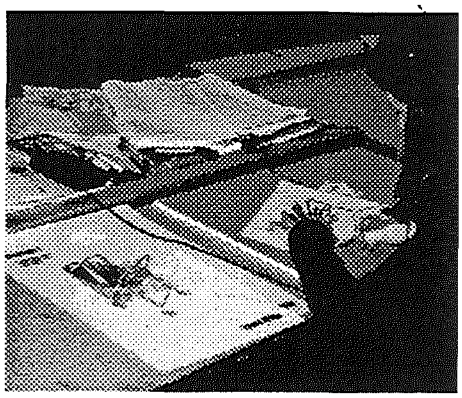
The same experiment was carried out twice with two different sets of four subjects. The first subjects were drawn from the pool of final year students of the Product Design Engineering course, session 1996-97 and the second set from the final year students of the same course, session 1997-98.

5.3.1 First experimental iteration

The initial iteration of the study observed student designers in the final year of the M.Eng/B.Eng Product Design Engineering course at the University of Glasgow/ Glasgow School of Art between November 1996 and February 1997 and concentrated upon the sketching part of the design activity. The production of sketches was regarded as a measure of ideas and information produced.

Four students were selected from a class of twenty-two by teaching staff . The selection was intended to illustrate a range of activity and varying scales of product. The students were not given specific tasks to do, nor strict time limits in which to do them. The students were observed at work on their individual, self-motivated projects. It is crucial to appreciate that these projects would have been carried out whether the experiment had been set up or not; this observation of a non-laboratory activity is more in keeping with an ethnographic rather than traditional protocol stance. The projects constitute a major part of the eight-month, final year curriculum though they were interrupted by complementary core engineering lecture material and study. There are no intermediary submission dates in the project; only a final hand-in around May/June of the second session (for this first iteration of the experiment, this was May/June 1997). The window for study was set to cover the conceptual phase period; reckoned to consist of up to fifteen weeks beginning in the fifth week of term. From staff experience the first four weeks are generally thought to consist of the search for a suitable problem area and initial background research.

Most of the material for encoding and subsequent quantitative analysis came from the students' sketchbooks, but qualitative observation was thought necessary to explain both trends and contradictions in quantitative results. Anecdotal material and assessments of the working habits of the subjects was obtained by placing the researcher in the participant-as-observer role (in this case taking the role of a part-time tutor available to all twenty-two students). The working environment is shown in Figures 5.1 and 5.2.

Figures 5.1 and 5.2: Observational working environment

The four subjects worked on a wide range of products varying in many ways, most obviously in size. The subjects chose the following projects:

• computer hard drive swap system	Subject W
• ski-tow	Subject S
• mobile grandstand	Subject A
• mobile electricity substation	Subject L

5.3.2 Second experimental iteration

After the first set of results had been logged and initial conclusions made it was thought wise to strengthen any initial findings by repeating the experiment and thus obtaining a second data set from another four subjects. On this second occasion the four subjects were drawn from the final year group of PDE students in session 1997-8. This second run uses an approach that can be described as within-methods but not within-subjects, since it involves four subjects different from the four chosen to take part in the first experimental iteration but analyses their work using the same measures.

Due to time constraints, carrying out regular observation on the new set of subjects at work for a second session was thought impractical. Instead, Unobtrusive Measure was the sole method of investigation used. Sketches were analysed retrospectively at the end of the session without observing the designers or the circumstances of the drawings' production. Bearing in mind the similar environment and population to that of the first study group, it was thought adequate to observe only the direct traces of conceptual design. Essentially, second time around it was assumed that the sketches 'could speak for themselves'.

The new four subjects' work displayed a wide range of product areas and product scales, as had been the case with the first experiment:

• disposable instant picture camera	Subject 2DK
• desktop three-dimensional scanning device	Subject 2HK
• small-scale investment casting oven	Subject 2L
• canal cruiser	Subject 2C

The second iteration possibly benefited from improved analysis techniques since the same observer was now more practised in determining the various qualities of the sketches. Two refinements were made to the analysis methods for the second experiment and were expected to improve the accuracy of the results:

• the refinement of the encoding sketch scale, discussed in 5.4.3, and the tightening of definitions reached through practical experience;
• the recognition of the importance of the *Duplication* transformation mode from the first iteration leading to a subsequent remodelling of the Transformation analysis scheme.

The retrospective gathering of the sketch material was not entirely straightforward however. In the first iteration of the experiment the subjects were advised to try and keep their sketchbooks tidy and to date all work. As the study intended to shed light upon the episodic and chronological qualities of sketching, this dating and ordering of work was crucial. In the second iteration no instruction was given, thus the work produced was only dated at the discretion of the individual subjects. With the resulting variance in the order and completeness of the retained sketch work it was by a simple process of elimination that the observer selected those taken for analysis; the four sets of work chosen were those which had dates clearly marked on each piece of work. It should be noticed that although there were many sets of quality sketch material to choose from, only the four selected were clearly dated and ordered.

The observer acknowledges that there is still a slight chance that some work may be missing. Conversely, it should be noted however that the artifacts gathered to provide this second set of results can be guaranteed to be free from any experimental influence.

5.4 Analysis of Sketch Work: Rules and definitions

To answer the stated research questions it is necessary to analyse the sketches obtained using a variety of encoding methods. Through the combination of these methods it is hoped that the study can provide insight into the issues of production, utility and design record inclusion. The following rules should provide a set of consistent results.

5.4.1 Conceptual sketches

The *Conceptual Sketch* is different from the other types of drawing employed by designers: the *Presentation Drawing* and the *Drawing for Manufacture*. Concept sketches and presentation drawings are sometimes confused since genuine concept sketches often perform a secondary function. They can be used to present ideas to clients and to those involved in a product's eventual manufacture, providing a kind of work-in-progress report.

Figures 5.3 and 5.4 are taken from one subject's project. Figure 5.3 is a conceptual sketch that allows the designer to try out an idea on paper. It is just less than 100mm by 100mm seen in its original size. Figure 5.4 is a refined presentation drawing, originally about the size of an A4 sheet, made to give a quick impression of the product in use to a wider audience which differs little from that shown in Figure 5.3.

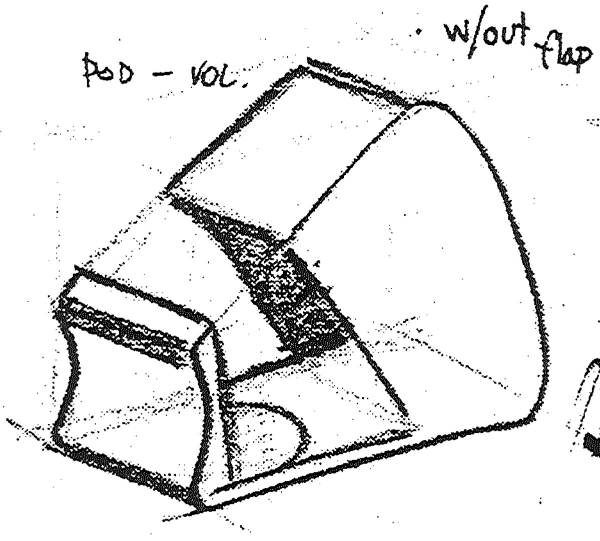


Figure 5.3: conceptual sketch from sketchbook of subject 2HK

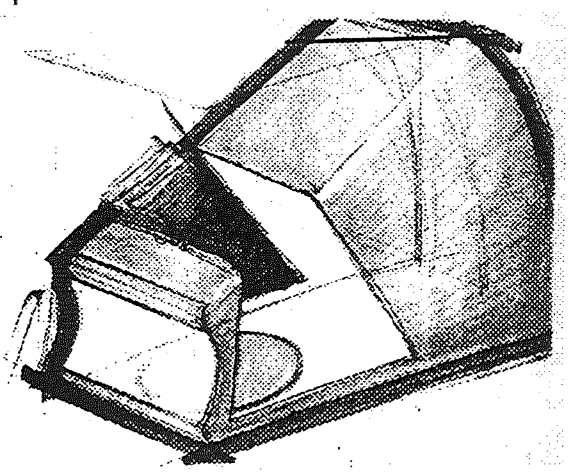


Figure 5.4: presentation drawing of same concept

Presentation drawings are merely laboured reworkings of conceptual sketches, traced or more carefully rendered, perhaps with detailed graphics and text but not furthering the design. Such presentation drawings, while fairly rare, were disqualified from analysis.

5.4.2 Individuating sketches

Figure 5.5 shows a typical page from the sketchpad of one of the students involved in the experiment. In analysing these pages each page must first be broken down into constituent sketches. The observer first identifies separate (though still connected) sketching episodes. Goel talks of 'individuating' when analysing sketches [Goel 95]. In his experimental work the subjects themselves were instructed to individuate the output by drawing rectangles around each separate drawing and in some cases would number them in sequence.

The retrospective method of unobtrusive measure involves a degree of interpretation and the analytical process takes longer than if the student was asked to individuate and number each sketch in the first instance. From study of the sketchbook material it is obvious that the students do not do such a thing as part of their own practice - such a demand would have been an additional requirement over 15 weeks, with possible intrusive influence on the experiment's outcomes.

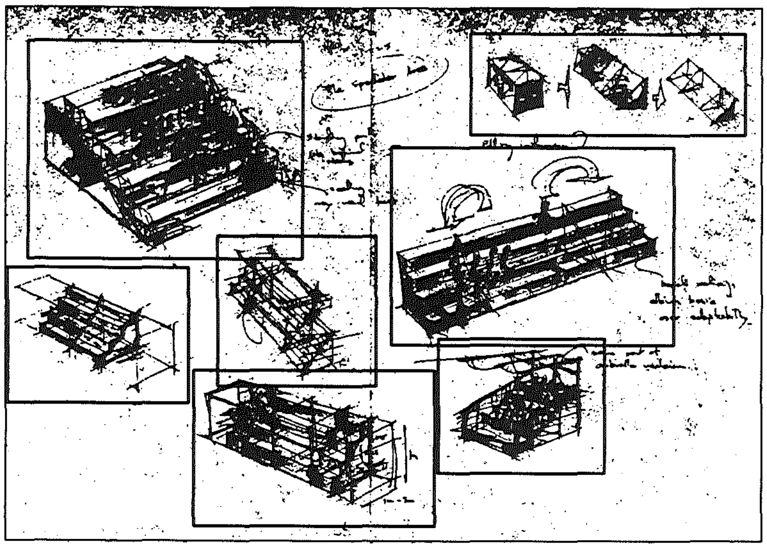


Figure 5.5: Individuated sketches on one page from student A's sketchbook

The seven individuated sketches in Figure 5.5 are shown by the overlapping rectangles on the sketchbook page, added by the observer.

5.4.3 Encoding: quantifying qualitative difference

To be able to appreciate the pattern of information flow in the conceptual sketching activity, some quantitative measure of the activity is required. In order to obtain this a qualitative judgement of some attribute of the sketch needs to be encoded; that is to say, classified in order to give some quantitative measure.

Each sketch on each sheet of the sketchbook was assessed for a measure of the information it communicated to the observer. To classify the level of information content within each drawing a simple scale of what has been termed 'Complexity' was constructed.

Complexity here was eventually defined to be a measure of the *detail* in each drawing - the intricacy of the mechanisms shown, the exactness of textures and such like. In initial analyses of the drawings there was perhaps a slight tendency to confuse the measure of detail with a measure of the level of *finish* in a drawing. The presentation drawing in Figure 5.4 is well rendered to show a degree of 'photo-realistic' three-dimensional form, and the edges are neat. A similarly well-rendered drawing of a 3D cube, despite containing highlights shadows, colours and tones could in fact contain as litte information as that contained in a hastily line-drawn 'black box', conveying little in the way of ideas.

In assessing the kind of sketching used by automotive stylists [Tovey 92] notes the use of 'artistic devices [used] to enhance the "desirability" of the sketch, based on preconceived "auto" enthusiasms', devices he also refers to less prosaically as 'bullshit'. Essentially, when analysing sketches to measure the level of ideas and exploration contained in each one, the observer must look beyond the sketcher's ability to produce beautifully rendered 'three dimensional' objects on paper and instead try to assess the amount of thinking going on at the *structural* level [Hinton 79a;79b][Kosslyn 80;83]. Qualities to look for include 'detail' and 'busy-ness'. The density of lines is probably more important than the quality of shading to represent form.

The scale used in the first experimental iteration was revised to produce the more refined guidline that is given here, as used in the second experimental iteration (for subjects 2C, 2DK, 2HK and 2L). For this reason, results in the second iteration are expected to provide a slightly more accurate reflection of the qualities of the sketches. The most simple of sketches typically found in the students' sketchbooks was rated a 'One' and the most complex and detailed rated a 'Five'. The scale was created by interpolating between the two extremes.
Figures 5.6 (a-e) give examples to illustrate the definitions which allow for the classification of each sketch.

The qualities to look for in each drawing are given by the following scale:

Complexity Level One (Least complex)

Monochrome* line drawing. These drawings are the least dense, typified by large empty areas of white space. No shading to suggest 3D form. No text annotations are used nor are numerical dimensions. Motion arrows may indicate moving parts.

* If a single colour is used then this also counts as monochrome (e.g. a drawing made in blue biro pen)

Complexity Level Two

Monochrome line drawing. More detailed and thus more dense than that in (1). One or two brief annotations may appear though they will probably not more than one ot two words each. As in (1) motion arrows may be allowed.

Complexity Level Three

Monochrome, again more dense than in (2) with rough shading perhaps used to give suggestion of form. The drawing may be briefly annotated to describe certain aspects of the idea. Dimensions might be apparent.

Complexity Level Four

Drawings at this level will be very dense, with very little white page showing through. The drawing will almost certainly be annotated, with some longer explanations included. Colour, or gradation of monochrome 'colour' may be used to illustrate certain concepts or arrangements, but not to suggest the true colours of parts. Subtle shading may be used to suggestive 3D form.

Complexity Level Five (Most complex)

Generally a very busy drawing - many lines will be used in its construction. There will be more marks on paper than white page. Colour may be used to represent the actual colours of parts of the product. Lengthy annotations will be used to ask questions of the idea or to explain it.

Since the drawings have been marked with the date of their production, the qualities can be assessed chronologically to produce an information pattern of conceptual sketch activity in the early phases of design.

The amount of information is not only dependent upon the complexity of the sketch. That is to say the bigger a drawing becomes, the greater the space for discussion. Thus, an assessment of the amount of information in a drawing should include a factor of size.

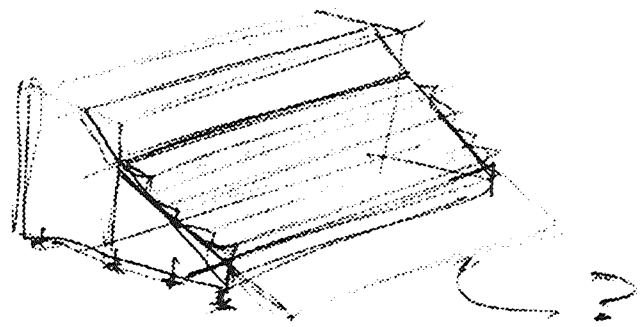


Figure 5.6 (a): Example of Complexity Level (1) sketch

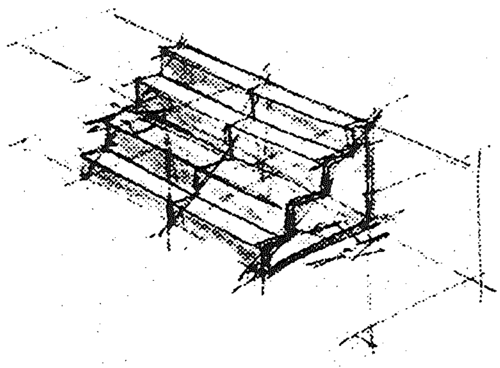


Figure 5.6 (b): Example of Complexity Level (2) sketch

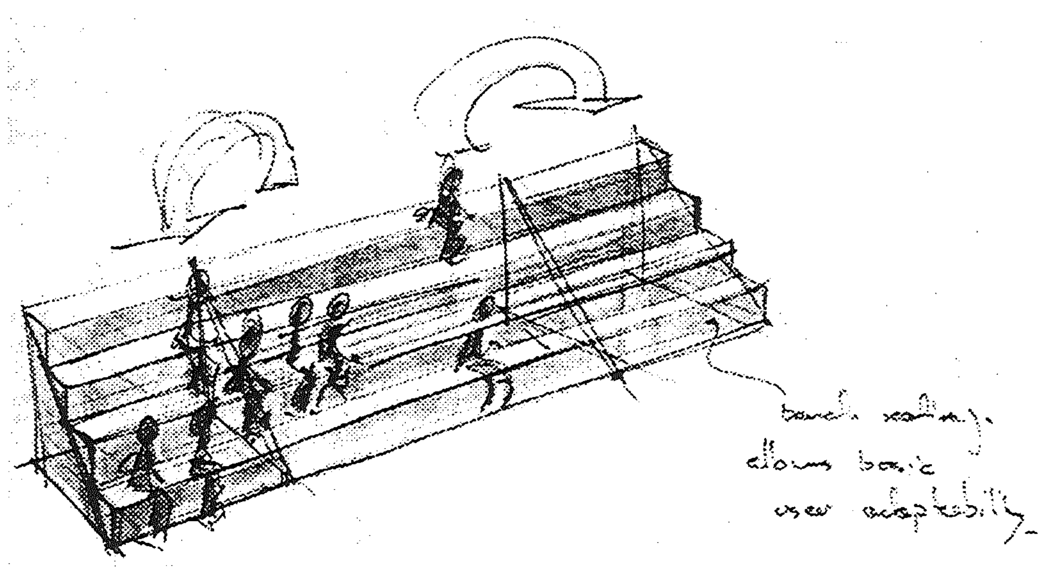
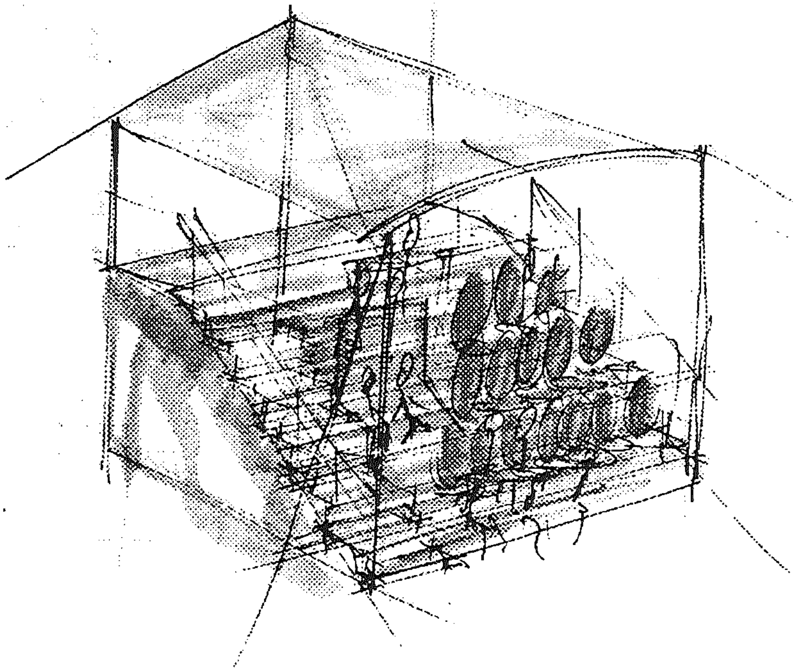
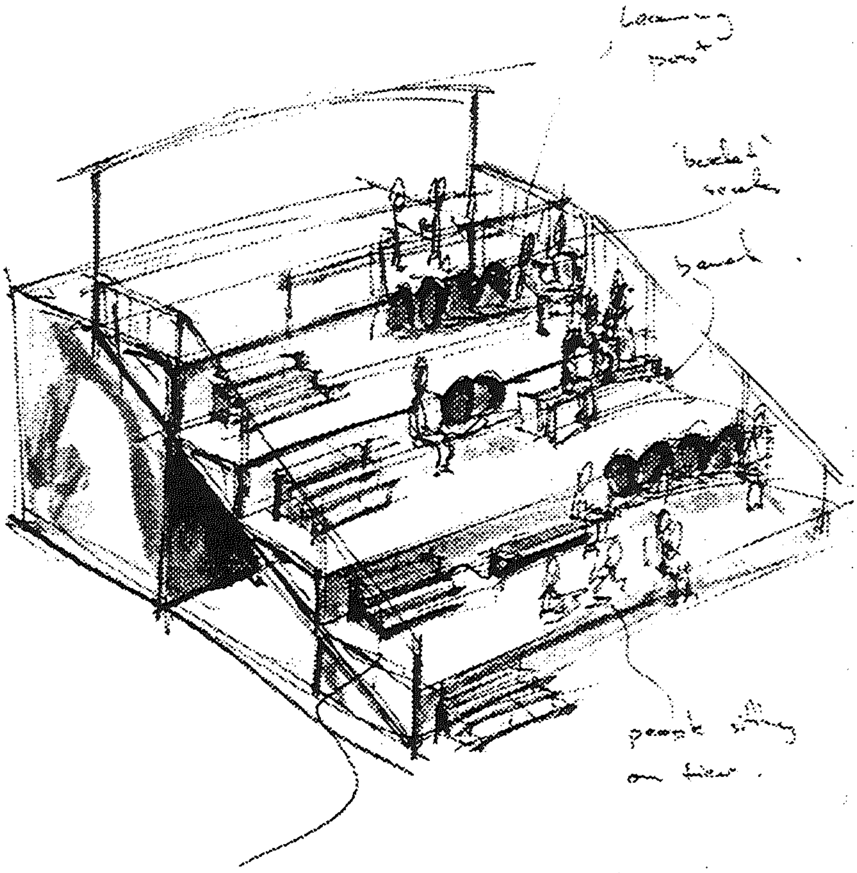


Figure 5.6 (c): Example of Complexity Level (3) sketch



Above - Figure 5.6 (d): Example of Complexity Level (4) sketch
Below - Figure 5.6 (e): Example of Complexity Level (5) sketch



Stand to fewer, larger tiers.

There is a mixture of seating - conventional 'bucket' seats, benches, leaning posts and seating on the tiers.

With an A3 sketchbook the largest sketch (size factor 5) must be considered a full page or near full page sketch, extremely rare as they may be. The smallest sketch was a thumbnail sketch - this was assessed from study of the students' material to be anything up to 50mm by 50mm. The other levels in the scale were assessed by interpolating.

SIZE FACTOR SCALE

1 - thumbnail sketch up to 50mm x 50mm
2 - up to 100mm x 100mm
3 - up to 150mm x 150mm
4 - very large - up to an A4 page
5 - full page - drawing covers most of the A3 page.

Now let: c = complexity of a sketch ($1 \leq c \leq 5$)

s = size factor of a sketch ($1 \leq s \leq 5$)

I_{ps} = Information held in an individual sketch, where

$$\mathrm{I}_{\mathrm{ps}} = (c.s)$$

and let: $\overline{\mathrm{I}}_{\mathrm{pw}}$ = the average information total per week

n_{pw} = the number of sketches made in a week

so that;
$$\overline{\mathrm{I}}_{\mathrm{pw}} = \frac{\sum_{i=1}^{n_{pw}} c_i \, s_i}{n_{pw}}$$

A note was also made of the media used to produce each sketch. Particular interest was focused upon whether sketches were freehand or were drawn by computer methods and pasted in to the sketchbooks. It was felt that it might be useful to analyse the kinds of tools used and how the choice of tools changed with time, if at all.

5.4.4 Qualifying transformations

The work of [Goel 95] was considered in the previous chapter's discussion of studies of sketching and drawing and sketching in engineering and was thought to suggest an interesting method for considering sketch output. For this reason the observer looked at every successive sketch produced during the two experimental iterations to decide which transformation had taken place in each case. An obvious change in thinking is lateral transformation while if the change is instead to a more detailed version of the same idea then a vertical transformation has occurred. A fuller definition is given in Section 4.3 and Figures 4.8 - 4.10.

The observer found it difficult to sequence the drawings within a page, and this made it hard to determine which drawings were successive. To this end 'successive' was extended to mean 'coming after' rather than 'consecutive' which it is apparently taken to mean in Goel's work. Jumping opportunistically from one idea to a second different idea and then on to an expansion of the first idea can only be realistically defined to be a vertical transformation from the earlier idea, whether consecutive or not.

Again it was important that what was being considered was the underlying structural make-up of the sketch and not the way in which it was drawn. If a sketch is drawn a slightly different way but is structurally identical to a previous sketch then it is termed a *Duplication Transformation*. This mode was identified after the first iteration of the experiment and is explicitly included in the method for the second.

Figure 5.7 shows a concept sketch from the book of Subject 2HK. Figure 5.8 illustrates how designers will occasionally redraw an item even if this performs no particular apparent function in terms of advancing the design. From study of the sketchbooks, its main purpose appears to be to consolidate a concept selection or to return to a previous concept for further development but it also seems just as common that it indicates a 'rut' in which the designer is stuck. This may appear similar to the reasoning behind the disqualification of presentation drawings, as

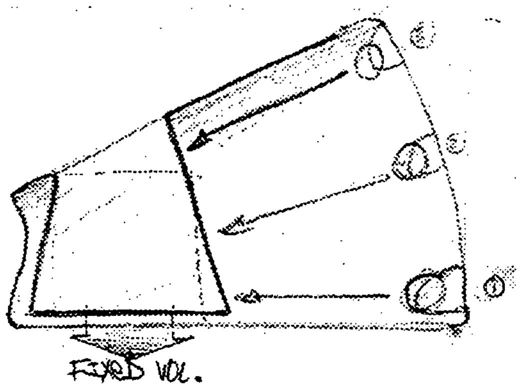


Figure 5.7: a concept sketch by Subject 2HK (in pencil)

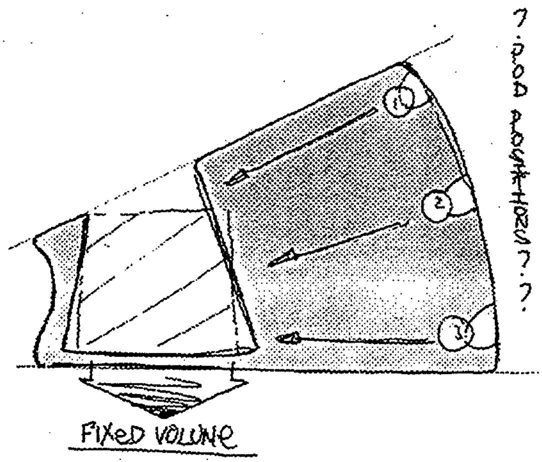


Figure 5.8: this later concept sketch by Subject 2HK (in ink and marker) is defined to be a duplicate transformation, since it is structurally identical to the concept in Fig 5.7

both are merely reworked copies of original concepts. In the case of *duplication* however, the sketch is not aimed at a wider audience - it is still a part of the designer's discourse with him/herself.

5.5 Discussion

This chapter has outlined the experimental methodology which is based on a combination of protocol methods with the extended time period of observation more typically associated with social science approaches. This chapter also outlines the experimental aims which are, broadly, to seek ways of incorporating visual material in predominating text-based records and also to discover ways in which sketch work might act to track the progress of a design project. The methods and rules employed in the two iterations of the experiment are given here, and the methods of the second are thought to be refined from those of the first. The next chapter presents the results of these experiments.

CHAPTER 6
EXPERIMENTAL RESULTS

6.1 Introduction

In line with the research questions identified and stated in Chapter 5, the results of the experiment, presented and discussed here:

- identify one possible way in which drawings can be linked to what are currently text-only records of design activity;
- illustrate the patterns of design as carried out by our subject group of novice designers;
- recognise ways in which the analysis of designers' sketch material can provide a useful track of the progress of design activity, informing the reflexive designer and thus the design process itself.

Different aspects of the experimental analyses will illustrate each of these points in turn.

Firstly, the experiment attempted to verify the presence of freehand sketching in the early stages of design. Table 6.1 illustrates that three of the four students involved in the initial iteration of this study use almost exclusively freehand techniques for drawing. The table also illustrates that each student has a preferred medium of choice, with around 70% of drawings being made with one or two

	Student			
Drawing media	**A (%)**	**L (%)**	**S (%)**	**W (%)**
Hard pencil	**40**	-	-	3
Soft pencil	11	**69**	4	**69**
Ballpoint pen	-	6	**78**	6
Fineliner pen	18	18	2	-
Colour marker	-	4	<1	-
Mixed f'hand Media	31*	3	16	6
Computer generated	-	-	-	16

* Subject A produced 28% of drawings with a mix of fineliner and monochrome marker

Table 6.1: Media used for drawing in the conceptual phase

specific media. Note that Student W produced some computer-generated material - the print-outs pasted into his sketchpad meant it could be included in this analysis. It is acknowledged that once drawing has moved on to computer it is difficult to track the 'number of sketches' produced, since the computer model is singular and dynamic and leaves no direct trace of its development.

Table 6.1 confirms that for early stages of the process, freehand methods of drawing are used - the experiment can thus be confirmed as studying *freehand sketching* activity.

6.2 Including Sketch Activity in the Computer-based Design Record

Records of design in current usage and the knowledge bases they constitute are, as we have identified, exclusively textual. While we might previously have considered sketches to be exclusively visual descriptions, in this experiment it was observed that the sketch work produced also included *annotations* - textual cues added to the drawing (Figure 6.1). These have also been observed by others such as [Tovey 92] but are largely ignored elsewhere. This study recognises their potential use in providing links between visual product descriptions and the text-only handling ability of current design records.

It was observed that the updating and revision of the PDS records used by the subjects during this project was slow and made in a few discrete stages, sometimes as much as six weeks apart. This highlights the shortcomings of what is still, despite the use of computers, very much a paper-based format. It appears that major amendments are made to the PDS before and after periods of sketch activity - updating of the PDS was observed in Weeks 3 and 6 for Subject L and Weeks 3 and 5 for Subject W for example. Reference to Figure 6.4 demonstrates this trend. It was also noted that especially large increases in the amount of text information produced tended to coincide with the end of the first peak of sketch activity (around Week 6 in most cases for the first iteration of the experiment).

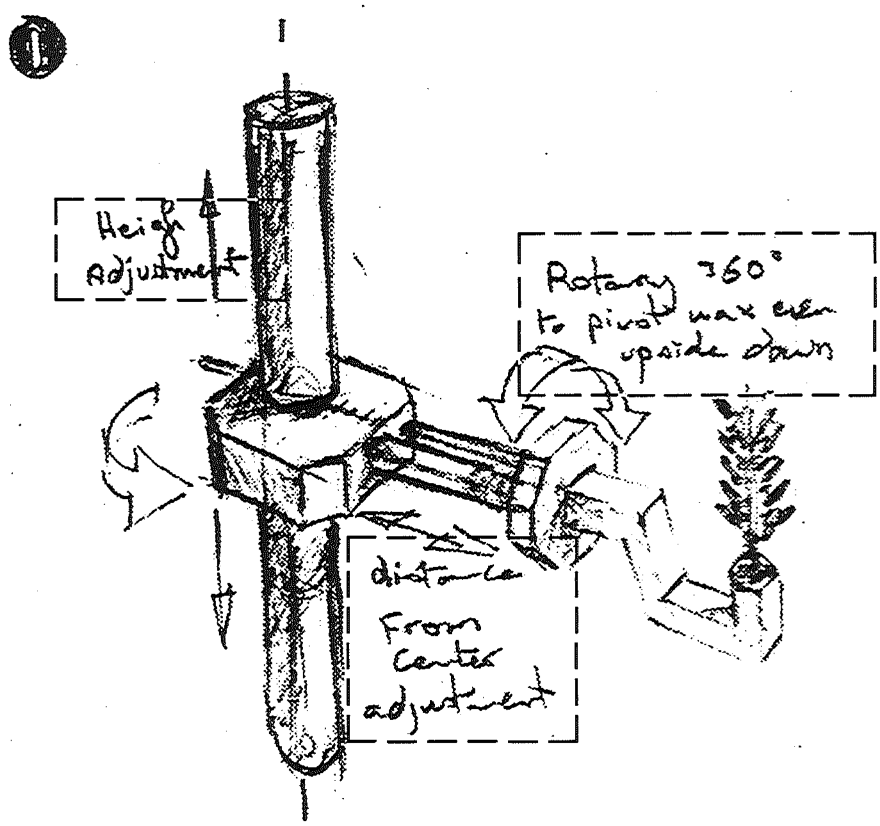


Figure 6.1 This sketch, by Subject 2L, has three annotations, marked on this figure

This apparent lack of dynamism and resistance to change perhaps indicates how separate the design 'sketching' and 'writing' tasks have become. The recognition of sketch annotations and the call for their acceptance into the knowledge base could encourage the two activities to become parallel and simultaneous, thus speeding up the communication of continuous change to the product description and design record. In this way the record can become a fuller representation of design as it happens.

6.2.1 Annotations - an experimental observation

An Annotation or *Image-Associated Attribute* is defined here, then, to be a written note added to a conceptual sketch. Since any annotation may provide an anchor for processing and inclusion in the design record, the Image-Associated Attribute is defined as including the naming of parts (e.g. 'housing', 'lever', 'caterpillar tracks') and also extends to include explanations and questions appended to a drawing (called 'Full Annotations' in Table 6.2). This definition does not include

SUBJECT	Total Number of Sketches	No. of Annotated Sketches	No. of 'Full' Annotations	No. of 'Parts' Annotations	Annotations Totals	%age of sketches annotated
A	179	29	53	13	66	16.2
L	232	21	29	4	33	9
S	375	83	107	71	178	22.1
W	88	27	44	9	53	30.6
2C	28	17	35	9	44	60.7
2DK	180	42	46	34	80	23.3
2K	157	81	120	11	131	51.6
2L	88	54	92	20	112	61.4

Table 6.2 Measure of textual annotations to sketches

dimensional values drawn on the sketch without English language qualifiers as such a figure is unlikely to match any kind of engineering case base enquiry. All of these definitions have been used as it is thought that if these annotations exist in sufficient numbers, they would need to match typical engineering database queries.

A count of the Image-Associated Attributes made in each Student's sketchbook over the observation period was carried out. Table 6.2 shows that the amount of sketches possessing associated text annotations ranged between 9% and 61%. Of these, many contained multiple annotations explaining and labelling different aspects of the product, as can be seen if the columns for 'Number of Annotated Sketches' and 'Annotations Totals' are compared. Overall these sets of figures display a general ratio of two annotations to one sketch.

The lowest percentage of sketches annotated was the 9% shown by the work of Subject L. It is interesting to note that in the course of the initial observation this subject admitted to having suffered from dyslexia. This may have produced a tendency to 'explain' concepts in pictures rather than words and thus the low annotation rate.

The next lowest score was the 16% recorded by Subject A. This subject was judged to be a very skilful sketcher, able to represent concepts convincingly and expressively on paper. Conversely, the subject judged to perhaps have the best drawing ability of all eight was Subject 2L, who displayed the highest score for annotating - 61%. From consideration of the results of A alone it might have been presumed that annotations are only used to 'make up' for deficiencies in the sketching abilities of the designer and are not needed by those with better drafting skills. The high usage of annotations by Subject 2L would tend to disprove such a notion. Annotations can add much additional information which sketches alone could not show; material qualities, clarification of certain mechanisms, the questions of the designer. A transcript of every annotation made is given in Appendix I. Again, the drawing ability of a designer should not be confused with his or her ability to think in three dimensions - we must always try to consider the underlying ideas being explored, those structural entities that underpin the two-dimensional sketch on paper.

From the results given in the far right column of Table 6.2, on average 34.4% of sketches were annotated for these subjects. It is thought that the ability to anchor what amounts to *one third* of all sketches to text-based design records would be a useful advance in design management.

6.2.2 The utility of annotations within the design record

It is thought that the recognition of the common occurrence of these annotations to sketches might enable the inclusion of sketches in the design record. The text-based nature of the annotations observed here means they can easily be included within current systems and knowledge-bases in the same way as such systems accept more typical text information in requirement list and specification type formats. The annotations can be used to provide responses to textual design queries, as with conventional textual design information. The textual response given by the annotation then activates the retrieval of the associated sketch from the visual digital design record (or 'sketchbase'). In essence then any sketch which is annotated textually becomes a useful part of the design record, able to be accessed by text-based query.

Examples given in Section 7.1.5 show how the above theory may be used in practice as part of the proposed computer support system to provide a worthwhile tool for the designer.

6.3 Sketches Tracking the Progress of Design

6.3.1 Transformation Modes

[Goel 95] identified that in the main there are two different types of design thinking, lateral and vertical, and suggested that they could be recognised in the sketches which designers produce to help them think. [Cross 89;94] also discusses these two predominating thinking modes and their roles within the overall process. The overall aim of any design project is to converge onto a final, detailed design proposal. Within the broadly *convergent* pattern of design however there will be times when it is necessary and appropriate to *diverge*; the overall design process is *convergent* but it will contain periods of deliberate *divergence* (Figure 6.2).

Divergent thinking is associated with widening the search for possible solutions to find new ideas or starting points [Cross 89;94]. It is about 'extending the boundary of a design situation so as to provide a large and fruitful search space in which to seek a solution' [Jones 70;80]. Cross associates convergent thinking with detail design, evaluation and selection tasks. Divergent thinking is thought to be

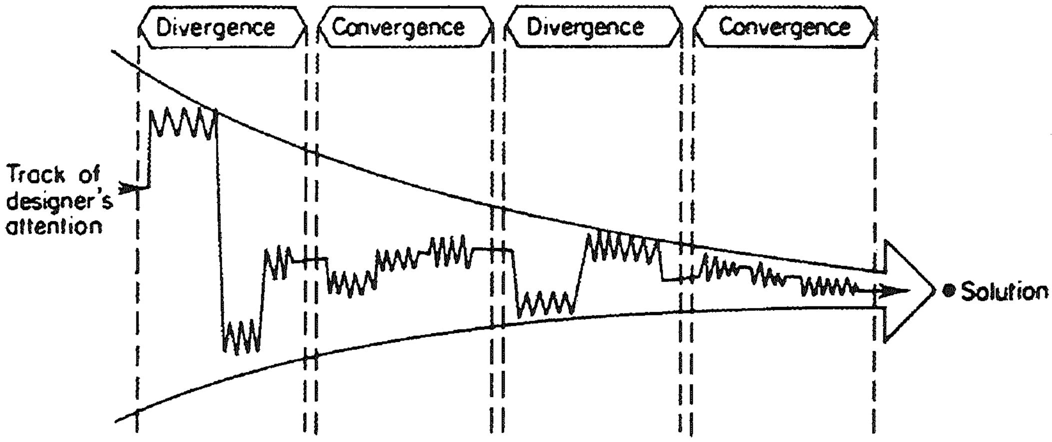


Figure 6.2: The overall process is convergent but it includes periods of both convergence and divergence [Cross 89;94].

important when attempting concept design and trying to generate many alternatives.

These convergent and divergent thinking styles may be seen as two halves of a dichotomy and this dichotomy is observed in other work. The distinction is apparent in the *linear* and *lateral* thinking styles discussed by [de Bono 70]. Linear thinking is said to proceed quickly to a perceived goal but may involve getting 'stuck in a rut' somewhere along the way. Lateral thinking involves an ability to shift the entry point to a problem so as to restructure it, coupled with a readiness to see other possibilities that this may open up.

These styles ought to be directly equivalent to the thinking styles implicit within Goel's Lateral and Vertical Transformations. Lateral transformations are necessary for 'widening the problem space' while vertical transformations 'deepen the problem space' [Goel 95]. The thinking styles discussed in the literature are thought then to be equivalent;

Convergent	Divergent
Linear	Lateral
Vertical	Lateral

Psychologists have suggested that some people are more naturally convergent thinkers and some are more naturally divergent thinkers. Thus some designers may be happier with one strategy than they are the other. Despite this preference no-one is thought to be *limited* to one or other style of thinking. Cross states that it is important to be able to change from one style to another in the course of a design project. He advocates above all the need for;

> '...a more flexible, strategic approach to designing, which identifies and fosters the right kind of thinking at the right time and within the context of the particular design project.'

There does not appear to be an overall *best* thinking style, only styles *appropriate* at a given time or in a given situation. Thus reflexive designers and their management ought to be aware which thinking mode they are predominantly involved in at any point in time. This awareness should help them to consciously decide which thinking mode will be most appropriate to apply next, so that design progresses efficiently. As Cross believes;

> '...clearly both kinds of thinking are necessary for successful design'

This thesis proposes that design will be improved by an awareness of the thinking mode currently employed and that this awareness can be gained by regular analysis of the transformation modes displayed in the designers' sketch work. This experiment, broadly speaking, studies the 'conceptual phase' and, while the literature suggests this phase is strongly linked to divergent thinking and lateral transformation, we may expect our subjects to exhibit periods of both convergent and divergent thinking over the fifteen weeks.

6.3.1.1 First experimental iteration

For the first iteration of the experiment each successive sketch was assessed to be the result of either a lateral or vertical transformation. Table 6.3 shows the sketches evaluated to be percentages of either lateral or vertical transformations in

Week	SUBJECT A			SUBJECT L			SUBJECT S			SUBJECT W		
	No.	L (%)	V (%)	No.	L (%)	V (%)	No.	L (%)	V (%)	No.	L (%)	V (%)
1							32	53	47			
2	12	66	33							4	75	25
3	6	66	33									
4	33	52	48	16	88	12	173	31	69	15	47	53
5	13	77	23	35	43	57				5	100	0
6												
7	7	29	71									
8	6	100	0									
9												
10	9	66	33							21	47	53
11	9	89	11	3	33	66	36	42	58	12	50	50
12	10	30	70	8	38	62	58	31	69			
13	12	0	100	68	66	33	31	48	52	8	38	62
14	11	73	27	38	37	63	33	42	58	16	44	56
15	37	70	30	34	41	59	10	50	50	7	57	43
Overall total	165	59	41	202	48	52	373	36	64	88	51	49

Lateral-biased Activity is highlighted in RED
Vertical-biased Activity is highlighted in AQUA
Balanced Activity (within + or - 4%) is given in BLACK

No. column gives the actual number of transformations
between sketches in each weekly episode

Table 6.3 Lateral and vertical bias in transformations: 1st iteration comparison to earlier work, as well as the number of transformations between sketches, for each week of the observation period. It should be noticed how the tendency of students to produce work that is either laterally or vertically inclined - or an even balance of the two - can be seen at a glance from this chart and this ought to very quickly give some insight into the thinking mode of the subject. We can assess the switching between ways of thinking over the period of observation by looking at the results for each subject in turn.

Subject A, who produced a reasonably large number of sketches over the 15 weeks, displays an initial tendency to produce lateral work. Between Weeks 2-5, three weeks show considerable lateral bias, although Week 4 shows an almost 50-50% split. Work done in the Christmas break weeks (7-8) shows a brief vertically-biased episode followed by a laterally-biased one. When A returns to his sketchbook in Weeks 10-11 there is another burst of laterally-biased activity. This is followed by a two week spell of very much vertically-biased work however. Another two week spell of lateral activity comes at the end of the observation period. Overall, Subject A's work displays a predominantly lateral start with alternate switching of lateral and vertical spells thereafter.

Subject L opens her account with a slightly late start but a spell of predominantly lateral work (Week 4), immediately followed by a week of slightly vertically-biased activity (Week 5). A large spell without sketching ends with two weeks of vertical activity in Weeks 11-12. There is a switch to a period of intense lateral activity (68 transformations) in Week 13 which is followed by a switch back to vertical thinking for Weeks 14-15. The week of lateral activity in Week 13 tends to make the overall activity look as though it is typified by alternate switching between thinking modes. There could be some concerns, however, that the opening spell of lateral sketch work was too quickly overtaken by vertical thinking - this may suggest a slight early fixation.

It should immediately become clear that the work of **Subject S** shows no single week where lateral activity dominates. Within the conceptual design phase, where the search for ideas is thought to be all-important, this can only be a discouraging sign. Though not clear from the results, on many occasions - perhaps as often as in 20% of cases - vertical transformations were so close to previous sketches as to be almost identical repeats. The observation of this phenomenon of *duplication* led to a refinement in the method within the second iteration of the experiment.

Subject W opens with what is a possibly too brief a spell of lateral activity (Week 2). This is followed by a spell of balanced activity and another short spell of lateral activity in Weeks 4 and 5. Subject W's work is typified by a very balanced approach overall - even those weeks where there is a notable bias towards one type of thinking it is only very slight (e.g. a 44-56% split in Week 14). The overall progress shown here is Slight lateral - Balanced - Vertical - Slight lateral, showing a dominant tendency towards very 'mild' alternating episodes. This might indicate very consistent if unspectacular work, considering that the period observed is the conceptual phase. Looking at the pattern, the final product outcome could be durable but is unlikely to be particularly innovative. This indication is qualified by the end result; for this well-defined problem the resultant hard drive casing arrangement was largely similar although within these parameters was incremental change in the form of some innovative new mechanisms.

The overall total figures illustrate that Subject A displays a slight lateral bias while Subject L and Subject W are split almost 50-50 between lateral and vertical transformations, in line with findings from a recent similar study of architects [Suwa and Tversky 97]. The sketch traces of Subject S give the clearest cause for concern by exhibiting a considerable vertical transformation bias within the conceptual phase - a phase thought to be typified by lateral thinking.

6.3.1.2 Second experimental iteration

As a result of the misleading figures thought to have been caused by the duplicating effect of extreme vertical transformation, the *Duplication* transformation was explicitly recognised as a separate transformation type during analysis of the second experimental data set. Figures giving a measure of duplication mode activity are included in Table 6.4.

Week	SUBJECT 2C No.	SUBJECT 2C L (%)	SUBJECT 2C V (%)	SUBJECT 2C D (%)	SUBJECT 2DK No.	SUBJECT 2DK L (%)	SUBJECT 2DK V (%)	SUBJECT 2DK D (%)	SUBJECT 2HK No.	SUBJECT 2HK L (%)	SUBJECT 2HK V (%)	SUBJECT 2HK D (%)	SUBJECT 2L No.	SUBJECT 2L L (%)	SUBJECT 2L V (%)	SUBJECT 2L D (%)
1									13	46	38	15	9	44	56	0
2									6	83	17	0				
3									6	50	33	17				
4																
5	4	75	25	0												
6	18	50	50	0					10	30	70	0	5	20	80	0
7																
8																
9																
10	4	25	75	0					20	15	85	0	7	14	71	14
11					25	20	52	28	9	0	88	12	1	0	100	0
12					14	29	36	36	34	15	85	0	11	18	73	7
13									18	22	78	0				
14					33	25	45	30	21	14	86	0				
15					96	6	85	9	19	32	68	0	54	41	41	18
Overall total	26	50	50	0	168	14	68	18	156	24	73	3	87	34	52	14

Lateral-biased Activity is highlighted in RED
Vertical-biased Activity is highlighted in AQUA
Balanced Activity (within + or - 4%) is given in BLACK

No. column gives the actual number of transformations between sketches in each weekly episode

The figures for Subject 2L: Week 11 have been given above in grey. These figures relate to just ONE single sketch - this is thought to have a distorting effect and so has been ignored elsewhere but is included here in the interests of completeness.

Table 6.4 Lateral, vertical and duplication bias in transformations: 2nd iteration

Subject 2C begins with a lateral spell (Week 5) followed by a balanced spell (Week 6) with a later vertical spell (Week 10). These observations are rendered almost irrelevant however by a late start and alarmingly low number of sketches produced over the period. Nonetheless, the utility of recording sketch work and the ability of sketch evidence alone to pinpoint work that is lacking should be made clear by this example.

Subject 2DK appears another case for concern. No drawings could be found to have been produced in the first ten weeks of the period. What work there is all occurs within the last five-week period of the window. There is an alarming tendency to produce duplicate transformations - in Week 14 the count is calculated as 30% of the total. Overall, these figures suggest very few early concepts being generated and a project that is short on ideas. Thus the vertical activity seen in Weeks 11, 14 and 15 is on very shaky ground; it is unlikely that there are any good ideas to further develop by vertical investigation.

Subject 2HK begins with an encouraging, predominantly lateral episode (Weeks 3 and 4). This gives way to a vertical trend which crops up in Week 6 and then occurs continuously from Weeks 10 to 15. The consistent work rate is a good sign, but over the period the pattern suggests early fixation and thus raises some minor concerns that the search for innovative solutions has again been curtailed too early.

Subject 2L demonstrates undoubtedly excellent sketching skills. This ability to represent objects as convincing 2D pictures may be deceptive however. The analysis method applied here tries at all times to consider the structural aspects of the product that underpin the sketch that appears on paper. Examining the work produced using Goel's methods seems to show that in fact, like the work of Subject 2HK, there are too few ideas generated in the earliest stages with possible early fixation as a result. The mid-period is predominantly of a vertically-biased nature although the intense period of activity in Week 15 is encouraging, suggesting a considerable amount of work of a balanced type and perhaps a late burst of near-lateral activity.

6.3.1.3 Discussion - utility of results

In view of the assessments of individual design performance on a week-to-week basis that could quickly be made from consideration of the results in Tables 6.3 and 6.4 it is proposed that a sophisticated parsing function able to distinguish between the three modes of *lateral transformation*, *vertical transformation* and *duplication* in the designer's sketches, checked against those already held in a design record, would be advantageous in providing a status report to the reflexive designer. Ultimately, parsing of visual material, such as suggested by [Gross 96], may be able to recognise and differentiate between the same-ness of duplication and the similarity of vertical transformations. Current systems would be likely to confuse the two, so more work is needed in optical identification. Lateral transformation would be defined as a much lesser degree of same-ness between sketches.

While this method of identifying transformation type can provide a useful input to enable the management of the design process it should be noted that this thesis does not make claims that such a system can predict the final outcome of a particular project. After all there is ‘many a slip 'twixt cup and lip’ - encouraging results one week do not necessarily mean that the next week will be as good, much less that the project as a whole will succeed. What the system can provide is a useful meter of the current state of a project. It gives quality feedback which management or the reflexive designer can use to determine their next move. It can provide reassurance that design is progressing to previously identified targets, or it can be used to help set new targets.

The experiment presented here analysed sketch activity using an arbitrary, convenient scale of Weekly activity. Thus data is considered in blocks of weekly sketching activity. It is envisaged that an automatic system developed in line with the guidelines given in this thesis would be able to analyse separate task-specific ‘sketching episodes’ which are thought to occur in industrial settings. This episodic study approach was not taken in this particular experiment due to the length and detail of in-depth observation which that would require. Such an approach would be possible with short one or two hour, laboratory-type experiments.

The episodic nature of designing is described in Bucciarelli's ethnographic account of day-to-day working at an American mechatronics company [Bucciarelli 94]. He talks of 'Beth's job' at several points - in this context Bucciarelli is referring to the tasks given to individuals to work at alone. These tasks, which Bucciarelli terms as taking place in 'the object world', involve designing for 'specific aspects, instrumental parts, subsystems and subfunctions' and typically involve sketching and notemaking. He describes these episodes as 'usually a solitary and intense experience'. These necessary episodes are a vital part of design and the issues raised by individual, in-depth investigation are resolved at various intervals by having 'all of the individuals involved join together to plan, decide, critique and integrate their efforts'.

From Bucciarelli's observations we can imagine that once the team has come together at each design meeting and discussed their individual reports and findings, new sub-problems will be formulated and each participant given their own new part of the design to investigate. Within the early stages of design, management may find it useful to consult instant, at-a-glance analysis of a particular 'design episode' carried out by an individual. By providing an initial indication of the kind of thinking exhibited by the designer - either lateral or vertical - as revealed by their sketches, the system is giving an insight into the progress of design. Management can immediately see that the episode fits or does not fit the thinking mode most appropriate at that particular time in the overall process and so make suitable efforts to redirect current thinking. In this way such a system can be seen to improve the efficiency of the design process.

6.3.2 Patterns of complexity

As discussed in Chapter 4, design theory predicts that drawing will proceed through advancing and increasing levels of 'concretisation and detailing' [Andreasen 94] as design progresses [Cross 87;94]. If this theory is considered alongside those discussed in Section 6.3.1 then we should be able to propose a typical or 'ideal' theoretical pattern of sketch information handling for the early stages of conceptual design.

The early stages, or conceptual design phase, should broadly speaking be typified by divergent, lateral thinking although this phase will contain both episodes of both convergent and divergent thinking within it. The complexity or detailing of the sketch work needs to increase as time passes and the design progresses from an information-poor state to one that is information-rich. These basic tenets are included in the 'ideal' pattern of the sketch information totals over the 15-week period (Figure 6.3). The 'ideal' model ought also to apply in an industrial setting although it should be noted that the gradient of increasing complexity is likely to be far steeper due to compressed time schedules.

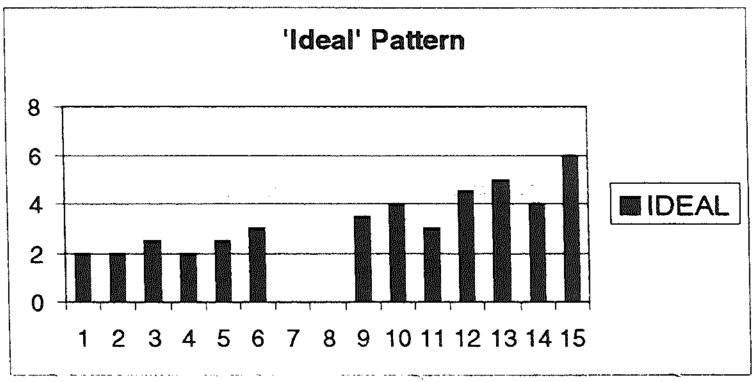


Figure 6.3 Ideal pattern of average information in sketches at the conceptual stages

At first there is greatly divergent thinking and the need to generate solutions leads to the production of many quick, simple sketches. Occasional early problems may lead to isolated episodes of more detailed investigation and thus slightly increased complexity levels may appear on the graph (Week 3). As design progresses, design investigation becomes more detailed and so too do sketches. There may still be the need to make quick investigations of uncovered problems and alternative solutions and information levels may drop briefly as a result (Weeks 11 and 14 in this example). The graph is typified by gradually increasing levels of complexity and detail. The overall level of complexity ought never to reach very high levels - such detailed investigations are not thought to be required at this stage of the process.

Consideration of the experimental results ought to demonstrate whether the sketches produced by our sample are of suitable complexity levels for the appropriate stage in the process and are thus good examples of efficient design.

6.3.2.1 First Experimental Iteration

The four traces produced by the subjects studied in the first experimental iteration failed to show any real common shape, bar the empty space around the Christmas break weeks where work appeared to cease (except in the case of Subject A - the reason for the break weeks' inclusion).

Subject A clearly has the most consistent work rate of the four subjects, with few gaps visible on the graph (Figure 6.4a). In Weeks 2 and 3 is the initial low complexity work expected from our idealised model, but this is quickly followed by an unexpected spell of high complexity work (seen in Weeks 4 and particularly Week 5). The complexity level of the sketch work seems to peak in the middle of the conceptual stage rather than at the end. Another unexpected result was that the spell in Weeks 12 and 13, which by study of the transformations therein was reckoned to be vertically-biased, actually had a low complexity level. While there is undoubtedly a close relationship between vertical transformations and detailed, complex work it is perhaps not as direct as at first thought. It is worth noticing that, overall, the sketch work of Subject A is at rather high levels.

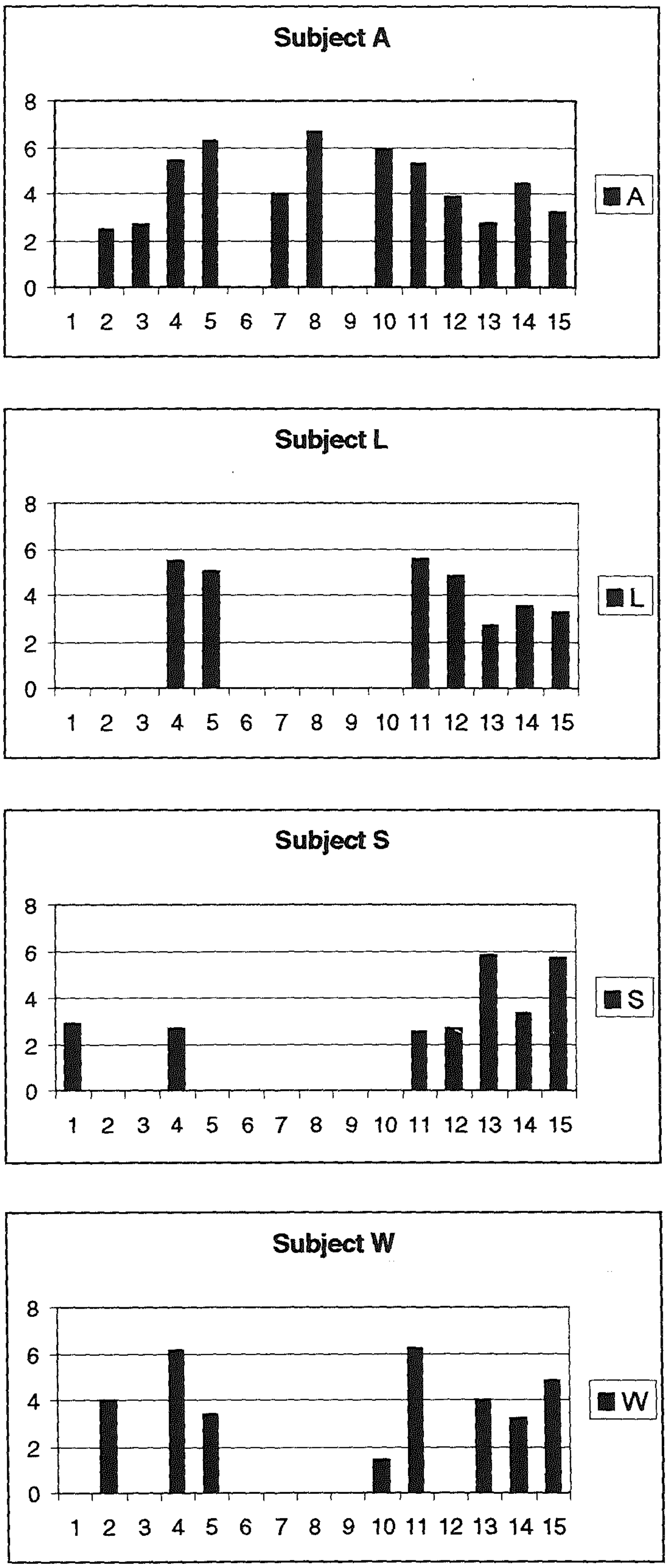


Figure 6.4 (a-d) Weekly Average Information Totals for first iteration of experiment

For **Subject L** the initial activity is perhaps of a higher complexity level than is needed. The average results overall are high, except for the lateral episode identified for Week 13. It would perhaps be preferred to see lower levels of complexity spread more gently over the available weeks than the rather more intense concentration of activity in short bursts that seems to be displayed by the graph. This style is observed in several of the other results. Subject L's graph trace seems to suggest that activity is occurring at slightly too high a level for effective lateral generation of concepts and this matches the observations made after consultation of the Transformation scores.

At first **Subject S**'s trace may appear an efficient one, with many low complexity scores displayed. When the lack of lateral transformations previously observed over the piece are considered however, attention turns to the low complexity activity shown in Weeks 11, 12 and 14. These were observed to exhibit vertical bias and yet they are low scoring in terms of complexity (the same contradiction as was observed in Weeks 12 and 13 for Subject A). In light of the examiners' decision (completely independent from this study) to award a low mark for this project overall, with regards to all aspects of the subject's design process, we should expect this trace (Figure 6.4c) to exhibit poor design practice. In view of this, perhaps work that is typified by both low complexity and vertical bias simultaneously is a contradiction in terms which reflects and indicates bad practice and so should be avoided.

The analysis of the transformations in the work of **Subject W** seemed to indicate a balanced activity with a lack of concerted lateral activity. Knowledge of the problem being solved, from information gathered by the observer, would seem to suggest a well-defined problem and a resultant narrow search space, which would explain the lack of variation in the activity. There is no real discernible shape to the activity but the overall noteworthy aspect is the consistently high complexity scores and these would be consistent with the narrow search space and reduced need for alternative solutions.

6.3.2.2 Second experimental iteration

With the refinements made to the definitions of the Complexity scale before analysis of the second data set, the second set of results are thought to provide a slightly more accurate picture of the information content of sketches.

The graph for **Subject 2C** (Figure 6.5a) is as disheartening as the conclusions reached by consultation of the transformation results. There are too few weeks of activity and what there is appears far too high to be appropriate at this stage in the process - certainly when not preceded by any spell of low complexity lateral activity. This peak of activity appears far too early in the process and as such is wasteful and a cause for concern.

The graph for **Subject 2DK** exhibits those troublesome low complexity/vertically-biased episodes which raised questions in the traces of Subject S. The high complexity level of Week 12 is thought to be unsuitable following only one week of low complexity, vertically-biased work. At a glance, the lack of sketch work in the first ten weeks gives great cause for concern.

The possible early fixation upon one design by **Subject 2HK** has already been commented on after analysis of the transformation modes within the sketches. Overall the low complexity over the period is promising, but the periods of low complexity, vertically-biased work (in Weeks 12-15) may indicate that the design has 'stalled'. If a design option has been selected (too early or otherwise) then the complexity of the drawings should increase to reflect the increasing depth of investigation.

The straight line gradient which can be drawn between the levels apparent in Weeks 2, 6 and 11 of the results for **Subject 2L** is the closest any of these graphs come to matching the idealised model for increasing average complexity levels. Unfortunately the result in Week 11 should be ignored however, as the average figure is in fact related to one single sketch. This is thought to produce a distortion effect on the figures. The complexity level shown in Week 13 is slightly higher

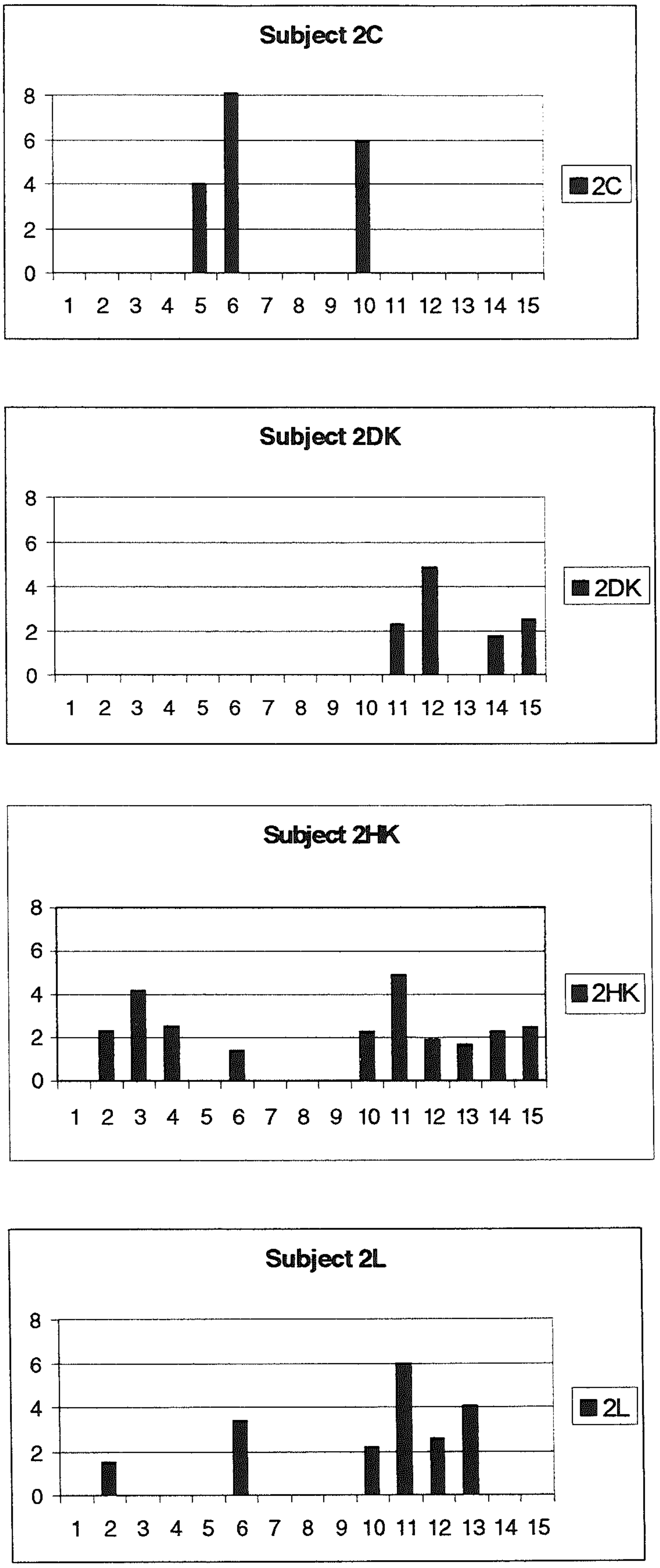


Figure 6.5 (a-d) Weekly Average Information Totals for second iteration of experiment

than that in Week 6 but is probably less than a manager would like to see if using the idealised model. The relatively low complexity levels exhibited by 2L overall (between 1.5 and 4) are thought to be suitable for the early stages of design.

6.3.2.3 Discussion

If the 'ideal' model proposed is agreed to be a reasonable model of efficient design then it would appear that the use of appropriate sketch complexity at the right time in the process is one area in which these novice designers could take advice. From the results it would appear that far too often time is being wasted in producing sketches that are more detailed than they need be when in fact what is needed is the generation of concepts via simple, quick sketches. Sketches that are detailed may even hamper lateral investigation. The conclusion for the subjects studied here, that too many detailed sketches are being made at the wrong time, fits with the conclusion from Section 6.3.1.3 that there were too few lateral episodes in the 'conceptual phase'.

Again, the judgements which can quickly be made from consultation of the resultant sketch analyses traces could provide additional utility to management and the reflexive designer. If it is identified, by study of the transformation modes, that lateral activity is the most appropriate course of action to take at a particular time in the process, then an accompanying low complexity rating ought to result. If it does not then there is the possibility that the number of alternative solutions proposed may be reduced. Complexity scores rising to medium levels should be sought near the end of the initial phases.

It has been identified that low complexity/vertically-biased episodes may occur and these are thought to have negative influence on the success of the project. More detailed real time analysis of such periods may be worthwhile in ascertaining exactly what is happening in these seemingly contradictory episodes.

It is worth noting that, from the results of Subject A in particular, some sketchers may work at a 'naturally' high complexity level. This may either be permissible, as long as the levels increase when design progresses, or should be 'trained out' of such designers in the interests of speeding up the process.

In conclusion it is proposed that a system able to automatically ascertain the level of complexity of a sketch - perhaps initially by calculating the density of lines - would be a useful tool for design management, providing corroborative evidence to be used in tandem with the results provided by the analysis of the transformation modes prevalent in the designer's sketch.

Chapter 7
Resultant System Model

7.1 System Description

The experimental study has observed the production of sketches within the early stages of design and as a result:

- has observed the common presence of the textual annotation made to the freehand sketch within the early stages of design. Further, the study identifies the potential of the annotation to anchor processing and thus enable the inclusion of freehand sketches within searchable text-based design records;
- suggests the usefulness of a mechanism to recognise the transformation mode (lateral, vertical or duplication) observable within a designer's sketch over short periods within the early stages of the design process, matched to management's desired mode of design investigation;
- has formulated a method to give a general indicator of the work rate of designers calculated from their conceptual drawings over short periods of time.

These results provide the following basis for a proposed computer-based support model. A *database and processing* system accepts *text* in a specification format framework (such as the PDS or Requirements List). Meanwhile *freehand sketch* input from the designer is split into a visual and, where included, a textual component. All textual design data is held in the 'textbase' section of the database and all sketch material within what has been called the 'sketchbase'. Resultant *hard copy facilities* and a *query-retrieval* system allow quick access to all inputted information. Automatic assessment of the inputted sketch information provides additional *assessment utility* for management in tracking the design project. By matching the designer's natural working processes as observed by experiment it is suggested that the system will find favour with the design community while improving designer efficiency.

This section next looks at each of the system's important constituent parts in detail. Their general arrangement is shown in Figure 7.1 and the system detail in Figure 7.2. The system can be considered as possessing six important parts and these are now discussed in turn.

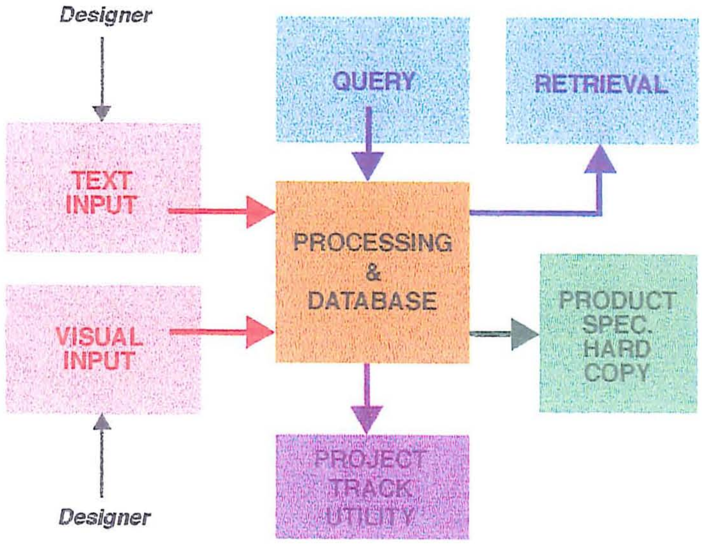


Figure 7.1 System model overview

1) Sketch input handling facilities
2) Text input handling facilities
3) Processing routines on text and visual input
4) Hard copy capability
5) Query and Retrieval facilities linked to the 'sketchbase'
6) Project Track facility, assessing qualities of material in the 'sketchbase'

7.1.1 Sketch input

The system is intended to accept two-dimensional, freehand sketch input via a suitable grabbing device.

As a sketch is entered in digital format two tags are activated automatically and assigned to each image. The first, the *Author* tag, identifies the 'artist'; the author of the sketch. This is easily enabled through initial password entry to the system or through logging on. The second, the *Date* tag, is linked to the system's internal clock and allows for the chronological and historical filing of inputted material in the system database.

Visual input is filtered in three ways, to assess various qualities of the sketch; firstly there is a measure of the drawing *Size* (done by pixel counting of the sketch

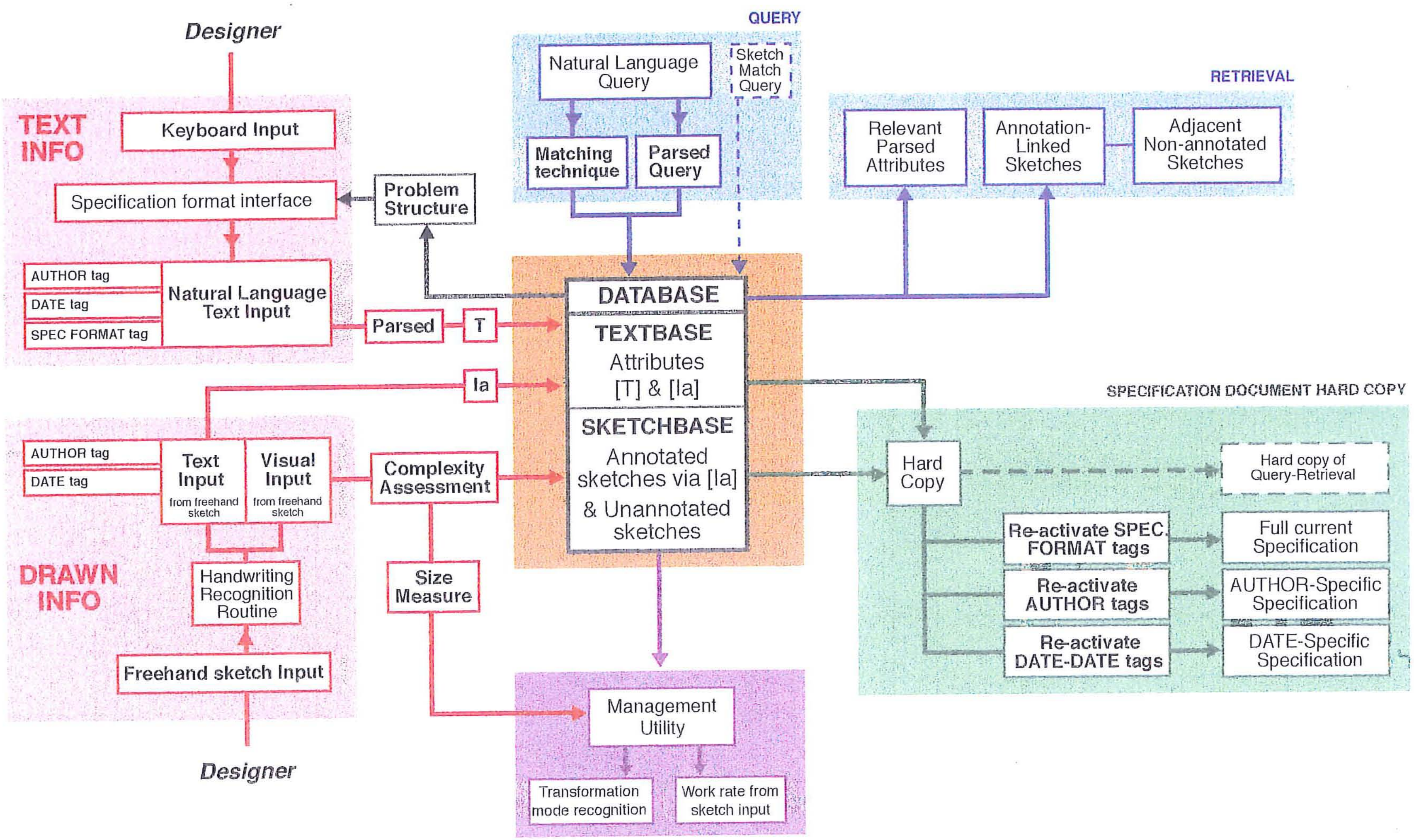


Figure 7.2 System model detail

at its original ratio), secondly an assessment of the relative *Complexity* of the sketch and thirdly the determination of the *Transformation Mode* by comparison between each inputted sketch and those already held in the system database. These three measures provide input to the *Project Track* utility.

Processed sketches are also held in the system database for subsequent *Query* and *Hard Copy* utilities. This system regards freehand sketches as containing both a visual component and a text component (although for a percentage of sketches the text field will be blank, as predicted by the results in Table 6.2). It is intended that through the application of optical character recognition routines, handwritten information included in the freehand sketch will be converted into recognised ASCII text strings. The attached annotations, or Image Associated Attributes, will enable sketches to be included in the database and will allow them to later be retrieved by query (this operation is detailed in Section 7.1.5).

7.1.2 Text input

The system accepts a 'set of verbal phrases' [Ulrich and Seering 88] whether in discursive natural language or in more terse four-or-five word phrases, since both have been identified in this study as common forms of textual information produced by designers.

The text information is submitted via the designer's selected specification or requirement list framework format. Users choose an Element in which to enter their material. Category schemes will reduce the specification to more cognitively-appealing forms. Preferably these will be created in line with the identified limitation that only seven pieces of information can be 'buffered' in human short term memory at any one time [Mero 90]. Interface formats can be chosen and changed by management or the designer. In the interests of design efficiency, entries to the system may be supported by a structured problem prompt held in a form of design matrix.

All entered pieces of information are automatically tagged with the relevant Specification Format Tag denoting the Element heading under which the entry has been made. The Author's identity and the Date of submission are also tagged automatically as outlined above.

Natural Language Processing techniques [Samad 86] can be used to reduce the discursive information to its constituent parsed phrases, each containing one clause or 'unit' of meaning. Each of these is called a *Text Attribute* [T]. Individual Text Attributes are then processed and stored within the database.

7.1.3 Processing of inputted information

The central processing heart of the system sorts and stores inputted textual and visual information for subsequent query/retrieval and hard copy purposes.

The parsing function produces parsed Text Attributes that will build to form the full product description. All submitted phrases can be held in their full submitted English form or reduced to their essential Text Attribute form, typically a four-or-five word clausal phrase that may or may not include numerical, quantitative data. These are given by [T] in Figure 7.2.

Text processing also extends to deal with the annotations added to visual sketch descriptions. These Image-Associated Attributes [Ia] can be parsed if necessary for storage in the database. Sketches without annotations, not directly associated with text attributes of type [T] or [Ia], are also held in the database.

The visual component of each freehand sketch input is examined, by means of a visual parsing function, to assess the complexity level of the drawing. This measure is then held in the system and used to provide input to the Project Track function.

Additionally, visual parsing examination and the comparison of incoming images with those in the database allows the system to specify whether an image is a lateral, vertical or duplicate transformation. Again, this information is passed to the Project Track Utility to provide a measure of progressing design.

7.1.4 Distributed hard copy

While the system is intended to work in a distributed, faster electronic on-screen format the system still enables the automatic building of a product description hard copy print out at any desired time using the entered attributes.

By reactivating the *Specification Format Element* tags applied to submitted text attributes, a print-out of all submitted, parsed attributes can be obtained, formatted under their Element and Category headings.

By reactivating the *Author* tags in addition to the *Specification Format Element* tags, an author-specific PDS can be obtained. This allows an individual designer to retrieve only their own submitted material if desired.

By reactivating the *Date* tags, a hard copy print-out of all submissions to the PDS over a specified period can be obtained. This can be used in addition to the *Specification Format Element* tags and the *Author* tags.

Sketches are not automatically included in specification documents, since they cannot logically be entered via an interface element and thus possess no *Specification Format Element* tag. A chronological hard copy of all sketches, both annotated and non-annotated, by *Author* or *Date* is available via the appropriate visual tags, which adds to the effectiveness of the distributed product description.

In addition the system can provide hard copy print-out of material retrieved by query, which extends to text material and annotated sketches.

7.1.5 Query and retrieval from the 'sketchbase'

Most importantly the system provides a query facility which allows access to all of the textual material stored in the database (*textbase*) and also to the visual material stored in the database (*sketchbase*) via textual annotation cues. This allows a designer to refresh their memory of the current description with regards to particular aspects of the design. It also allows for speedy retrieval of relevant information required by a researcher investigating a product retrospectively. The matching Text Attributes [T] and Image-Associated Attributes [Ia], along with their accompanying images, are displayed in a windows-type menu form, and can be printed by conventional hard copy means.

Queries are entered, ideally in natural language terms. These queries are then parsed using natural language processing techniques to retrieve relevant Text Attributes and Image-Associated Attributes (and their accompanying images) for the perusal of the designer or researcher.

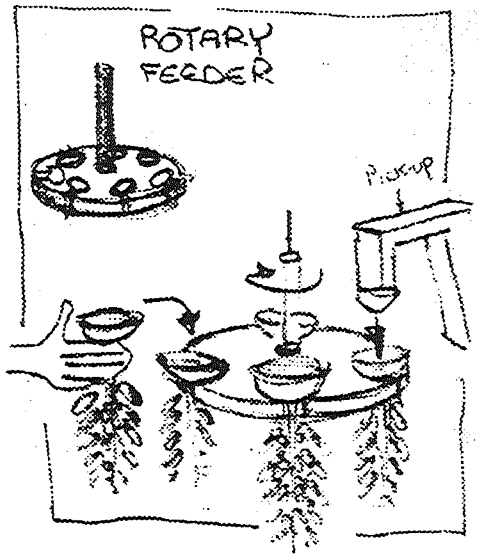
An alternative and more readily achievable method, given current processing technology, enables retrieval using simple matching techniques. Entered 'keyword' queries look for matching words within the stored attributes and display the matched entries. A direct example of this method is given in this section.

As discussed in earlier chapters, sketches are the *lingua franca* of conceptual design. They can supplement stores of textual attributes held in requirements lists and such like, which can sometimes be inadequate within the earlier stages of design. Both types of data produced at the stage of the design process observed in this experiment can be best summed up as dealing in the exploration of *ideas*. The intentional switching between lateral and vertical thinking in sketches leads to a split between the creation of original ideas and the further detailing of those ideas.

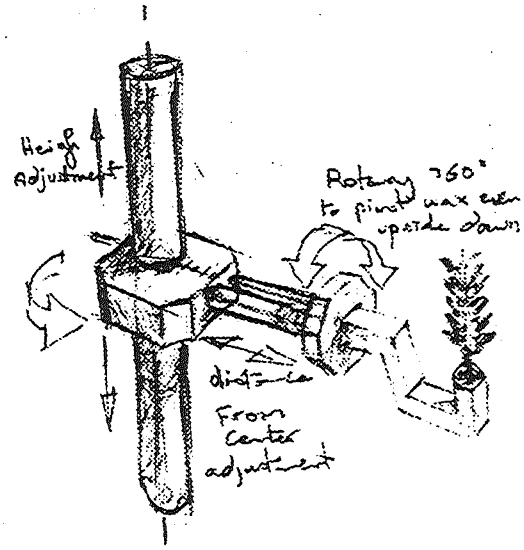
Thus any search through the knowledge base of textual and sketch information produced in these early stages is assumed to be a search for ideas. The examples given here show the envisaged use of a computer-based support tool presaged by the results of the experiment. This study sees retrospective searches through the 'textbase' and 'sketchbase' of conceptual design as a useful tool in the event of failure or rejection of selected design options further 'down the line' in the design process. The examples here detail the use and utility of such a sketch search system.

It is assumed that from the body of ideas suggested and explored in the early stages of conceptual design several key ideas will be selected for evaluation by systematic methods. Those successful ideas that fulfil the criteria stated at the time of evaluation will then proceed to further detailing, engineering and successive evaluations. Within the principals of contingent design however it must be accepted that as well as the product description or 'design' evolving and changing dynamically throughout the process, it is quite possible that the constraints and boundaries upon the design and the resulting criteria for evaluation may also change as design progresses. In such situations where constraints evolve so as to make a previously viable design solution redundant, designers may wish to refer back to previously rejected concept ideas. Such concepts may now be viable under a different set of constraints.

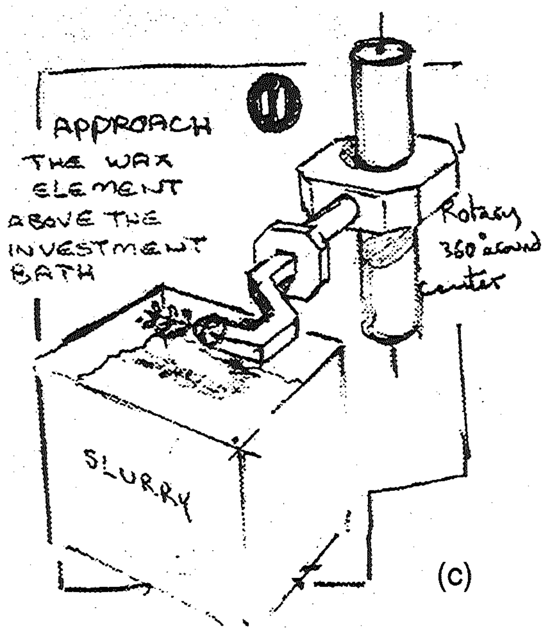
Let us take as our example the small-scale investment casting device designed by Subject 2L and as observed in the experiment. The real sketchbase provided by this data set will illustrate the use of a query-retrieval system including sketches. Imagine that a casting machine based upon a rotary feeding system has been selected after the initial conceptual design phases. Upon further investigation of this concept or with a change in the set of constraints defining the design, the rotary feeder system has proved to be problematic or simply not feasible. Rather than scrapping the work completely and beginning conceptual design again with the new constraints set identified, bearing in mind the associated time penalties that may incur, the designer can make recourse to previously rejected concepts and test their suitability for further development.



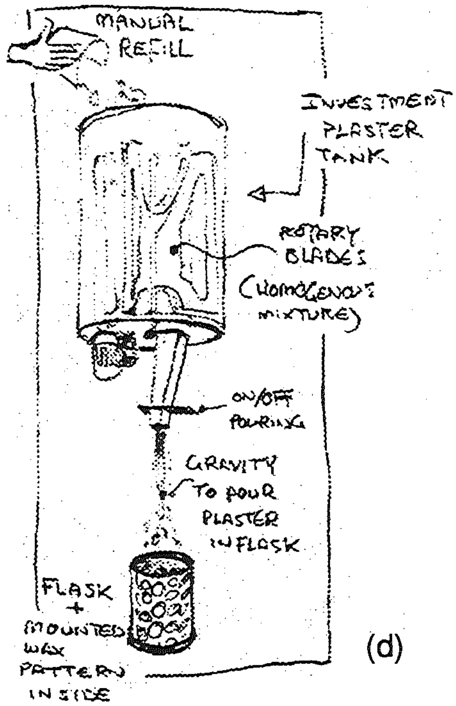
(a)



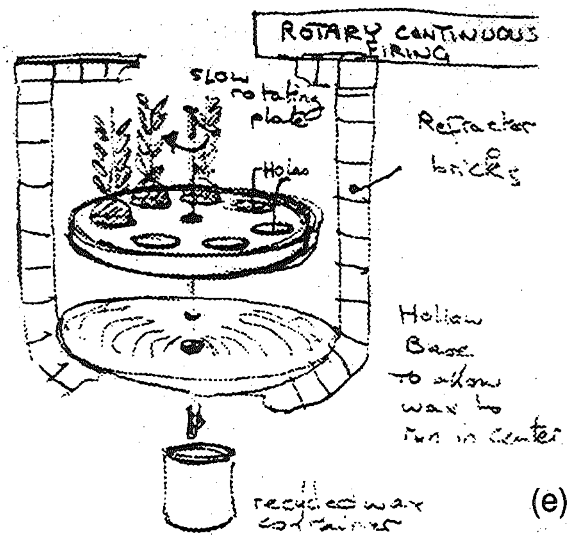
(b)



(c)

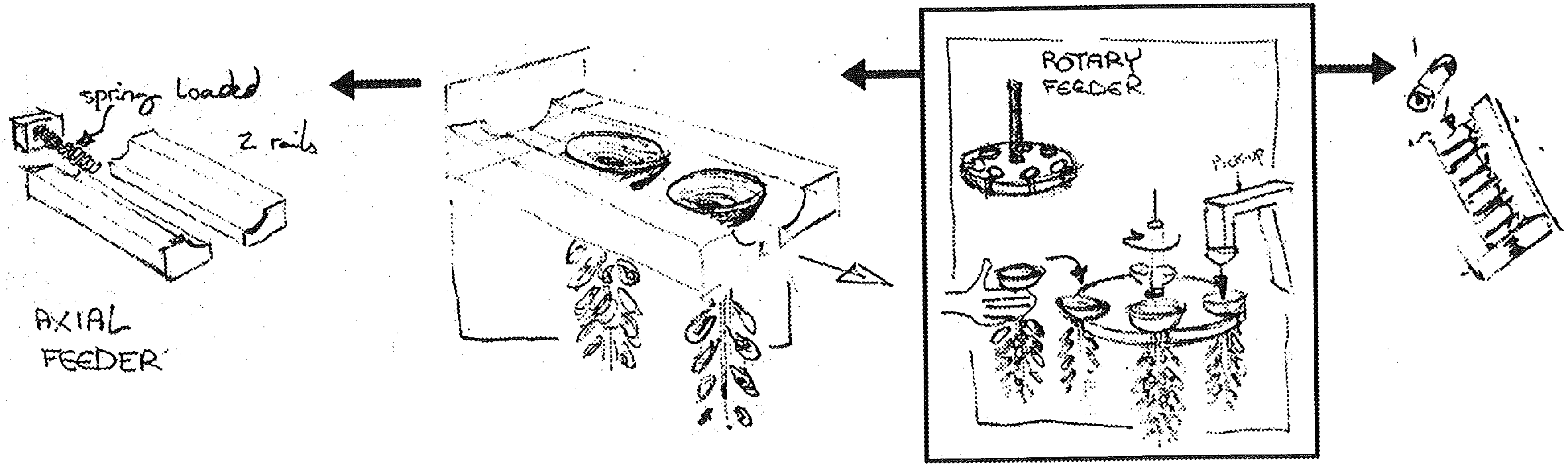


(d)



(e)

Figure 7.3 (a-e): Sketches retrieved as a result of the text query "ROTARY" (work of subject 2L)



ADJACENT (-2)   ADJACENT (-1)   RETRIEVED BY QUERY   ADJACENT (+1)

Figure 7.4 : Initial sketch retrieved by query is used as entry point to the sketchbase
(work of subject 2L)

The textbase can be accessed using text queries and, through the identified utility of textual annotations to drawings, so can the sketchbase. Figure 7.3 shows the five sketches retrieved from the conceptual design record as a result of the submitted Query statement 'ROTARY'. These concepts all involve some sort of rotary component and have been retrieved through the occurrence of the word 'rotary' within their associated text attributes. Any of these might, upon closer inspection, reveal an application of rotary feeding different from that of the now rejected concept and this can be taken forward and developed.

Figure 7.4 shows how the text query and subsequent retrieved sketch can act as an entry point allowing comprehensive navigation through the sketchbase. Figure 7.3 (a) is selected in this example; any sketch can be chosen for further searching. The Rotary Feeder is an entry point that allows searches to be made chronologically or by transformation type. Here sketches held 'before' and 'after' in the time-stamped record of inputted sketches can be accessed. The two sketches previous to the text-query-retrieved sketch show an axial feeder solution - a subsequent search on 'AXIAL FEEDER' can reveal all previous information pertaining to this concept. The axial feeder concept can now be reconsidered in the light of the changed design constraints. Note that the chronology of the design record means that via searches for annotated sketches the designer can also access *non-annotated* sketch material such as shown by 'ADJACENT (-1)' in Figure 7.4.

The above example shows how sketches could now be accessed using text-based query-retrieval methods similar to the kind currently utilised within commercially available software solutions such as DOORS. A second possible method could use a less familiar type of query - matching drawings in the 'sketchbase' to an inputted *sketch query*. In this type of query the inquirer will draw a sketch of the sort of thing they wish to find in the sketchbase - all similar stored instances can then be retrieved by means of various image-recognition algorithms.

Work is ongoing in matching hand-drawn sketches to hand-drawn queries although a reliable, working system seems some way off. An experimental system attempted to match 25 sketch queries to 25 sketches in a database [Lopresti, Tomkins, Zhou 96]. A typical sketch query and the matching sketch the system is supposed to find are shown in Figure 7.5. Some queries suggested multiple matching database entries by way of response. Of the 25 queries, three provided three matches, nine suggested two possible matches while the remaining thirteen found a single matching sketch. The creators concluded that the algorithms used sometimes performed impressively but on other occasions the intended match was ranked much lower than obviously dissimilar sketches in the database. It should be noted that this type of query is less familiar than the typed-in query and it may be more difficult for designers to adapt to such a method in the short term.

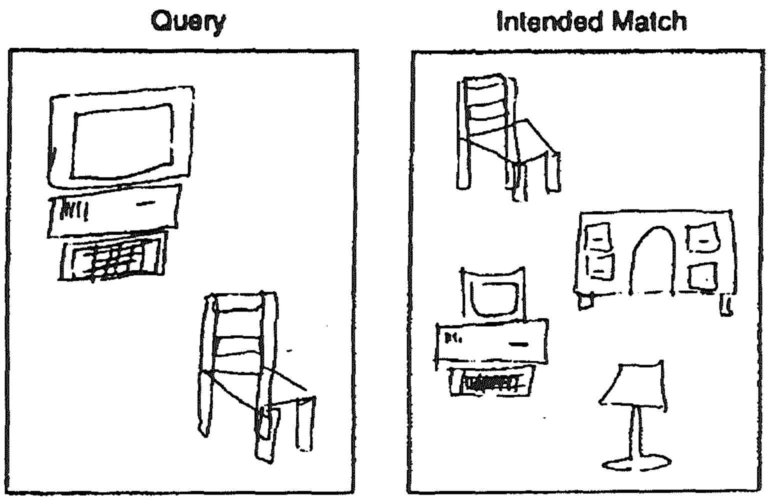


Figure 7.5: Example of a query and its intended match in the database. [Lopresti, Tomkins, Zhou 96]

7.1.6 Project Track: assessment utility

Through the application of visual parsing routines to inputted sketch material the system provides an additional utility to management and designers. This utility tracks the progress of the design and the designers' inputted work and gives some measure of the work produced.

By quantifying a measure of the complexity of each inputted sketch, via visual parsing routines (inititially based on the recognition of *line density*) and an assessment of size by pixel-counting, the system calculates the information held within each sketch. By comparing these totals with the amount of sketches produced, the ratio of individual or collective work rate or *sketch effort* is calculated. These ratios may be calculated on a weekly basis or for a specified DATE-DATE period and display to management a measure of sketch activity.

By visual parsing of inputted sketch input and comparison with previously inputted images now held in the database, the system assesses the level of sameness between new and old drawings. Suitably different drawings represent lateral transformations, relatively similar drawings are vertical transformations, while near-identical successive drawings are regarded as duplicate transformations. By assessing the percentage of each mode (lateral, vertical, duplicate), the system can identify the dominant mode of transformation at any time in the process.

The lateral and vertical modes may be dominant or balanced at any given time in the process. It may be useful for management to have some indication of mode since they may prefer a certain mode to be dominant for particular sketching episodes. If, for example, management requires a more expansive sketching episode at a certain point in the design process then they can check to see if the sketches currently being produced contain a lateral bias, indicating the creation of many concept options. When a chosen concept is being developed and engineered a vertical bias may be preferred. Over long periods and many episodes of sketching in the conceptual phase an equal balance of the two is expected. Using this method the system can identify the current status for consultation by management or flag a warning to a designer tending towards the inappropriate thinking mode.

Chapter 8
Conclusions & Recommendations for Future Work

8.1 Conclusions

This thesis reports the results of a research project which has aimed to investigate the early stages of the design process and improve the communication at this stage. It proposes that this is achieved through including any visual material produced within a suitable recording mechanism. This research is novel in its focus and in some ways in its approach.

The experimental approach is novel since it prefers the use and unobtrusive measure of artifacts produced as part of a real design problem investigated over a long period of time instead of the more typical laboratory-based protocol methods. The study recognises the technology push that has led to the creation of computer-based support tools which do not match designers' processes in the early stages and instead advocates the observation and study of designers at work, to provide quality input that enables the generation of suitable models for support.

The research has focused upon a particular stage in the design process, rather than try, in a prescriptive manner, to suggest a universal solution to the entire design cycle, from ideas to manufacture. It is believed that a piecemeal approach to research of various stages and problems within the design process will form an improved cumulative picture of design across the research community by providing complementary models of design and design support.

In conclusion then, this study identifies the artifacts produced by a selection of individual designers within the early stages of design and assesses their rate of production. It then suggests the preservation of these intuitive methods, while recognising inefficiencies within them. The study recognises the benefits of traceable design in an area traditionally unsupported by such strategies and suggests that means be devised to enable the recording and storage of these recognised, intuitive artifacts. Recording of the inputs and artifacts of early-stage design has other benefits; the research also suggests that a track of design work rate can be provided by the analysis of the recorded intuitive sketch work only.

This study builds on the work of [Goel 95] suggesting that effective design, within its early stages, depends upon the careful and intentional use of lateral and vertical transformations at appropriate times and that guidance in choosing the suitable approach can be made from the analysis of the designer's sketches. Further to the work of Goel, this study recognises the importance of the duplication mode of transformation and the negative effect it has upon progressing design.

This research has as its main deliverable a suggested suitable model which harnesses computer capabilities while recognising the intuitive processes exhibited by the observed designers. In preference to trying to solve the problems using existing - and in some cases unsuitable - technology, this study proposes an idealised system that uses the next generation of today's technologies. To enable the development of this next wave of support technologies, the following section of this chapter identifies 'weak' areas which will require future technological research to make the system realisable.

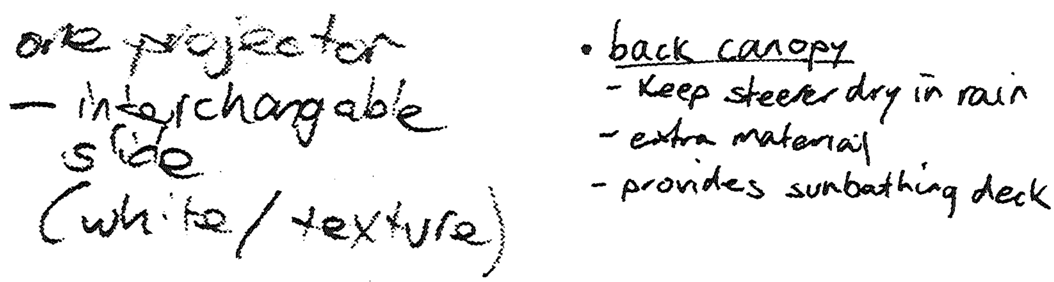
It is hoped that by its approach and through its main findings, the research has identified a system model that will lead to more efficient use of designer effort, improved, shorter timescales and better design results in engineering by improving communications between all those involved in the early stages of design.

8.2 Areas for Technological Research

Within the proposed model, areas for technological research can be identified that will make the system outline feasible.

8.2.1 Annotation processing techniques

For the systems described in Chapter 7 to be made practicable, methods of capture will be required that can convert handwritten annotations (Figure 8.1) to ASCII text strings both recognisable to and compatible with a digital design record.



(a) (b)

Figure 8.1 Examples of subjects' handwritten annotations (both at same 1:1 scale): a) by subject 2L; b) by subject 2C

Within the computing science research field, work is ongoing in handwriting recognition. Research investigates topics such as alphanumeric character model recognition [Favata 96], complete word recognition (both in terms of lexical understanding and identification of complete word segments) [Kim 96] and English language phrase-recognition [Kim, Govindaraju, Srihari 96]. As a result there have been considerable advances in terms of both speed and accuracy. This research continues, driven largely by the need for the electronic sorting of letters by the recognition of handwritten postal addresses. Such techniques would make feasible the analysis and storage of textual annotations made by hand on paper.

Commercial solutions currently available offer the recognition of text written by hand on electronic tablet devices using stylus tools. Microsoft use the *Jot* handwriting recognition system within their handheld PC devices and digital workbooks. Jot features a choice of two character sets for best matching to handwritten input. It also uses a zonal approach to distinguish between upper and lower case letters; characters written below a line on the tablet workspace will be identified as lower case, with those that cross the line identified as upper case. Recognised character strings can then be sent to a variety of Microsoft applications.

IBM handheld workpads and 'Palm Pilot' devices meanwhile use 'Graffiti Power Writing Software'. For text recognition, users must write characters to match the Graffiti alphabet (Figure 8.2) with defined shapes, starting points and a desired vertical orientation.

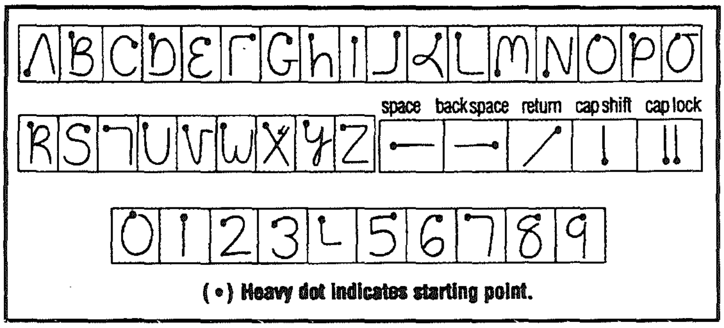


Figure 8.2 Graffiti handwriting alphabet (IBM 1998)

Both of these readily available approaches enable the recognition of handwritten annotations within electronic design environments accepting input from tablet workpads. The limitations of 'electronic sketching' however, as discussed in previous chapters, also limits the usefulness of the Graffiti and Jot approaches. In view of this, this thesis recognises the importance of research into the recognition of handwritten text on paper.

8.2.2 Visual parsing techniques

Work is required to improve the parsing of the inputted sketch material. This would provide for the assessment tracking utility of the project. Particular work is needed to better identify similarity and difference between incoming sketch material and images already held in the database. This is required so as to identify the type of transformation occurring.

8.2.3 Non-intrusive sketch capture

Work is required to identify a device capable of transforming two-dimensional images drawn freehand on paper into a digital format in a speedy, non-intrusive way. This is a key factor in the step towards successful integration of the proposed system into design practice.

8.3 Recommendations for Future Work

This work is as up to date as possible in recognising areas of current research, uses up to date experimental source material and includes near-realisable technological solutions in its suggestions for the proposed system model. It must be recognised however that unforeseen technological developments may impact upon the area of study. One area of possible change concerns the capture of conceptual artifacts. While the non-intrusive capture of 2-Dimensional sketch material seems a logical step away from the intrusive methods of digital sketch capture available today, something like the capture of low-tech (i.e. non-CAD) 3-Dimensional work may be a possibility in the near future. To prepare for such a development will involve the recognition, through observation, of the 3D models produced by practising designers.

Future research directly linked to the study presented here could extend to cover the use of sketches in group settings within our academic sample group in order to discover how the communication links would be improved by the use of an approximation of the system suggested here and to test the theory of linked but individual 'episodes'. The next step would be to transfer this work to an industrial setting, which is characterised by greater sources of 'experimental noise' and greater amounts of exchanged information.

The system model presented in this thesis provides a method for capturing conceptual design in forms suitable for the improved evaluation of those products, within systems suggested by the likes of [Rodgers, Patterson and Wilson 95]. This is the uppermost limit of the system in terms of its coverage of the total design process. It does not provide support for the *transition* from intuitive models to computer-built models at the next stage of design definition. A linking movement into this area is perhaps the next logical progression from the study presented here. The activities undertaken within this transitional stage constitute almost certainly the most under-researched part of the process and to understand these activities is one of the greatest challenges facing the design research community at present.

Research in this transitional phase will involve going beyond the identification of intuitive design techniques, as have been presented in this study, to understanding the underlying cognitive processes. This will require the input of both psychologists and engineers and will perhaps lead to the creation of wholly new digital technologies and tools which will match exactly the intuitive processes of design engineers.

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Appendix I

Record of textual annotations to sketches

1.1	Subject A
1.2	Subject L
1.3	Subject S
1.4	Subject W
1.5	Subject 2C
1.6	Subject 2DK
1.7	Subject 2HK
1.8	Subject 2L

Annotations - Subject A

SUBJECT A

Page No.	Sketch No.	Quote Annotations	Parts Annotations
1	1	adjustable support	
	7	6 tiers of 7 each - with (1.4m wide) gangway. Roughly 42 seats.	
3	3	loading part [???]	
5	5	side of caravan flips down to pull out	
	6	inflatable seating	
6	2	a) pushed out by hydraulically-powered pumps b) two pieces here to fall down from side	
8	4	problem with flat bits not fitting over joints	
9	2	a) problem with number of seats and b) guard rails set in c) flipping seats mean easier access d) folding mechanisms for floor e) no litter bins f) no steps g) no disabled access	
10	1	a) could have seats b) could just be steps c) if there are only steps need bigger pitch	
	2	a) There is a mixture of seating - conventional 'bucket' seats, benches, leaning posts and seating on tiers b) people sitting on tier c) stand has fences, larger tiers d) steering position	leaning post, 'bucket' seats, benches
11	1	pads to show where people can sit	flip seats
	4	circular seating allowing people to turn	bench seating, bucket seating
12	1	a) standing part fits behind seats b) seating may [???] fence	
	2	folding mechanism	
	3	bench seating allows basic user	
	7	same sort of umbrella mechanism	
14	4	a) free-standing area b) fold up table c) people standing - these bits are too small to lean on	
	5	looks a bit tight	

Annotations - Subject A

16	1		snack bar, male toilet, female toilet
	2	a) circular snack bar arrangement b) large serving hole c) problems with ease of [???]	
	3	a) need to find out info about size required for portable toilet b) snack bar probably doesn't have cooking facilities	table, toilet, storage
17	1	a) misused space at back b) I don't like the look of this	
18	1	a) problem with wind - need to find info on tent b) 'free form area' - sit, lie, do whatever you want c) bench for people only staying for a short time	
19	3	may need extra member to stop failure for buckling	
20	4	I seem to be stuck in a rut - all the drawings are the same	
24	1	a) don't overload b) weakest part - rigid seating c) strong - allow a lot of people to sit on benches	
	2	a) linking things for fences b) widening stairwell - impressive feeling plus allows easier access	
	5	a) standing area b) seating gets narrower as gets lower	benches
29	7	flap which falls on bar and covers other hinges	

Annotations - Subject L

SUBJECT L

Page No.	Sketch No.	Quote Annotations	Parts Annotations
1	1	Two separate rooms - one for switchgear, one for control room	
2	1	a) Hydraulic feet that allow unit to be lifted off the ground - this also allows wheels to be removed b) roof is able to blow off in the event of a fire c) back of this comes off to get at cable end boxes i.e. where the termination takes	
	3	a) Extendable unit. Roof moves up and walls move out. b) This allows room for height to work in and room better - also room for end boxes for the termination of cables.	
	4	make-off box	
	5	roof action i.e. think of camper vans	
	6	edges of unit: something that sticks and could be more difficult to vandalise	
6	2	Extendable unit: extendable side; both panels are removable o the long sides. This allows access to the back of the cubicles.	
7	2	lights could be used at night to light up the walls	
	3	slide off walls - the shape makes it difficult to vandalise and makes the door hidden	
	4	thickest part of wall	
8	1		extendable sides, switchgear panels, control equipment, removable panel
	2	however roof needs to come off totally in the event of a blow-up	
	3	Roof is not attached once unit is landed. Is secure in transit.	
9	1	a) end boxes that have to be terminated b) hole in the underneath so jointer can get room to terminate c) Trench is dug away before the mobile unit arrives. Unit is parked over trench. d) cable that has been terminated	
	2	a) The termination box is too near the side - this could lead to problem when all the switchboard panels have been bolted together b) 3 core cable not very flexible (polymeric material)	

Annotations - Subject L

13	3	a) rigid structure is pulled out this way from the unit to support the weight of the switchgear b) supporting leg is lowered so side expansion is stable and will take the weight of switchgear c) structure that switchgear is bolted to is moved out on to expanded structure
14	5	pull structure out from side of unit to support unit to allow heavy switchgear to be pulled out
	6	No use - no access to bottom of
	7	flexible structure that pulls out (rigid structure)
15	8	growth lengthways rather than wide?
30	4	two wheels or four wheels?

Annotations - Subject S

SUBJECT S

Page No.	Sketch No.	Quote Annotations	Parts Annotations
1	2	ski pulled up by motor and wire	
	12	Transport by car to site: unload; take to slope; set up at top of slope; start up, use once or continuous	
2	1	car luggage rack	
	2	hand winch, like fishing reel	
	4	pulled up hill; motor knocked out of gear	
	5	power needed	
3	1	bench on skis	
	7	bungie ski-ing	
4	2	parachute up slope	
	3	propeller	
	4	not suited to snow boarding	
	5	a) bazooka? b) spring recoil; explosive; air/compressed CO2	
	7		pulley, winch, wire, gun
	8	works on principle of [???] line	
5	6	a) spider tow b) legs held in snow	winch, casing
	8	magic carpet	
6	5	like fishing reel	
	11	self-propelled vehicle	
	12		mat
	13		chain
8	1	looped rope	
9	2	How is it going to be transported? Rucksack; sled; self-propelling	
10	1	a) taught rope b) slack rope	
12	5	a) buried in snow or store rope b) plastic mould	pulleys, motor
14	9		motor, pulley
17	9	a) carry on back b) light or heavy	
	2	drag - takes advantage of snow	
	4	carry between two	
	5		stretcher, sled/sledge, luggage rack

Annotations - Subject S

	6	skidoo	
20	3	slow moving device	
21	1	a) outer shell b) rope store c) spike sticks in snow d) need space here	fuel, pulleys/rollers
	2	size?	electric motor, battery
24	4		fuel tank, handle
26	2	store rope when not in use	
27	1	set up and go	
	7	engine at bottom of rope	
28	2	Pull up rope, attach anchor to snow, engage winch, set up sled, go down and round with rope, set up bottom tripod, start	
	5	take product up slope	
	6	a) product climbs up - caterpillar tracks or pulled up by its winch b) skidoo & ski tow	
29	1	moulding	
	2	disengable gear to retrieve spool of rope	spool for rope, main engine crank, motor, cooling vents & exhaust, handle, pulleys, handle, moulding/sled
31	1	need tension in rope if motor is at bottom of the slope	motor
	2	slack: slippage of motor shaft against rope	
33	1	a) force of person pulling b) force on spring = 1 person pulling c) direction of rope	motor
	2	a) not moving b) motor ticking over	
	6	if it gets knocked, automatic cut off	
34	5	a) flat surface for snow b) plastic construction c) spikes for ground/snow/ice	
	10	spongy/rope covers	
35	1		motor
	2	a) plate digs into snow b) plastic moulding/glassfibre	motor, anchor, spool, rope

Annotations - Subject S

		c) motor at foot of hill - 4 stroke Honda/Brigg & Stratton	
		d) spool to store rope	
		e) sled can be pulled or driven	
	3	pulleys pivot to take up slack when person pulls on rope	anchors
	4		motor, spool, anchor
36	1	fix person to rope	britonhook, bar
	2		button
	3		Poma button
	4	skier	
	5	snowboarder	
	6	a) something you can hold	
		b) has to be comfortable	
		c) has to come off of rope	
	7	sledger	belt
37	4	a) lightweight	
		b) elegant	
		c) easy to maintain	
		d) no weather protection	
38	4		motor, rope spool
	7	frame - steel or aluminium	
39	5		motor, spool
40	1	Transport device - skidoo	motor, spool of rope
	2	a) on snow - drag	controls, footstep, spool, motor
		b) on grass - carry	
	4	get out of car, use to travel to slope, set up (deploy)	
	5	stop; walk up hill with fine rope; plant stake; set machine on; put up anchor; go	
41	1		rope, chain
	3		pulley guard
	7		motor, spool unit
42	2	winds thin rope in	
43	3	mount in rope spool	
44	2	could take apart easily for easy servicing	motor, spool rope, controls, pulleys, anchor/pulley end plates
	5	a) tubular frame	

Annotations - Subject S

		b) plastic moulding sandwich	
46	1	a) slides up and down	spool, anchor
		b) extruded plastic handles soft to touch	
		c) aluminium frame	
		d) minumum structure; strong; light; corrosion resistant; relatively easy for low level manufacture	
		e) no weather protection for engines	
		f) no insulation	
		g) no guards	
	4	a) aluminium tubing	
		b) soft plastic extrusion	
	5	aluminium frame - TIC weld	anchors
	6	spikes go into ground/deep into snow	
47	1	a) could add guard to sensor	fuel
		b) height adjust	
		c) plastic formed body or glass fibre body	
	2	a) mesh allows air to cool	anchor, pulley
		b) weather proof	
		c) insulation	
		d) aesthetic appeal	
		e) identity	
		f) no safety problem	
	4	need space for bipod/tripod	
	5	a) formed by two separate parts	
		b) vacuum form or injection mould - like topper [???] but need to produce lots	

Annotations - Subject W

SUBJECT W

Page No.	Sketch No.	Quote Annotations	Parts Annotations
1	1		control, data store, server, terminals
	2	Alarm: corrupt hard file	
	3	maintenance identify the faulty drive by warning LED	
2	1	push to lock; pull + button to unlock (like car door). May be spring loaded	
	2	push to lock; push to reject. Must be spring loaded (like retractable pen)	
3	1	a) push to release b) springs by elasticity of ABS	
	3	a) hinge without springiness b) ABS	
4	1	push push switches - click-click	
5	2	a) assembly alignment poles b) curve in at rear to help location (up, down, backwards)	
	3	moulded spring at front	
	4	a) moulded springs? b) for better action use swing gates at front too - but must be tracked to control movement. Limits also Req's [Requirements?]	
6	1	a) Looking at moulding springs into ABS: simplifies assembly and reduces parts b) complex inj. moulding req'd c) low adjustability after manufacture	
9	3	IDEA: use lever release instead of button	
	4	a) fewer parts b) easier cheaper assembly	
10	1	a) electromagnetic absorption b) permanent magnet interface c) electromagnetic/permanent magnet interface d) need mechanical lock for drop test e) could buy software controller f) Load hard file - permanent magnets - on drawer and cage. Lock in place - pulse signal to electromagnets to release and eject (>>Force)	
12	2	force components	
12	7	low resistance, high resistance	
13	1	a) spring force	

Annotations - Subject W

		b) spring lever c) snap fit d) handle	
	3	Spring support; lever can only move up and down in the gap, thus holding the spring in place	
14	1	use plunger to make conductive contact between drive and cage	steel plunger, steel spring, hard file, EMC shield
24	1	carrying drawer with finger through handle hook	
25	1	handle forms	
26	1	more handles	
27	1	What is it like to hold? Sharp? Knobbly? Slippery?	
	2	a) grip surface (finger pads?) b) sharp bits - dutch bends	
28	1	a) fillet edges b) distinct button c) smooth handle	
30	1	steel	PCB

Annotations - Subject 2C

SUBJECT 2C

Page No.	Sketch No.	Quote Annotations	Parts Annotations
1	1	water into canal - to gearing - to generator - to electric motor	
	2	solar panels	
2	1	power	
3	2	a) roof slides back b) dining/lounging space c) walls fold down to provide more floorspace d) walking on walls?	
4	2	a) sunbathing deck b) extended window c) smooth curves - more elegant, cruiser-like style	
5	2	a) back canopy keeps steerer dry in rain b) provides sunbathing deck	
6	1	a) water flow b) lock gates c) large mass of water could provide energy every time lock gates are opened	
7	1	retractable roof - more light, more sunshine	
	2	a) open air saloon b) traditional tiller steering	
8	2	a) towing section - 2 berths, kitchen, saloon b) 2 berth carriage - toilet, storage c) steering position d) playpen carriage - 3/4 small children play softly e) larger saloon - common area. storage	
10	1	open-air dining and lounging	
	2	a) top slides back b) sides fold out c) table rises d) steps disappear Bond style, steps appear Bond style	
	3	a) open air dining b) sliding roof c) folding out sides	
11	2	a) perspex dome b) steerer's view	

Annotations - Subject 2C

12	**1**	pivoting platforms - more lounging space, walkway between boat & water. One on both sides to balance the boat.	
	2	platforms fold down from sides so as to not exceed width limit	
13	**1**		tiller, interface, solar panels, lighting, batteries, water level, nozzle, gears, electric motor

Annotations - Subject 2DK

SUBJECT 2DJK

Page No.	Sketch No.	Quote Annotations	Parts Annotations
3	1	lens extends ??? of camera as door opens	
	3	a) flash on light	
		b) knobs on back?	
	5	closed position - shutter ??? - cannot take ???	
	6	a) close up lens	view finder, lens cover, MORE
		b) close up knob (embedded)	
	7	open position - flash on - take a pic	
6	1	fits in briefcase	
	2	left hand	
	3	a) closed for storage	
		b) lens (closed to protect)	
	4	open for use	
	6	pull to open	
	7		viewfinder, pic counter, MORE
10	1	possible control positions	
11	2		flash tube assembly & boards, S12 flex lead, MORE
14	2	a) v. cheap plastic with cardboard securative [sic] cover	
		b) keep light out instructions	
	4	serrated cardboard cover - comes off for storage ???	
15	1	folded storage position	
	2	should flash go somewhere else	
	3 & 4	does it need to fold - this would increase the cost of production - is it justified?	
16	1	solid - off shelf/??? in plastic pack - ??? - ???	
	2	serrated cardboard	
	3	a) no close up	flash, view, shutter button, MORE
		b) possible shutters ???	
	4	aluminium back protects from ??? and ???	
	5	battery pack as power source when	
	6	ripped card edge	
	7	pre-printed film	
	8	a) double use	
		b) cheap & throwaway	
		c) not concerned by package	
		d) sold in '10' '20' sizes	
		e) different themes - party, birthday, Christmas	

Annotations - Subject 2DK

19	1	a) simple box b) how to raise unit	
	9	mirror - what angle? - 45deg.	
24	1	curved front - to protect lens	
47	1	As flash unit is raised, view finder raises automatically by gears. May involve bellows.	viewfinder, flash unit, MORE
48	7	make the camera compact/simple/reliable	
51	1	a) viewfinder raises automatically b) lens folds up as flash unit raises	
	2	lens fully raised	
52	1	possible shape for front (make it as appealing as possible)	
	2	use bellows that Hugh gave me	mirror, pics, MORE
56	1 & 2	worked out positions of each module	
57	1		bellows, mirror, shutter, MORE
	2		mirror & bellows, shutter, MORE
58	1	viewfinder raises automatically as ??? raises	

Annotations - Subject 2HK

SUBJECT 2K

Page No.	Sketch No.	Quote Annotations	Parts Annotations
1	1	a) pad: all points known b) when wrapped, points pick up in key areas	
	2	a) wrap object b) laser scans pad - sensors pick up in appropriate pos[ition]	sensors
	3	a) pad emits laser b) sensors pick up relating positions	
	4	object rotates	
2	1	user interface	probe laser deflection sensor
	2	a) sensor rotate around object b) put sensors on key parts of object - rotation of laser pinpoints pos[ition] of object	
	3	moves down, scanning layers of object	
	4	a) start flat to zero b) all points relative to centre	
	5	sensor pad wraps object	
3	1	a) takes up too much room b) rotates around object c) scans in one pass - hopefully quicker	
	3	rotating mirror	
	4	creates sheet laser	
4	1	as scanner moves down object rotates	
5	1	dome scanner moves around object - maybe have to flip object for full 3D image	
	2	a) scanner circles object and moves up and down b) rotary feeder	
6	1	manual scanner handheld... already exists	
	2	a) beacons triangulate position of handheld scanner b) resistance heating	
7	1	a) dual camera b) manually scan image c) sensor to define position in space d) camera on top of computer if distance has to be 1.75m	
8	1	Beacons which triangulate position maybe not accurate enough. Sensor/transmitter on scanner would have to be in the right place.	
	2	a) ceiling has sensors/targets so camera can see and determine position b) scanner has vertical camera/sensor so wherever you scan it knows position	

Annotations - Subject 2HK

9	1	targets in positions around objects so camera can see objects and targets - defines position in space
	2	a) scanner like a camera b) 3D images stored c) take images from different sides/angles d) keep data 'til later - manipulate on computer to match wireframe to create whole 3D image
10	1	a) use tripod - keep steady and easier to calibrate b) use external lights/texture map c) rotating stand, easier for whole object scanning - angles of images all the same - makes it easier to make whole 3D image on computer
	2	a) to scan cup: 6 positions minimum b) bottom positions capture outside features
11	5	what's minimum distance between object and camera?
12	1	distance between cameras - can it be constant?
13	1	transparent casing
14	1	camera movements: distance between cameras/distance between camera and turntable
16	5	metallic, silver, futuristic finish
18	1	with flap
	2	without flap
19	2	Object not in centre of turntable - what happens? Best if roughly in middle.
21	1	have to work out optimum distance
	3	Also work out angle of cameras. Best to point at centre of turntable.
22	1	a) 2 digital cameras - colour/high resolution b) 1 projector - interchangeable slide (white/texture)
	2	fixed vol[ume]
23	1	fixed vol[ume]
24	1	a) fixed vol[ume] b) pad positions

Annotations - Subject 2HK

25	1	3 zoom positions	
26	1	a) focal length distance changes b) 50mm (lens) and wide angle c) 55mm - £150	
27	1		lens, slide, glass protector, consenser lenses, bulb reflector
	2		texture slide
	3	a) to 200m for different objects b) servo motor - computer-controlled	
28	1	a) optimum angle so all sizes of object will be seen b) optimum distance between cameras	projection unit
	2	a) screw thread adjusts focus b) May be necessary to change focal length? Maybe not? Depends if blurred texture pattern is OK.	
29	1	a) ??? b) less reliable c) larger shape	
	2	if turntable moves at an angle less no. of pods, greater reliability, smaller casing (height)	
30	1	3 pods or 3 movements with simple	
	2	2 pods or 2 movements with angled turntable - higher reliability	
33	1	slide mechanism	
34	1	slide scanner apart to open/turn on: saves space; keeps cameras untouchable; provides opening; clear access for turntable	
35	1	vents to release heat from projector	
	2	removeable back section for technician, not user	
	5	once extended, click into position: holds turntable in fixed position	
	6	attached to back section, fixed, pre-cal[ibrated]	cameras/projector
37	1	hinged bars hold in position	
	2	how do you slide?	
38	1	extended bar - better than hinge	
	4	a) slides open b) side panel pops into position	
40	5	a) motor in/connected to hinge?	

Annotations - Subject 2HK

		b) also need motot in arm for turntable - has to be fairly flat
41	1	hinged - more reliable, less space
42	1 & 2	Two fixed positions
43	2	same width as depth of computer tower
44	1	a) sunk in b) on bearings - stronger, balanced, smoother c) maybe have 'clicky' set positions 1deg. intervals
	2	hinged section
49	1	underneath sensor feels position (angle)
	2 & 3	like Braille
50	1	a) SV input b) maybe have transfomer for encoder/projector
51	1	a) Pod - digital cams (soundvision). Stored positions/zooms in comp[uter] b) Projector - low voltage, small watt bulb, wide angle lens, focus on middle object c) texture/white slide, mechanism to change slides d) hinge - solid, accurate positioning 0deg, 20deg, fine tune e) turntable - solid/secure, shaft encoder (RS)
52	1	a) simple hinge b) use stand to hold at 20deg.
	2	use relay/solenoid (2 positions/computer controlled)
53	3	for transportation easier to carry (2 people)
54	1 & 2	Stand to support turntable at 20deg. when scanning larger object detail. Won't be used often.
55	1	solenoid - computer-controlled, white/texture
	2	a) for stand opening mechanism same as computer monitor controls b) push & click to close, push & unclick to open

Annotations - Subject 2HK

56	1	a) spring force
		b) rim on outside of turntable
		c) use special supports/attachments to hold object on turntable
		d) temporary adhesives - permanent if cheap turntable
	2	a) for locking in position
		b) solenoid under ball bearing/spring useful if object is big/heavy and turntable is at an angle
57	1	a) clicks from degree to degree
		b) ball bearings at edges of turntable [for] stability

Annotations - Subject 2L

SUBJECT 2L

Page No.	Sketch No.	Quote Annotations	Parts Annotations
1	4	emf motors positioning	
	5	block moulding	
	6	rotate in 3D	
	7	wax ??? ???	
	9	mould same temperature as tank	
2	1	a) extractor power source b) feeding access closed c) user interface	
	3	feed pattern in machine	
	5	a) operator feed in/out b) rubber mould marking	
3	1	Claws system: as the common features of items to handle are their bases for pouring the metal	
7	1	To fix base of tree (sprue) - to enable moving tree through various operations	
8	1	Danger: mass of tree may snap when rotating	
	2	Inertia force very big	
	3	Centroid far from rotating axis	
9	1	Best if moment of inertia of tree as close as possible to rotating axis	
10	1	manual feed	
	2	drain to recover wax	
11	3	a) axial feeder b) spring-loaded	
	5	rotary feeder	
12	1	air suction	
	2	a) resistance heating b) surface to not stick to wax once hot c) add a small quantity of wax to melt and stick	
13	2	a) rotary 360o to pivot wax even upside down b) distance from centre adjustment c) height adjustment	
	3	a) approach the wax element above the investment bath b) rotary 360o around centre	
	5	dip wax component into investment	
14	1	a) manual refill b) investment plaster tank	

Annotations - Subject 2L

		c) rotary blades	
		d) homogenous mixture	
		e) on/off pouring	
		f) gravity to pour plaster in flask	
		g) flask & mounted wax pattern inside	
	4	when flask in position pour investment plaster	
	5	investment plaster reservoir	
	6	release plaster when trigger is pushed	
15	1	a) extract fumes	
		b) recycle wax	
	2	feed in and out	CHECK HERE
	3	a) rotary continuous firing	refractor bricks, recycled wax container
		b) slow rotating plate	
		c) hollow base to allow wax to run into centre?	
	4	a) inclined plate	
		b) linear continuous firing	
		c) holes to let liquid wax to fall onto inclined plate	
		d) slow rolling	
		e) recycle wax	
16	1	metal grains	crucible
	2	a) feed in and out	
		b) melting furnace	
	3	Option 1 - single crucible furnace	
	4	a) Option 1 - single crucible furnace	
		b) avoid manual handling of red hot stuff	
		c) feed out crucible	
	5	tilt crucible for pouring	
17	1	sealed lid	
	2	crucible confined in a refractory chamber	
	3	a) hinged	
		b) resistance induction or gas heating	
	4	a) tracks/rail bearings	
		b) too much space taken by lid once in open position	
18	1	2 halves lid (2 hinges)	
	2	a) 1st - rotate at hinge	
		b) 2nd - slide down	
	5	aperture - as camera	
19	1	rotating axis (to tilt crucible)	flask, sprue base, gear box, extractor MORE
	2	a) mount crucible in a plate with hole	
		b) plate: refractory materials - ceramics, metals	
	3	mount (tilt) crucible in fabricated holder	

Annotations - Subject 2L

20	1	a) direct pouring b) manual to tilt crucible c) runner from inside to outside d) flask independent (outside) e) swan neck	
21	1	semi built in flask	
	2		hood, extractor
	3	a) semi built in flask b) hood to cover fumes during pouring - fixed or mobile c) window to follow and control pouring d) pull lever to pour metal e) temperature panel display (furnace extractor)	
22	1	action - to bring up the sprue base and flask into furnace	sprue base, refractory base, refractory walling, extractor hood, etc
	2	a) fixed point b) foot lever system to bring flask up into the furnace	
23	4	a) fix flask on mobile base b) base to slide along 2 rails	
	5	pneumatic	