Time estimation in mechanical engineering design.

Weston, Nicholas John

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TIME ESTIMATION
IN
MECHANICAL ENGINEERING DESIGN

Submitted by

Nicholas John Weston

for the degree of PhD

of the University of Durham,

School of Engineering

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NUMBERING

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TIME ESTIMATION
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Abstract

This thesis describes investigations into the phenomenon of time estimation in mechanical engineering design. Time estimating in this context refers to estimating in advance the approximate duration of a new design project, for the purpose of preparing schedules. The thesis describes background to the estimation problem, including practical and theoretical aspects of design, design management and market conditions. The research presented is based on data gathered from industrial collaborators, therefore detailed descriptions of the collaborating firms are included. A quantitative study is described which demonstrates that current estimation techniques are not infallible; and that there can be a statistically significant link between the estimated and actual completion times. A process of grounded theorising, based on expert interviews, is presented. Models of the design estimation task were generated by this process, and are included. Differences were found in the models for the estimation of times in an Engineer to Order (ETO) environment, and estimation in a Volume Manufacturing environment. The models were corroborated firstly by checking if they could be recognised and endorsed by the experts from which they were generated, and secondly by checking if they could be recognised and endorsed by an expert not involved in the original model generation. Correspondence was found to be good. A modified model of time estimation is presented, taking into account the findings of the corroboration exercise. Finally, an example of a simple tool for assisting the estimation process is included.

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Preface

This thesis is the result of my own work. No part of the thesis has been submitted for any other degree in this or any other University.

Nicholas John Weston

Durham

September 1994

Contents

Acknowledgements

My thanks go to my supervisor, Professor John Simmons, for all his persistence, encouragement and advice during the period of this study. Much gratitude is also due Dr. Mike Holgate for fulfilling the role of supervisor at Durham during the later period of this study, and for much useful advice on the preparation of this thesis. Lynne Baxter and Dr. Paul Gardiner must also receive thanks for their work in providing comment on the research.

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For more extra-curricular support I would like to acknowledge Andy M, Bill, Billy, Bod, Caroline, Claire, Jed & Ali, Michael & Kate, Louise, Peter, Richard, Robert and a dog called Sam. The greatest thanks however, must go to Sarah.

This work is dedicated to my mother, father and brother, Robin, who have suffered me this last twenty-five years.

1. Introduction

The research presented in this thesis investigates the issue of time estimation in mechanical engineering design. It includes a discussion of the problem area below, and chapters describing:

- relevant extant academic literature
- the research methods used during the investigation
- the companies that collaborated with the research
- a quantitative study of design time estimation
- the modelling of the design time estimation process
- the corroboration of the model of the estimation process
- conclusions of the research as a whole including some recommendations for further work

The rest of this chapter describes background to the research problem. Discussions encompass engineering design; design management; market types for new designs; problems faced by design managers, and the impact those problems can have. The chapter closes with a guide to the structure of this thesis.

1.1. A history of design

It is important to grasp the context within which the modern design office is operated. Later chapters will discuss the generic and specific environments which prevail in design. As a background to these chapters and other analysis which follows, the following section traces the development of working practices, and the forces for change which have acted in design over the centuries.

1.1.1. The meaning of design

A brief note on the meaning of design is required before a history can be presented with any purpose.

The word 'design' not only has different meanings in that it describes both the solution to a problem and the process by which that solution is achieved, it means different things to different people within the field of 'design'. In any work on the subject therefore begs the inclusion of some discussion of the nature of design, and also the definition of the problem area in order to clarify the context of the work and the position of the author in what is an intrinsically grey area.

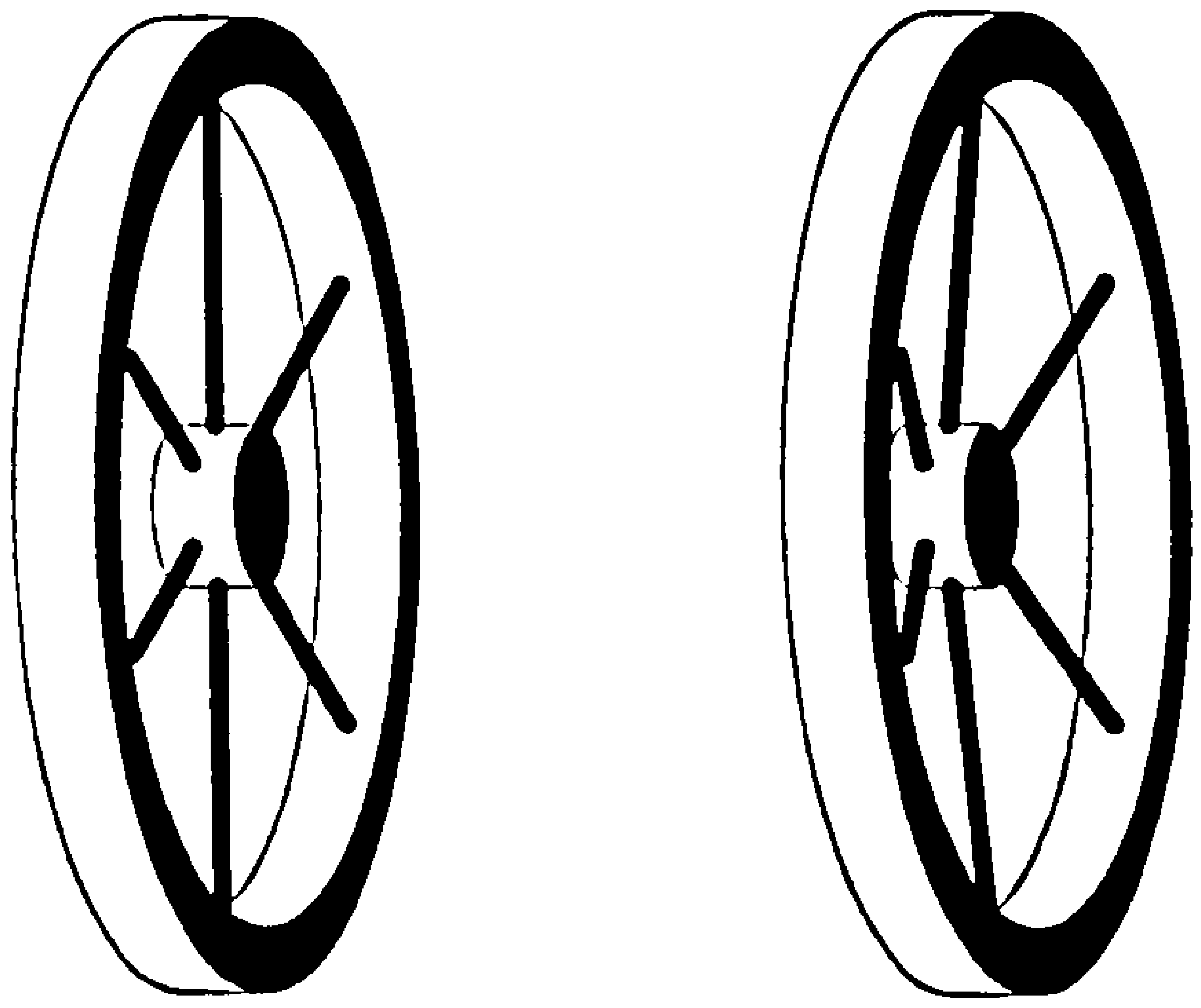
Design has been defined in many ways, encompassing not only the design of physical objects, but also systems and organisations. Some general definitions of the design process are presented below, with varying degrees of accuracy and usefulness.

- Engineering design is the use of scientific principles, technical information and imagination in the definition of a mechanical structure, machine or system to perform pre-specified functions with the maximum economy and efficiency (Fielden 1963)
- Finding the right physical components of a physical structure (Alexander 1964)
- A goal directed problem solving activity (Archer 1965)
- The optimum solution to the sum of the true needs of a particular set of circumstances (Matchett 1968)
- The continuous identity which maps the attribute space on to the function space (Yoshikawa 1988)

Some of the above refer to the design solution, some to the design process, and some to both. In the first case they convey, with different degrees of success either the properties of a design solution in general, or the properties of a *good* design solution. In the second case they present a definition of either the properties of the design solution process, or a perceived 'best' way to produce a design solution.

1.1.2. Craft evolution

As society developed, people with specific skills and talents became aligned into the craft structure. This organisational system provided the basis for the first readily identifiable design system. At this time the form of products was developed by a series of small trial and error modifications to the functional attributes of the physical object. The example given by Jones (1973) is of a spindle sided wagon. In the seventeenth century these were the most effective way of transporting heavy or bulky items. To be effective these wagons needed strong wheels. The wheel-wright serves an apprenticeship and learns that the wheels of such a wagon are dished so that the rim extends beyond the hub (figure 1.1). If the rim and hub are in the same plane the wheel collapses under lateral forces, but the wright may not understand why the wheel is dished rather than any other solution to the problem.



Flat Wheel Dished Wheel

Example of Craft Evolution

Jones (1973)

Figure 1.1

There are no drawings of the wagon, so any development of the accepted design is done as an accumulation of small changes as each new wagon is built. Development is restricted to small changes because the amount of time invested in each new wagon makes the risk of a change causing one to fail too great. If a change is seen to be successful it will be selected and the design evolves.

1.1.3. Design by drafting

This method was introduced in order to allow large projects such as large ships or buildings to be made. Such projects are too large for one craftsman to tackle effectively. The drawings were used to fix critical dimensions so that the work of many individual craftsmen could be fitted together.

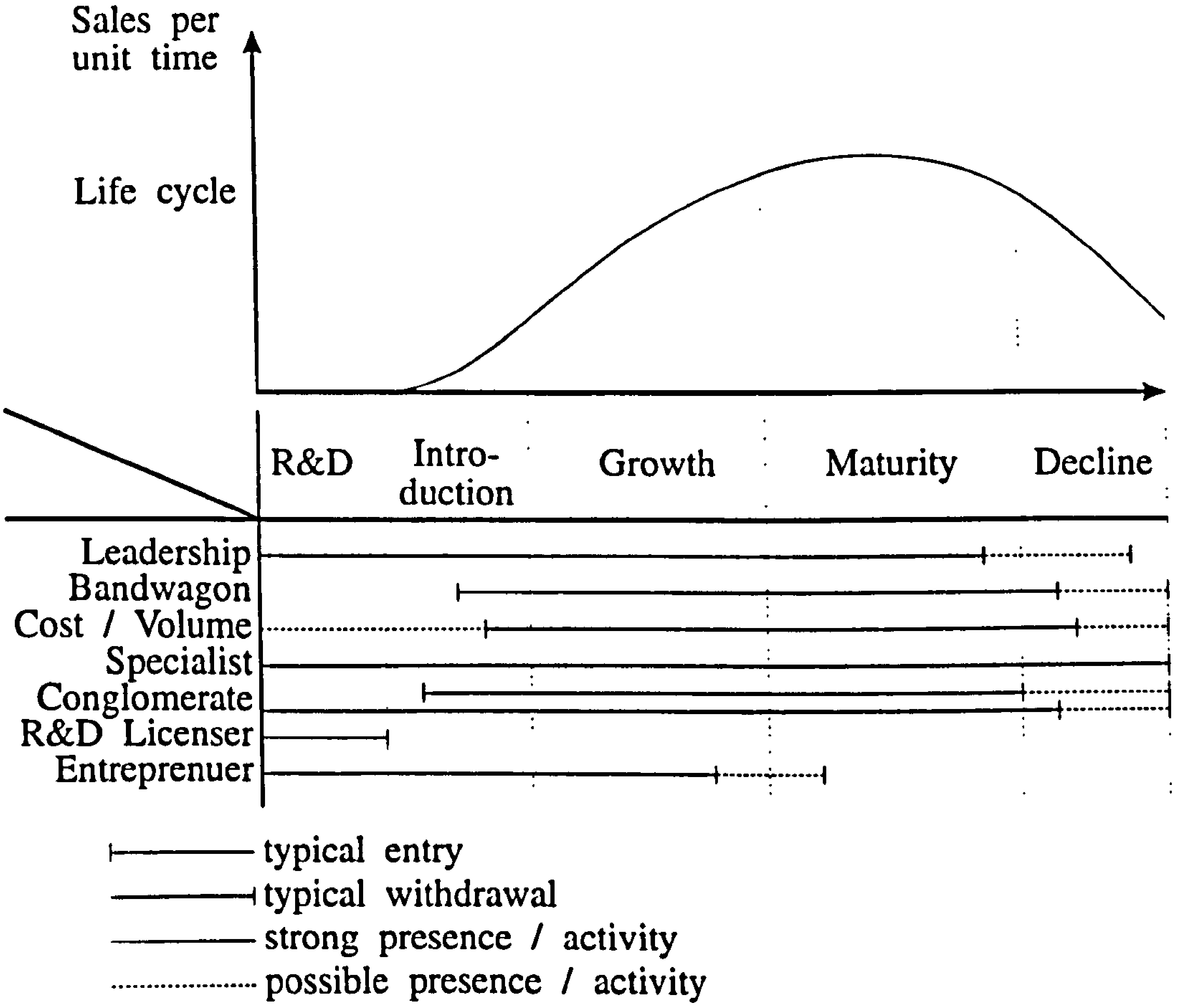
During the industrial revolution design by drawing developed into a means of dividing labour such that the rate of production as well as, or instead of, the size of the projects, could be increased (Jones 1973). An item which is split up into several small, standard components may be worked upon by several semi-skilled people. This allows it to be completed much more quickly than a product with an identical function which is individually crafted by one skilled person. This has two major side-effects. Firstly, flexibility in the manufacturing process is reduced. Secondly, there is an associated loss in manufactured quality from craft products, and an emphasis on setting and achieving manufacturing tolerances.

A consequence of the rise of design by drafting was to separate the intellectual difficulty of conceiving of a new product from that of making it. Thus the distinct job of designer as we know it today was created.

1.1.4. Design by innovation

The level and applications of technology are getting higher, and the rate at which that technology advances is increasing. New designs are planned on a basis of untried technology, or technology which has been tested only on a limited basis. The designer is in this case having to deal with a large number of unknowns. This ill defined problem - solution space is further complicated by the fact that previous experience is of only limited use, and the eventual solution is initially some distance into the future when technologies are changing at highly significant rates.

The advantages of this type of development are the advantages associated with large steps in technology - securing a significant competitive edge; the monopoly of a service or product type; the overall increase in personal or company expertise. These advantages may last for decades if a firm can license a technology or develop it, but are sometimes vulnerable to the 'bandwagon' strategy many companies adopt (figure 1.2) If such projects are to be possible and cost effective, it is essential that a feasibility study establish if conditions are favourable in terms of whether it is a technically soluble problem; whether it can be achieved within cost; whether there is a market demand of sufficient volume at the projected cost; and whether there is sufficient factor of safety in the projections to allow for possible problems in development. Even if the feasibility study is positive, there is always the possibility that an unforeseen intractable problem makes the project impractical, wasting time money and resources. Because of the complexity of the issues in innovative design there has been a quantity of research into the area (see section 1.1.5.)



Company R&D Strategies
Eschenbach and Geistauts (1987)
Figure 1.2

1.1.5. Prescriptive theories

Design by innovation (section 1.1.4) places great demands upon designers and design managers. This in turn produced a large amount of research during the 1960's into prescriptive design strategies (Jones 1973). The strategies impose a structure of varying rigidity upon the design process, in order to improve one, or a set of areas of difficulty within it. Such methods from the 1960's include Systematic Search (Archer 1965); Systems Engineering (Goode & Machol 1957); and Page's Cumulative Strategy (Page 1966). More recently Pahl & Beitz (1984) and Pugh (1990) have produced prescriptive strategies based more firmly on industry practice and requirements. A broad overview of modern prescriptive design research is given by Finger & Dixon (1989 a).

What has become apparent from the work of the 1960's is that, with the exception of Value Analysis, industry has been unwilling or unable to adopt the methods to any significant extent. There may be any number of reasons why this is the case:

- high resource requirement

- high time requirement
- unworkable solutions
- unrealistic targets
- generation of 'non-solutions'
- high, unmanageable levels of interaction
- highly redundant solutions
- organisational incompatibilities between existing and intended systems

This last problem gives an indication of why Value Analysis has been accepted more readily than any of the other strategies developed around this time. Value Analysis requires a design to be completed to a very high degree of detail before its method can be applied. This has meant that design office practice has suffered the bare minimum of changes during implementation. Indeed, it is common that the design staff have only a secondary role during the Value Analysis process. The process has required an extra stage adding to the product development process, not a major reorganisation of the whole design function.

1.2. The genesis of design management

As may be expected, the management of design has not remained static as the task of design itself has changed. In one sense the task of design management was almost non-existent until the specific job of 'designer' came about. The only specific task of design management in the craft evolution era of design was to decide what design changes in a new item were permissible, and what design changes were not. It must be born in mind that a change in design is not a change in a sketch or plan of the object, but a change in the actual fabric of the item. It is therefore probable that this sort of management decision would be a craftsman deciding upon the basis of experience, whether a change would be beneficial or detrimental, and either taking appropriate action personally, or advising an apprentice.

It has been noted in section 1.1.3 that design by drafting changed character somewhat during the industrial revolution. Before the industrial revolution the purpose of employing this method of design was to enable many craftsmen to work effectively together on a large project. In most cases a single designer would be responsible for setting up a framework whereby the different craftsmen's work could be integrated, which enabled craft skills to shape the final item in a not inconsiderable way. On such a project, the design work required before commencement would have been small compared with the final production time, and the amount of liaising with the craftsmen required of the designer during the production phase.

Many of changes of the industrial revolution, combined with the use of drafting, allowed products to be broken down into simple, repeated components. The result of this was to enable many people to work effectively on the same product. This produced two problems which affected design management. Firstly, there was a need for components to be accurately defined in terms of form, material, and possible manufacturing method. Secondly, in order to maintain quality, there was a need for the detailed consideration of tolerances by the designer. This resulted in more emphasis being placed on the pre-production design phase. The extra time and work this required would have necessitated further management of the design process. It is possible that the extra work would force the designer to make use of an assistant, or the division of the design work between more than one designer, with all the organisational complications that implies.

Because of the complex and high technology nature of items produced by design by innovation it is most usual that large teams of people, each with different areas of expertise, would be responsible for the development of a new product. The projects are often developed in an uncertain and unstable technical and financial environment. In order to be effective in terms of the rate and quality of work, and the control of costs and deadlines, efficient task and time management must be implemented.

As might be expected, the task of design management has become more complex and demanding as the design tasks undertaken, and the methods employed to achieve them, have become more demanding. Each development has required more expertise and specialisation in design, making design management more significant. From the minimal design management of the master craftsman being able to decide or advise on the usefulness of a design change; through the cross-over of craft evolution and design by drawing before and during the industrial revolution; to the tight task and time management required in post industrial revolution design by drawing, the problems of managing the individual have been increasing. Design by innovation emphasises further the issue of team management first introduced in post industrial revolution design by drawing, and makes more extreme still the need for tight task and time management.

1.3. Aspects of Engineer To Order (ETO) and Volume Manufacture Design

The majority of design operations can be divided into Engineer to Order (ETO) and Volume Manufacturing. There are a great many areas of similarity and contrast between ETO and volume manufacturing, obvious and subtle. This section introduces some of the issues which will be expanded upon in the light of specific examples. It will be seen from the examples that it is not uncommon for a firm to lie on the continuum which runs between the two extremes of ETO and volume manufacture.

The thesis presents case studies and data from three firms, two of which are almost exclusively ETO, and one of which has one operation which is completely volume orientated, and another operation which has some of the characteristics of ETO and some of the characteristics of volume manufacturing.

The typical design organisation of a volume manufacturing company is almost always run in multi-person teams, with each person bringing different skills to a project. The new product development may be done on simultaneous engineering principles, or with traditional serial development, with the project passing from person to person, but it will typically involve many people with different skills before the completion of its design stage.

ETO may employ the same large teams and variety of skills as volume manufacturing, but it is not uncommon for one designer to be responsible for one project, even in large firms with a high turn over of new designs. It is also possible for these two contrasting styles of organisation to be present in the same office, as some projects require one type of approach and some the other. Whilst it is possible that one designer is able to undertake a whole project, often there is technical and design consultancy from departmental experts, which introduces an element of the team working system.

The technology employed by ETO firms is often complex and specialised, but because the knowledge is used repeatedly, there may only be a small requirement for innovation on each successive project. The designers in an ETO firm are usually well progressed along their learning curve. In volume manufacturing the same can be true. A design team can build up a great deal of knowledge which allows them to undertake new project development in a similar way to ETO designers. Volume manufacturing differs because it is much more likely that a new product may require new technology, or technology outside the experience of the design team. Often volume manufacturing designers start each new project well down a learning curve which must be climbed before the project can be completed. The concept of familiar technology forming a design, and new technology forming a design has been discussed by Pugh (1990), who describes these two constituents as 'static' and 'dynamic' design. However, it must be made clear that static design does not necessarily mean low technology, nor dynamic high technology.

1.4. Aspects of different design markets

The existence of different market requirements has shaped the selling process for volume manufacturing and ETO. Table 1 summarises and contrasts the different aspects of the selling process for the two development strategies. Some of the entries merit further explanation.

The contact between customer and producer in the ETO environment is through a tendering protocol, whereas in volume manufacturing it can take many forms. The manufacturer may sell directly to the final customer, to a wholesaler, or get another firm to specify the product in a project they are undertaking for the final customer.

In the ETO environment the success of a project is not simply dependent upon the supplier. The quality of the specification and background information supplied by the customer has a great influence on the outcome, as does the customer-supplier relationship. In contrast, the customer in the volume manufacturing has no responsibility for the success or failure of a project.

The economic environment fluctuates, and large capital expenditure is often the first thing to be cut in times of recession. This can have a profound effect on the orders of some ETO firms. ETO firms are often willing to cut profit margins radically so that an order can be won. This enables them to recover overheads (at least partially) which would be crippling if no orders had been won. In the case of volume manufacturing the economics are more subtle. A firm may design a 'loss leader' in order to obtain market share for later products on the basis of reduced profit margins. In this case prices and volumes have to be carefully balanced in order to keep control of losses.

	Engineer to Order	Volume Manufacturing
The Selling Process	Invitation to tender	From retail, through selling by an agent, to pushing for specification product by contractors
	Highly technical sales staff	From non-technical sales staff to moderately technical
	Responsibility is shared between the customer and supplier for project development	Customer bears no responsibility for project
	Profit margin may be reduced at times of low demand in order to recover overhead (contribution orders)	No development of foreseeably unprofitable products
Market Characteristics	Detailed market knowledge needed, and usually present, at the tendering stage. Redundancy present in communications between engineering facilities and the market	Market research needed if an informed view of the market is required, which is not always accurate. Designers are insulated from a detailed understanding of the market requirements
	Highly specific requirements	Requirements vary from general to quite specific, although never as specific as ETO
	Various levels of technology	Various levels of technology, with more risk attached to the use of high technology in the volume manufacturing environment

Table 1

1.5. Time pressures on design

There are various pressures on the design process which militate against completion to schedule. These can be both external, for example late changes to design specification, or internal, such as the discovery of problems unforeseen in planning. The following sections discuss the pressures which influence the way targets are set for design work, and the pressures which affect the timetable of design work.

1.5.1. Time targets in design

The common influence for setting ETO and volume manufacturing project completion targets is what the market demands. In an ETO business, when tendering for a new job, information about time scales will be available. This information may be extremely precise, for instance if the machinery is to be used in the harvesting of a crop which will be ripe on a certain date, the work must be complete and the machine commissioned and tested by a date which is fixed in absolute terms. If there are several contractors working on a single large project one may be relying on another for prompt completion, so completion times will again be tightly fixed, but must be relative to the other work undertaken by collaborating contractors. It may be apparent from the documents accompanying the invitation to tender, or simply background knowledge of the market sector, completion by a certain date is a market hygiene factor, and no tenders which fall beyond that date will be seriously considered. These dates may allow for some slack, or require tight scheduling, but the engineer responsible for the tender will judge the best completion date which is a compromise between ease of scheduling and likelihood of winning the order, taking into account how badly the firm needs the order.

In volume manufacturing the format, quantity, amount of detail, and accuracy of data relating to the required completion time is vastly different. With no market research, data about market requirements and timing can be almost non-existent. Market research can produce large quantities of information, which may be detailed and accurate, or may be vague and inaccurate. Other factors which influence new product introductions are existing product life cycles and the times at which new product 'launching pads' are available. If a new product is to replace an existing line which is coming towards the end of its life cycle, historical sales data from that product can help to determine the optimum market entry time for the product's replacement. These, and completely new lines can often be most effectively launched at trade fairs or road shows, or sometimes towards the end of the financial year when surplus departmental budgets can be safely spent, without fear of being caught unable to cover some unforeseen contingency. This information can be integrated to provide dates at which certain stages of a project must be completed. For instance, life cycle data may indicate which year and in what quarter a new product can most effectively be introduced, and the date of a trade fare may fix the time when the product must be complete, or a working model available.

1.5.2. Time pressures during design

External pressures on design time in both ETO and volume manufacturing are more numerous when more parties outside the design office are involved with design development. Examples of influences on external pressures would be a volume manufacturing firm using an outside consulting firm for industrial design, or an engineer to order firm using a specialist sub-contractor. It can be argued that pressures external to the design office can be caused by other departments within the firm. For example, completed prototypes may be laboratory tested, and require changes to be made in the design. All links formed outside the design department introduce the possibility of misunderstandings, which in turn can lead to late changes of specification; failure to meet specification; failure to agree deadlines and failure to agree mileposts. External pressures can also come about from agencies not connected with the development of the design. Legislation may be introduced which requires a change in specification, or a competitor introduce a product or be granted a patent which requires alteration of the launch date or design.

Internal pressures can be caused by unforeseen circumstances, or failure to plan design work. Pressures due to unforeseen circumstances can be due to unexpected technical problems in the design; staff illnesses; or loss of expertise through staff turnover. Failure to plan design adequately can result in unrealistic deadlines; under-staffing due to holidays; shortage of resources because of under budgeting; and communication breakdowns both within the design team and with outside agencies.

1.6. Failure of design management

It can be seen in industry that design developments commonly over-run in terms of time and cost, and produce work below the original specification. Almost every day newspapers carry articles describing shortcomings in defence or large civil engineering project development. The Nimrod and Trident development programmes are two examples from defence. The Nimrod project was so over budget and under specification it was axed. The causes of these overruns and shortfalls are not restricted solely to acts of God, and therefore must be to some degree predictable. This in turn infers that there are both limitations and imperfections in current design planning strategies.

A literature review has revealed that there is a lack of understanding in the academic domain of design planning strategies (see section 2.2.4). This thesis describes research into existing design time estimation methods to provide a basis for improving the efficiency and effectiveness of engineering design time management.

1.6.1. Consequences of failure in design management

The consequences of failure to manage design are different for ETO and volume manufacturing companies. Whilst there are basic common features to the problems for both types of firm there are subtle effects which are clearer when the two types of company are reviewed separately. This fact forms part of the justification for the differentiation of company types described in this thesis.

ETO firms for the most part have a higher turn over of new designs than volume manufacturing firms. They therefore have the opportunity to develop their expertise in estimating design times more readily than volume manufacturers. This being the case, mistakes are made, and unforeseen problems do arise. The consequences of these range from the need to work overtime in the design office, to litigation by the client company. Failure in design management in an ETO firm affects profitability in the following ways:

- Overtime. Whether this is in the design office in order to ensure delivery of drawings to a manufacturing department on time or with minimum delay, or whether it is in the manufacturing department to make up time lost in the design stage, the extra wage bill will affect the profitability of the project and in turn the profitability of the company.
- Penalty charges. These charges are becoming a matter of routine in contracts for certain industries. They are included in an attempt to minimise any loss a customer may incur through late delivery of a made to order item. This may be a loss of market share, loss of production time, or loss of good will. This again affects project, and company profitability.
- Litigation. It is an expensive process which bears considerable risk, but if a customer has sustained a significant loss, which can be recovered in no other way, the law may be invoked when a contract is breached, and a court may award damages against the supplier. This again affects project, and company profitability.
- Loss of good will. If a supplier fails to deliver on time and there is stiff competition for a later order, more reliable suppliers are more likely to win the contract. This affects company profitability in a way which is difficult to quantify, but potentially large.

- A knock on effect. One late project can divert scarce resources away from less urgent projects which then fall behind schedule and become progressively more late and urgent, until they too result in the problems listed above. Again, this affects company profitability in a way which is difficult to quantify, but potentially large.

Volume manufacturing firms may be market or technology lead, but in either case there is a window of opportunity which exists when a new product launch can be successful. This window has different characteristics for different firms, but if it can not be achieved there is little chance of a new product recouping the investment put into it. In a market led firm, failure to have a market presence at the right time may threaten the viability of that firm in the particular sector. At the very least marketing strategy would need changing, resulting in wasted effort, extra work and a lost opportunity. In a technology led company coming to the market late may place the product in the 'bandwagon' category (see figure 1.2) for example. Products in this area are highly 'value engineered' in order to move large volumes by cutting unit cost whilst still maintaining profit margins. An innovating firm which is late to market will not have spared the time for detailed value analysis in its urgency to get to the market, and so will be faced with cutting profit margins in order to move the large volumes required. Whether the lateness to market causes a product to move into the 'bandwagon' category or any other, the technology led company will be in the position of selling (into a market niche which is outside the intended area, and which may be outside its expertise) a design which is inappropriate. Any lateness to complete new product development which results in the market 'window of opportunity' being missed therefore has a profound affect on the profitability of that new product, and the company as a whole.

1.6.2. Causes of failure in design management

Design management has been underway for many years but remains an inexact discipline. It is only to expected therefore, that the causes of its failure are numerous and complex. A large part of this thesis will be devoted to their discussion. Thus, this section serves only to introduce some of these problems, and leaves detailed description and analysis to later sections. Time pressures in design have already been discussed in section 1.5, and so will not be revisited. The rest of this section will be divided into internal and external pressures for convenience.

Internal pressures include failure to estimate or provide the correct level of resource for a project, and inappropriate division, allocation, or management of tasks within the design office. Some problems, such as failing to take into account staff holidays could be judged to come within more than one category, for instance internal time pressures or inappropriate management of tasks within the design office. However, a problem which falls outside all categories has not yet arisen.

External pressures include target changes, for instance specification or completion date revisions, and failure of outside agents to deliver. Again the two categories are not mutually exclusive.

Of course, the achievement of perfect design management does not imply that all projects will be profitable. There are many factors, internal and external, which decide the final profitability of both project and company. Projects must pass through many departments within a firm, and even when shipped the company is still subject to both the local and global economy. Even so, when design management goes wrong, the chances of a profitable outcome are significantly smaller.

1.7. Thesis content and structure

This research presented in this thesis was aimed at discovering three things:

- whether design time estimation takes place, and the context within which it might be performed
- whether there is a link between the time estimated and the time taken to complete a design
- the process by which an estimate may be produced by an expert

Each subsequent objective in some part builds on the work of its predecessors - obviously if it had been discovered that time estimation for new design projects was not done then the study would have had little significance as industrially based research. These objectives are described further in section 3.1.

The thesis divides into three sections. Chapters 1-3 introduce the work, establish the background literature and introduce the methodologies used during the research. Chapters 4-7 describe the data collection, processing and results. The results comprise descriptions of the collaborating firms in chapter 4, description of a quantitative study of design estimation in chapter 5, development of the models of the estimation process in chapter 6, and the corroboration of that model in chapter 7. The final chapter (8) draws together the conclusions of these preceding chapters, and presents some proposals for further work. Figure 1.3 graphically represents the way the thesis presents the results, illustrating each stage, which chapter it appears in, and the way the information from the firms, Labman Automation (LA), Thorn Lighting (TH), Michell Bearings (MB) and Brown Brothers (BB) is transformed into results at each stage.

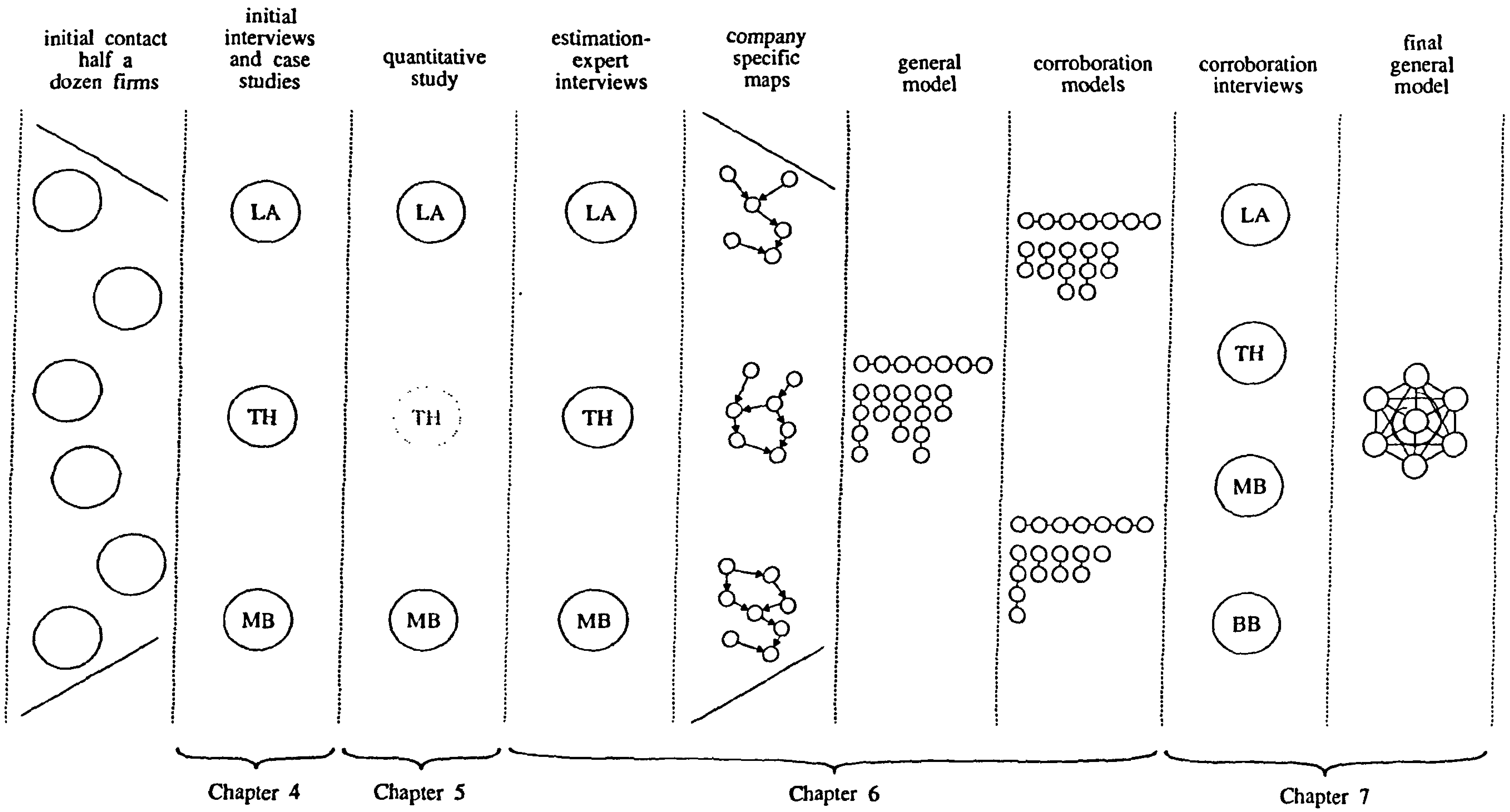


Figure 1.3

Schematic of the thesis contents.

2. Review of literature

2.1. Introduction

This chapter describes literature relating to the research in two distinct ways. Firstly, the theoretical background of design and design management is discussed. Secondly, possible methodologies for this type of research are presented from examination of the literature.

As will become apparent from the discussions below, there is a paucity of published work relating to the management of the early stages of design projects, and even less where design time is considered explicitly. The work which does relate to these early stages either ignores, or trivialises the estimation problem. For an exploration of planning and estimation of time, literature outside the design discipline will be examined.

2.2. Design and design management

Some history of the design area has been introduced in the previous chapter. This will not be expanded upon here, except where literature relates to current practice, or recent research. This section will in effect include prescriptive (or normative) design research, descriptive design research, and design management research. Many of the papers deal with samples of data taken from more than one project or firm, but some are case studies. The case studies provide a useful illustration of industrial practices, as well as informing this research with regard to the advantages and pitfalls of such methods.

Finger and Dixon (1989 a,b) present an extensive review of the mechanical engineering design field. They too divide some of the research into what is prescriptive and what is descriptive. They describe the two categories in the following ways:

Descriptive models of the design process:

> 'Many researchers from different fields have studied the question of how humans create designs; that is, they have studied what processes, strategies, and problem solving methods designers use.'

They continue:

> 'The spirit of this research is in sharp contrast to earlier work that focused on the development of techniques such as brainstorming, inversion, analogy, etc., that were designed to enhance the creativity of the designer rather than to categorise, study, or model the cognitive processes themselves.'
>
> Finger & Dixon, 1989a.

Prescriptive models of the design process:

> 'Prescriptive models can be divided into two categories: those that prescribe how the *design process* ought to proceed and those that prescribe the attributes that the *design artefact* ought to have.'
>
> Finger & Dixon 1989a.

Finger and Dixon do not attempt to strongly define the boundary between these two categories, including some research as having elements which fall into both. In attempt to clarify how this review will divide the research areas considered, descriptions of three categories used here are included below:

General design theory:

> Research which aims to describe design in a universal, and theoretical level.

Prescriptive research:

> Research which *prescribes* the attributes or functions of a design method, problem or solution, whether based upon philosophy, intuition, or informal observation.

Descriptive research:

> Research which *describes* the attributes or functions of design methods, problems or solutions which is based on formal observations, or formally grounded in knowledge of the domain.

Some explanation of the terms used in this latter description may be of benefit. 'Formal observations' refers to observations made in a controlled repeatable manner, of the phenomena of interest. 'Formally grounded' refers to work which is inductively derived from the phenomena of interest, through systematic data collection, analysis and provisional verification (Glasser and Strauss 1967, Silverman 1985, Strauss and Corbin

1990). The first implies that the subject is taken out of its normal environment in order to be tested, the second allows the research to be done *in-situ.*

These three categories may be of vastly unequal size in terms of the quantity of research which falls into each one. One would expect that historically, descriptive research is of a smaller volume than prescriptive. That there is a smaller volume of descriptive research can be observed in the publications (although the balance may be seen to be changing in recent years). However, sections 1.7 and 3.1 state that the work contained in this thesis is concerned with the investigation of the actual process of time estimation. The implication is that the work presented here is based on what design time estimators actually do, and therefore is descriptive in nature and not prescriptive. Hence, the literature discussed here favours the descriptive work.

2.2.1. General design theory

Much work has its roots in this category, and then extends into prescriptive or descriptive work. Pahl and Beitz (1984), Hubka (1982), Yoshikawa (1988) and Suh (1990) all offer theoretical descriptions of the design process. The descriptions can be on the most general level, as in the cases of Yoshikawa and Suh, or conceived with technical systems in mind. All this work sees the fundamental process as one of transformation. Pahl and Beitz, and Hubka present both the transformation and a structure as fundamental to the process, whereas Yoshikawa, and Suh allow the structure to be independent of the process. In the work of both Yoshikawa and Suh the mapping (or transformation) and associated definitions and axioms form the body of the theory. The mapping and axioms are only placed into a structure in order that the description can be utilised in some way. The ways in which the descriptions are utilised do not form an indivisible part of the design theory. In the case of the work by Suh the description is utilised in deducing guidelines for the design process, and recommendations for good design. In all cases the work by these authors is prescriptive in its application, with perhaps an arguable exception of Yoshikawa, where the intention is the automation of the design process, and not the imposition of good design practice on designers.

Briefly, Yoshikawa describes the general design theory in the following terms:

- The design requirement is the intersection of an abstract concept in functional space.

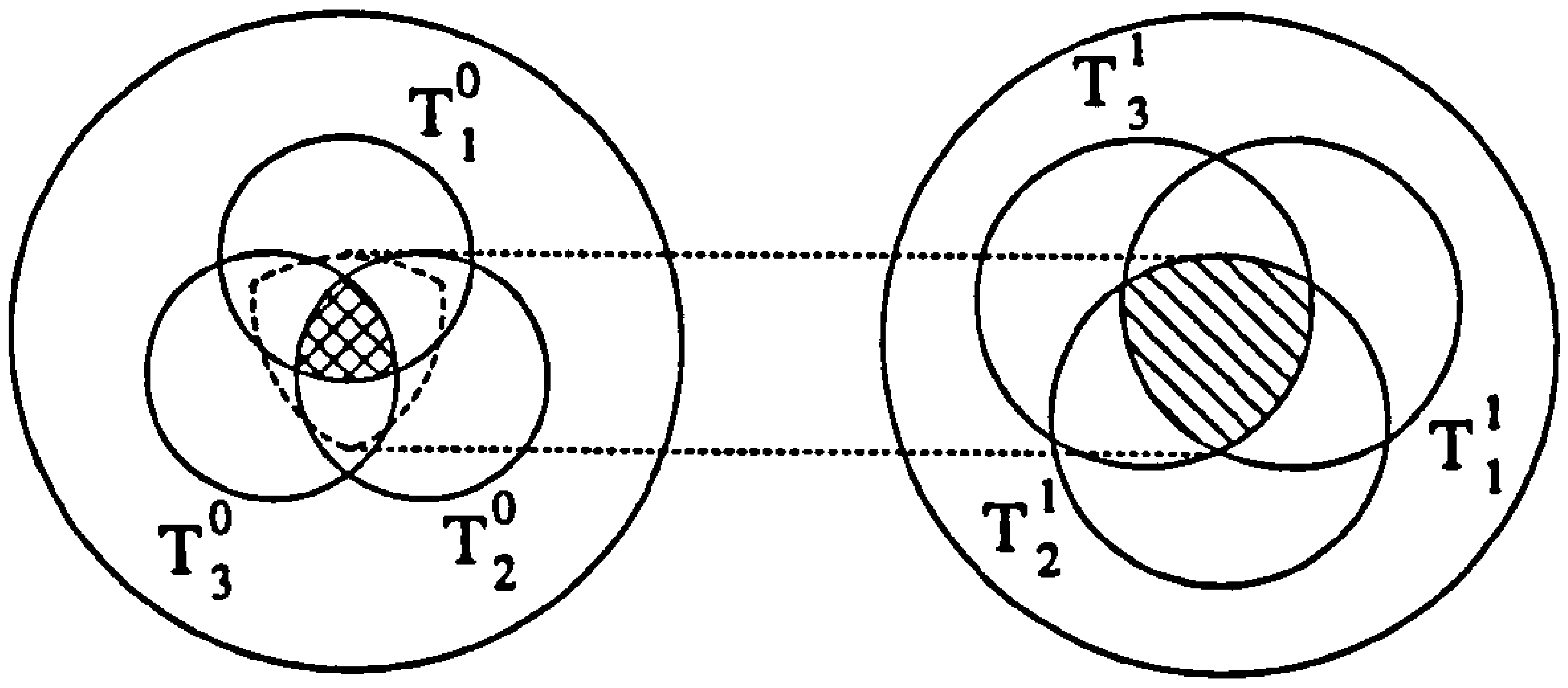
- The design requirement is a filter.

- The design solution is the intersection of the abstract concept in attribute space.

- If design is possible, the identity mapping from the attribute space (S,T^0) to the function space (S,T^1) is continuous.

The terms used merit some explanation. The design requirement is the purpose or task the design solution is intended to serve or perform. The functional space is a space where entities exist. When exposed to a circumstance the entities display a function. Thus the intersection of a group of these entities describes a function or set of functions which are the requirements for one particular design problem. The attributes of an entity are its properties, such as physical, mechanical or geometrical properties and etc., which can be observed by scientific means. A collection of entities with the right attributes forms the design solution.

Schematically these theorems are represented by figure 2.1.



Attribute Space (S,T^0) Function Space (S,T^1)

Figure 2.1.

From Yoshikawa (1988)

The first of the theorems printed above says that the design requirement is described as

$$T_R^1 = T_1^1 \cap T_2^1 \cap T_3^1$$

The crux of this general design theory seems to be the representation of the design process as a mapping operation from the functional space, that is the requirements described in an abstract sense, to the attribute space, that is the object described in a physical sense such as an article, drawing or plan.

The beginnings of this concept can be recognised in the observations of Alexander (1970.)

> "The form is that part of the world over which we have control, and which we decide to shape while leaving the rest of the world as it is. The context is that part of the world which puts demands on this form; anything in the world which makes demands of the form is context.

Fitness is a relation of mutual acceptability between these two. In a problem of design we want to satisfy the mutual demands which the two make on each other. We want to put the context and form into effortless contact of friction-less coexistence."

From Alexander (1970)

Suh (1990) offers no definition with the rigour of Yoshikawa, but presents two fundamental axioms by which good design might be achieved. From these axioms many corollaries and theorems can be developed which are sometimes general and sometimes only useful for one particular type of problem.

The two axioms are:

The Independence Axiom

- **Maintain the independence of functional requirements (FRs).**

The Information Axiom

- **Minimise the information content.**

From Suh (1990)

The analogy with set theory goes further, the attribute space and function space being divided into discrete elements. The elements of function space are represented by functional requirements (FRs) and the elements of attribute space represented by design parameters (DPs). Interpreting the independence axiom as a matrix multiplication, Suh describes three cases of design problem, uncoupled FRs, de-coupled FRs, and coupled FRs. The general matrices describing these cases are:

$$\S 2.1 \quad \begin{Bmatrix} FR_1 \\ FR_2 \\ FR_3 \end{Bmatrix} = \begin{bmatrix} A_{11} & 0 & 0 \\ 0 & A_{22} & 0 \\ 0 & 0 & A_{33} \end{bmatrix} \begin{Bmatrix} DP_1 \\ DP_2 \\ DP_3 \end{Bmatrix} \quad \text{Un-coupled}$$

$$\S 2.2 \quad \begin{Bmatrix} FR_1 \\ FR_2 \\ FR_3 \end{Bmatrix} = \begin{bmatrix} A_{11} & 0 & 0 \\ A_{21} & A_{22} & 0 \\ A_{31} & A_{32} & A_{33} \end{bmatrix} \begin{Bmatrix} DP_1 \\ DP_2 \\ DP_3 \end{Bmatrix} \quad \text{De coupled}$$

§2.3 $$\begin{Bmatrix} FR_1 \\ FR_2 \\ FR_3 \end{Bmatrix} = \begin{bmatrix} A_{11} & A_{12} & A_{13} \\ A_{21} & A_{22} & A_{23} \\ A_{31} & A_{32} & A_{33} \end{bmatrix} \begin{Bmatrix} DP_1 \\ DP_2 \\ DP_3 \end{Bmatrix}$$ Coupled

In each case the 3 x 3 matrix is the design solution, it maps the functional requirements to the design parameters. In the uncoupled situation altering a DP only affects the corresponding FR so design development is a straightforward systematic process. With the de coupled case the adjustment of DP's must take place in strict order, and with the coupled design the solution can be almost impossible to find analytically. These matrices describe three very simple cases. In some designs the number of FRs may exceed the number of DPs and Suh describes methods of simplifying tasks and overcoming these problems.

Hubka (1982) discusses design in the context of technical process and technical systems - the design theory represented is therefore anchored to technical or functional design rather than visual or 'artistic' design such as architecture or graphic design. Thought processes involved in the performance of design tasks are examined, along with their implications for the existence of a general design procedure, and the acquisition of design skills. The research in this area is acknowledged as incomplete, and inconclusive (Hubka, 1982, pp 27,31). Hubka's model of the design process is also a transformation process, but it has structure and divides requirements into categories, such as technical and economic. Also included to some extent are the processes of communication, within the process and externally (with flow both inward and outward). The model structure is illustrated in figure 2.2

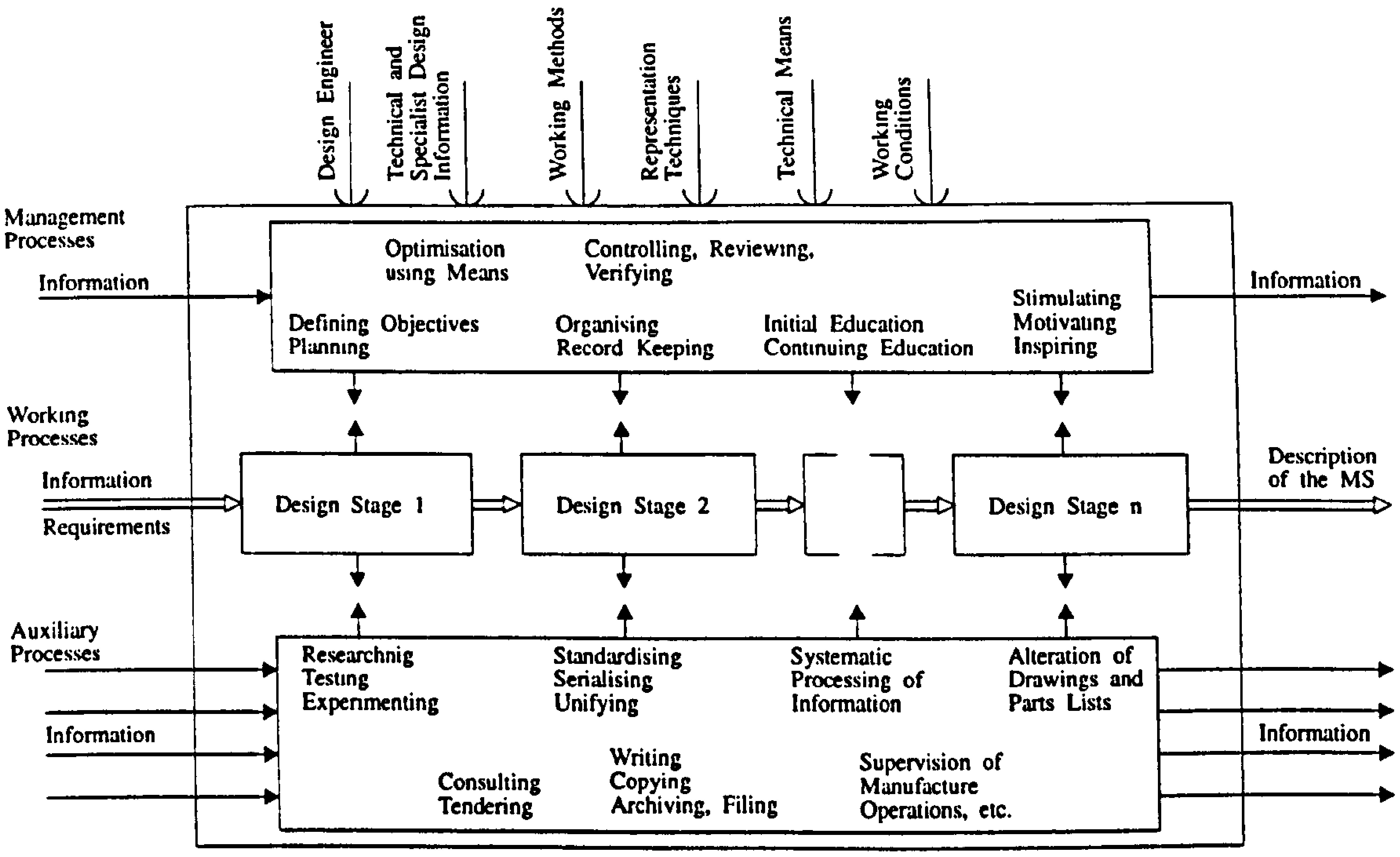


Figure 2.2

From Hubka 1982 p31

It may be argued that the description has elements of prescriptive nature, and as Hubka elaborates and illustrates the model with a case study, the prescriptive tone becomes stronger.

In common with the work Hubka presents, Pahl and Beitz (1984) have in mind the perspective of design as a technical discipline somewhere between science and technology. They see the designer's main task as:

> 'to apply his scientific knowledge to the solution of technical problems and then to optimise that solution within the given material, technological and economic constraints.'
>
> From Pahl and Beitz 1984, p1

They note that a completed design solution remains static in a changing environment. The environment within which the design is developed is also dynamic, and has a great effect on many other functions of industry. This dynamic nature results in complex information flows to and from the design office, and different requirements for design organisations. Three different organisational models are presented for different design requirements. These requirements are '*original designs not commissioned by an outside client*', '*large, one-off products, ... adaptive designs*' and '*mass production*'. It is unclear whether these are based on formal or informal observations, or are theoretical models for best practice. The models place different boundaries between the functions of the designer and other departments in a firm, and allow different communications mechanisms. They also divide design problems into three types, which are not precisely fixed. These are:

> -original design
>
> which involves elaborating an *original* solution principle for a system (plant, machine or assembly) with the same, a similar, or new task.
>
> -adaptive design
>
> which involves *adapting* a known system (the solution principle remaining the same) to a changed task. Here the original designs of parts or assemblies are often called for.
>
> -variant design
>
> which involves *varying* the size and/or arrangement of certain aspects of the chosen system, the function and solution principle remaining unchanged. No new problems arise as a result of, say, changes in materials, constraints or technological factors.
>
> From Pahl and Beitz 1984.

Pahl and Beitz quote statistics of the VDMA (German Association of Mechanical Engineering Companies) to support their assertion that a good designer is both creative and flexible. The work then goes on to define the requirements for a systematic (prescriptive) design method from a technical, management and human factors point of view. A methodology with the aim of satisfying these requirements is prescribed.

VDI 2221 (1987) and BS7000:1989 both draw on this work. VDI 2221 concentrates solely on the systematic approach to design - a stepwise planning and design method - in a general way. It includes examples from mechanical, process, precision and software engineering, and it is claimed that the standard is based on wide ranging design research. However the document presents only one (albeit general) serial design methodology. BS7000 is aimed at three levels of design management and is more overtly focused on assisting the management of the design process. Again, a theoretical design process is included, which is both highly simplified and idealised. Neither standard includes specific reference to time planning or estimation. Both mention in passing, the need to clarify requirements and set management plans, although no advice is offered on systematic ways to achieve these objectives.

As described above, the models of Pahl & Beitz, Hubka and Suh are expanded in order to prescribe a methodology for good design. This prescriptive domain of the discipline is discussed briefly in the following section.

2.2.2. Prescriptive research

As design problems have become more demanding, whether through problems of complexity, technology level or scale, the demands of the design process have become greater. Since the 1960's a whole range of strategies aimed at achieving good design have been developed. These methods include systematic search - identification of variables and relationships of the design problem, the definition of boundary conditions, then the optimisation of variable values (Archer 1965); value analysis - identification of the function, cost and values of elements of the solution and the search for lower cost alternatives (Miles 1961); systems engineering - identification of a systems inputs and outputs, identification of functions which can match the inputs to the outputs, then the selection of physical components to perform these functions (Goode and Machol 1957); man-machine system designing - similar to systems engineering, although the larger system is considered, along with the role of human operators (Jones 1967b); and Page's cumulative strategy - critical aims, and external factors which militate against them, are defined, un-ambiguous criteria are then developed and used to accept or reject proposed sub-solutions (Page 1966).

Since their development these early prescriptive techniques have been tested to a greater or lesser extent, and their failings documented (Jones 1973). These failings include difficulty in identifying and quantifying variables, inputs or outputs; difficulty in identifying sub-systems, requirement for resources or time that is not available, or simple mismatch between the results of the method in practice, and the professed results required. The only one of these strategies which remains in common use is that of value engineering. It can be argued that this strategy is not strictly one of design, but one of re-design. In order for the process to begin, there has to be a design extant, in a form close to that which would be suitable for production. Because of the time and resources required for this strategy it is only economic for products which are going to be made in large volumes (Weston & Simmons 1993).

The implicit, and sometimes explicit assumption of these design methods is that, if followed, they will result in better designs. More modern prescriptive work includes the more specific targeting of desirable attributes of design. This is distinct from the work of Pahl and Beitz (1984) and Hubka (1982), which prescribe a methodology by which good design may be achieved. It has similarities with the work of Suh (1990) in that it is the properties of the artefact which dictate the method of design. Other examples of these prescriptive models of the design artefact include the 'Design for X' where X can be manufacture, quality, cost, time to market etc., and 'total design' strategies (Clausing and Pugh 1991, Corbett *et al* 1991, Andreasen 1990, Noori 1989, Pugh 1990, Pugh and Morley 1988). Many of these methods require that the management of the design environment is altered, and some work has been done which describes the process of change, either from a theoretical standpoint or as a collection of case studies.

Very recent work has endeavoured to establish whether experienced designers follow the design methodologies they are taught. The work of Frike (1993) not only explores whether design methods which are taught are used in practice, but also examines the influence of the precision with which the design problem is defined. Unfortunately the author makes some subjective judgements which are not acknowledged in the analysis of the results.

2.2.3. Descriptive research

Finger and Dixon (1989a) assert that descriptive research has largely been undertaken in order that computer-aided design tools can be made better, from the human perspective. Other uses apparent in the literature (Takeda 1990, Dorst 1993, Coyne 1990 and Adelson 1989) include the complete automisation of design by computer and the teaching of novice designers.

Descriptive models aim to describe the method and processes by which human designers produce variant, innovative and creative design (Steier 1990). There may be some ambiguity as to the use of the term 'cognitive' in this area. It is most commonly used as an umbrella term to describe subjects pertaining to human mental processes, but is also sometimes used to describe a very low level mechanism by which rational synthesis and choice is seen to be produced. This is usually implied in the term 'cognitive model'. Cognitive research is a category of descriptive research. Descriptive research aims to represent how design is done, whereas cognitive research aims to represent how the designer behaves.

There have been attempts by many researchers to formalise the design process using mathematical and logical reasoning (Yoshikawa 1988, Suh 1990). This approach is criticised by Gero and Coyne (1985):

> 'Design paradigms based on mathematical models inherit the properties of the mathematical models on which they are based. Thus, it is possible to prove such characteristics as feasibility and optimality about a resulting design. However, such a design paradigm has limitations in two

> major areas: the processes used are far removed from the way humans carry out this process; and much of design can only be represented symbolically but not mathematically.'
>
> From Gero and Coyne, (1985)

The applications and results of cognitive theory are wide and varied, with little agreement on results. As Finger and Dixon (1989a) observe, many hypotheses have been developed, but there has been little work on designing and performing experiments in order to accept or reject them.

Coyne (1990) presents approaches to the development of intelligent CAD. The first is a high level cognitive system which models the designer's decision between competing alternative designs or problem solutions. He sees the decision being made on the basis of the explanation for each alternative proposed. This explanation can take several forms from ease of manufacturablity to a design grammar - that is a justification such as 'My design is influenced by the weavers' cottages of the early 19th century, therefore windows in the upper story will be large and butt up to the roof'. In synthesising the explanation for one part of the design, the designer produces implied constraints for the rest of the design. Previous decisions need to be checked for compatibility with later explanations, and inconsistencies removed by redesign. One fault with this approach is that a design can be made more acceptable by the alteration of the explanation rather than the design. This highlights the subjective nature of this method.

It is a feature of cognitive research that it usually addresses only a small part of the design field. Work by Adelson (1989) models the process of learning by analogy in software designers. She uses protocol analysis (see section 2.3) to model the cognitive system of humans, and adapts it to a computable form. The system is very knowledge intensive, and this becomes a problem when much of the knowledge required is only implied. In software engineering implied knowledge is limited, in that all data types and classes have rigidly defined properties, as do the control functions and structures. In mechanical design there is not only implied knowledge required in defining constraints, but also in the forms and functions employed to produce a solution. Where the fields of software and mechanical design do overlap is in their agreement that designing involves 'reasoning about the relationship between function and structure, about constraints on the ordering of sub tasks.'

Ullman *et al* (1988) attempt to use protocol analysis in the study of the mechanical design process with the aim of producing intelligent CAD. They point out that: 'The design goal in software design is, in essence, a data flow behaviour'. They agree with Adelson's conclusions in that:

- Designers rapidly develop a kernel idea and refine it during the design process.
- Designers keep a current mental model of the state of the design that is transformed, as the design progresses, from abstract to concrete.
- Designers make a strong effort to keep the development of the design balanced. They focus their effort on parts of the design that are most abstract; attempting to keep all parts of the design at the same level of detail.
- They spend about half of their time simulating the behaviour of their designs. The simulation process serves many functions: it helps the designer integrate constituents from several parts of the design; it serves as a kind of agenda to keep track of sub-tasks requiring attention; it allows comparison to the goal and methodical refinement.

They point out that the cognitive processes involved in what they call 'one off designs' and 'product designs' are different, and continue to look at one off design in detail. They also note that 'We do not yet have an objective definition of levels of abstraction'.

Maher (1990) splits the design process into three phases, design formulation, design synthesis and design evaluation. Design synthesis is then split into three possible models:

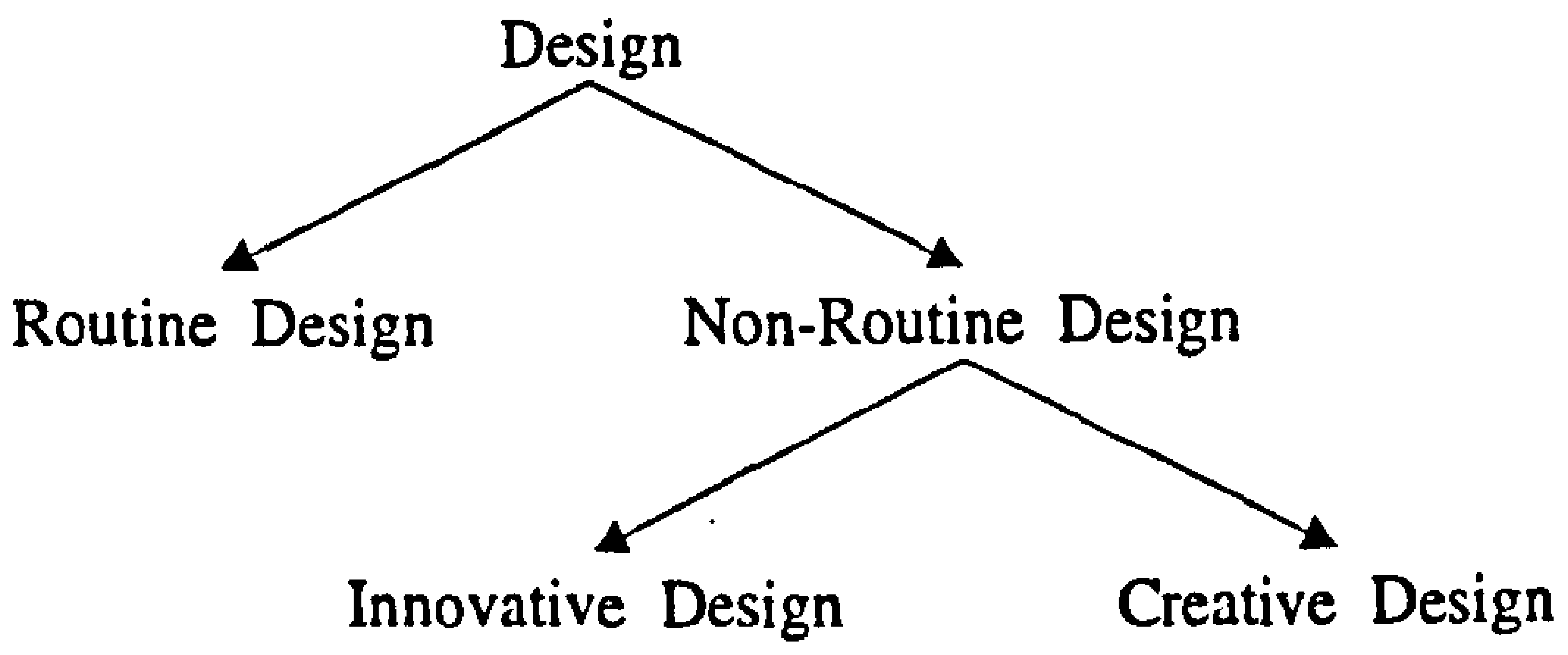
- Decomposition - a large problem is split into sub-problems repeatedly until the problems are small enough to solve and re-integrate.
- Case based reasoning - select and transform appropriate previous solutions.
- Transformation - like case based reasoning, but the start point is a generalised solution and the synthesis is controlled by transformational rules.

These are not necessarily cognitive models; but may match up to processes used by humans. The correspondence has not been adequately tested.

Takeda *et al* (1990) have produced a general design theory which they try to integrate with cognitive theory by the use of protocol analysis. They divide the design process into five steps, which disagree entirely with the work done by Maher (1990) and Ullman *et al* (1988). Where they do agree on the design process is in the development of a solution. They state that their results 'shows design as a gradual transformation from the functional space to the attribute space'. This compares with the transition from abstract to concrete noted by Ullman *et al* (1988).

Workshops at Carnegie Mellon University have tried to review what is known in the field of AI and Engineering Design. They have established some agreement on current research, but not enough to produce an agenda which could be seen by all as the way forward (Steier 1990).

One issue which was discussed at the workshop was the nature of routine and non routine design. Coyne proposes the tree structure:



From Steier (1990)

Where the terms are defined by:

Routine design	all functions and structures of the design are known before design begins (parametric design is a special case of this.)
Innovative Design	not all structures are known.
Creative Design	neither structures or functions are wholly known.

These can be compared with the divisions of Pahl and Beitz (1984) detailed in section 2.2.1.

It can therefore be seen that the field of descriptive design research is relatively young. However, since conflicting theories are starting to emerge of how design is performed, some experimental verification would be extremely useful in order to clarify the current state of knowledge.

2.2.4. Design management, time management and planning

Svengren (1993) observes that:

> Design management is not new but research within the field is quite young.

From Svengren (1993)

Outside the work of prescribing design methodology there is an extreme paucity of academic literature relating to engineering design management. This section therefore attempts to draw together work from disparate areas of engineering, management science, psychology and ergonomics.

Many of the prescriptive theories of design have made some suggestions relating to how to manage the communications required in a large design project (Hubka 1982, Pahl and Beitz 1984, Andreasen 1990). Fewer have acknowledged the scheduling problem as one of time estimation and planning. Verho and Salminen (1993) include some prescriptive advice on how to schedule design tasks, claiming that time planning for un-coupled tasks is easy, and time planning for coupled tasks difficult. This design scheduling work is presented within the context of volume manufacturing, and in such a situation, their prescriptive method requires that goals be set for business objectives above all others. Hundal (1993) notes the importance of temporal issues in competitiveness:

> '[the Japanese] have realised the monetary value of time, i.e. it is a consumable resource which must be factored into every decision of the company.'
>
> From Hundal, 1993.

Both Hundal (1993), Andreasen (1990), and Stauffer and Morris (1993) note the effect of committing expenditure early in the design phase. In the case of Stauffer and Morris they quote figures of between 60% and 80% of product cost being set whilst only 5% of the development budget has been spent. However, they fail to mention factors influencing the delivery *time* (rather than *cost)* of new designs.

Woods (1966) discusses estimation of uncertain quantities from the point of view of estimation within large companies. The effects of communication up and down the companies hierarchy are explored. Whilst time estimation in particular is not tackled, some interesting and relevant phenomena are reported. Such phenomena include the sources and effects of bias in communication, and differences in perception. He states that if an estimate is to be passed to a superior it may be deliberately under or over-estimated, either in order that the subordinate will be comfortably able to fill quotas resulting from that estimate, or in order that the superior may be impressed with turnover. The distortion of estimates due to performance measures being in place is noted. Differences in perception between individuals is observed, some being risk takers, and therefore more likely to be optimistic with estimations, and some more cautious, being more inclined to err to the more pessimistic side of the true figure. The paper proposes the manipulation of estimates as probability functions, with optimistic, pessimistic and typical estimates being used to define distributions.

Cognitive models of planning have been proposed, although these tend to focus on establishing required tasks and their sequencing. Design time estimation is a domain where the tasks and their sequence are known in some detail, it is the assessment of their duration which presents the problem. Hayes-Roth and Hayes-Roth (1979) present a study of meal planning, including deciding the menu and the tasks required to prepare them, through observations and analysis of verbal protocol. Studies of time planning and the perception of time have concentrated on the control of continuous processes (de Keyser 1990, Norman 1990, Sanderson 1989). de Keyser observes that there are four mechanisms where by the passing of time is perceived:

- Observation of actions combined with prior knowledge of when they take place
- Observation of processes and prior knowledge of their duration
- Internal clock (some studies suggest that the 'natural minute' is just over 60 seconds for most people)
- External reference, such as observation of a wall clock

However, these studies are of little use since they deal with planning horizons of a maximum eight hours ahead (the length of one shift in process control).

It can be seen that there has been little work done in the area of time estimation for planning, and none in any area with the duration and uncertainty similar to those of new product design. The following section will discuss some methodological issues relevant to extending knowledge in this field.

2.3. Research methodologies

The object of the research presented in this thesis is to investigate the phenomena of time estimation for the purposes of scheduling design work. The investigation was therefore aimed at establishing whether estimation takes place; discovering whether any link can be seen between the estimated times and the actual times; and, given that these first two objectives could be met to any satisfaction, modelling the mechanism by which the estimates are produced. This section outlines some of the issues apparent in the literature which have relevance to these three objectives.

Svengren's observation of the paucity of design management research has been noted above (Svengren 1993). However, the time estimation task as performed in design management is acknowledged in the literature. The tendency is to treat the phenomenon as a downstream problem rather than an upstream task, that is to say, the reporting of inaccurate schedules implies that estimates are made, although the performance of an estimating task is not reported. Crabtree *et al* (1993), Smith and Eppinger (1993), Areblad (1993) note the problems with keeping to schedules. In some of these cases the causes of slippage from schedules are noted, but the way the schedules are arrived at is never investigated. Figures for slip are sometimes presented, but are not broken down into slip caused by design changes, slip caused through extended design phases, slip due to poor communications, slip due to production engineering problems, slip due to necessary re-tooling, or any of the many other categories which may be used to classify delays in the development of a new product. The slip is measured over the whole development cycle, and it is therefore impossible to deduce whether the design time estimates are accurate or not. This research therefore requires the observation of the design and design planning processes, as distinct from other processes of new product development, wherever possible.

The need for observation suggests a method whereby the process of time estimation for design planning may be studied. Participant observation has been used successfully by Hales (1986) to study engineering design of large projects in the industrial context. The application this method can range from complete participation in the situation being observed to almost non-participation. When complete participation is undertaken reports are made during natural breaks in the observers tasks, sometimes without the knowledge of the people in the environment being studied. This method can raise both practical and ethical problems. Silverman (1985) summarises some of the problems of participant observation expressed by many authors:

> 'First, its focus on the present may blind the observer to important events that occurred before his entry on the scene. Second, as Dalton (1959) points out, confidantes or informants in a social setting may be entirely unrepresentative of the less open participants. Third, the observer may change the situation just by his presence and so the decision about what role to adopt will be fateful. Finally, the observer may 'go native', identifying so much with the participants that, like a child learning to talk, he cannot remember how he found out or articulate the principles underlying what he is doing.'
>
> From Silverman (1985) pp 104,105.

Hales (1986) undertakes a study with a considerable degree of participation, the people working in the environment being aware of his observational role, and some organisational changes being made in order to facilitate the collection of data.

Newell and Simon (1972) use observation and verbal protocol to investigate problem solving in general. The problems studied are those of crypt-arithmetic, logic and chess. Logic and chess are self explanatory, crypt-arithmetic describes problems of the form:

$$\begin{array}{r} \text{DONALD} \\ +\underline{\text{GERALD}} \\ \text{ROBERT} \end{array} \qquad \text{D} \leftarrow 5$$

Each letter represents a digit (0,1,...9) and the task is to find which letters represent which digits.

None of these problem types can be seen to have a great deal in common with the time estimation problems. They are characterised as a search for a solution in a finite solution space. Only chess has the scope external influence. Even so estimation for design times would be similar to trying to play a game where the opponent may or may not make a move, and the rules which govern the opponents pieces can only be guessed at by the estimator. However, even if the findings of the work are not directly applicable, it does suggest other methods for doing this type of research.

Some studies of design methodology have attempted to understand the process by collecting and analysing verbal, written or visual protocol, through the use of notes and audio or video tape recordings. The protocol analysis work includes that of Adelson (1989), Ball (1990), Ullman *et al* (1988) Minneman and Leifer (1993). Analysis allows a picture of the sequence of operations to be built up, knowledge of the information flows involved can be gleaned, and on the deepest level, a model of the cognitive processes involved in performing a task can be deduced. The work of Adelson and Ullman *et al* attempts to gather data with the minimum of disruption to the working practices of the subject under observation. This approach to protocol analysis - using verbal reports as data is proposed and discussed by Eriksson and Simon (1986). Changes to working practices are necessary, but are minimised, and attempts are made to monitor their effects. Ball, Minneman and Leifer deliberately change the working practices, with the intention of facilitating the process, as well as observing it. In both cases they use a computer program to provide information. Ball uses the information contained in a flexible data structure to aide a single designer. Minneman and Leifer use a computer system to facilitate communications in a group process, and track current concepts under development. The results are different in that Adelson and Ullman *et al* attempt to model what is happening, whereas Ball, and Minneman and Leifer model what happens in an artificial situation.

The area of design time estimation is almost entirely un-researched, so any possible changes made to the estimation process would be without theoretical or practical grounding. Researching the area using the methods of Ball, or Minneman and Leifer would therefore be unjustifiable. It is therefore important to develop a methodology which will produce theory grounded in knowledge of the estimation process, which is acceptable to any industrial collaborators. The work of Glasser and Strauss (1967), and Strauss and Corbin (1990) on the philosophical and practical issues of generating grounded theory, and Eriksson and Simon (1986) on the use of verbal reports as data therefore guide the development of the research methodologies described in the following chapter.

3. Methods

3.1. Introduction

This chapter covers the methods used to observe the time estimation process as it relates to mechanical engineering design. Observations in turn allow theories about the phenomena to be developed and tested. Therefore the chapter also covers methods of developing and testing theory. The methods were designed to:

- discover if design time estimation takes place, and the context within which it may be performed
- establish whether there is a link between the time estimated and the actual time taken to undertake the design
- to investigate the actual process of time estimation, with the aim of producing a description of the 'expert' process in order to explain the phenomena observed to occur in the process

The description - or model - of the expert's estimation process was intended to allow estimators to gain insight into their work. A model could also guide the information recorded about completed projects which could most usefully assist subsequent estimation problems. It could be used to aid new practitioners in learning the skills required to produce estimates for a design time.

For the first of the aims given above, establishing the existence of design estimation problems and practitioners, un-structured interviews were conducted with around ten designers and design office managers in a range of company types. Many different firms were approached, of which five provided some amount of information. These five were represented in the more detailed studies by three which each displayed different market and order winning positions. The firms' design managers and design office managers gave first hand testimony regarding the estimation problem. This testimony covered many issues as they related to the estimation problem in mechanical engineering design. Two of the major ones were the context within which any estimation takes place, and the factors which influence estimate accuracy, and the demand for it. A description of the context also resulted from the case studies performed within the firms concerned.

The second aim of establishing if there is a link between design time estimates and actual design time was achieved using quantitative methods. These methods were also used to investigate a possible link between the proportion of dynamic and static design content in a new design (Pugh 1990), and the time required to complete it.

In order to understand the actual process of developing a design time estimate a combination of semi-structured interview techniques and protocol analysis were used. The model produced had to be tested against the practice employed by the estimators, which required both semi-structured interviews based around the models, and the use of corroborating documentation drawn from the case studies.

The firms involved with the research were Thorn Lighting, a volume manufacturing company which design and supply lighting systems; Michell Bearings, an engineer to order company which design and supply large marine and land based bearings; Labman Automation, an engineer to order company who design and supply laboratory robot installations; and Brown Brothers, who develop and supply ship fin-stabilisers and fluid swivels which are used by the offshore oil industries. Brown Brothers were only involved with the very final stages of the research, the corroboration of the results produced.

The text in the remainder of this chapter describes the research strategy and methods employed in more detail.

3.2. Quantitative investigation

The quantitative study was used, where possible, to establish whether there was a link between the time estimated for a piece of new mechanical design work, and the actual time required. Within Michell Bearings links between the ratios of static and dynamic content of the new design problem were also investigated, where the dynamic content was measured by its linkage to the area of new drawings or the number of new drawings.

3.2.1. Hypotheses

The three hypotheses were:

$$H_1 \Rightarrow \left\{ \begin{array}{c} \text{The time taken to complete a design is related} \\ \text{to the area of new drawings required} \end{array} \right\}$$

$$H_2 \Rightarrow \left\{ \begin{array}{c} \text{The time taken to complete a design task is related} \\ \text{to the number of new drawings required} \end{array} \right\}$$

$$H_3 \Rightarrow \begin{Bmatrix} \text{The actual design time is related} \\ \text{to the estimated design time} \end{Bmatrix}$$

All three hypotheses were tested at the first site, Michell bearings. The intention was to test the main hypothesis, H_3 in all three main collaborating firms. Unfortunately the data was not extant in any coherent format at Thorn Lighting. The reason this data was not extant was because within Thorn project development times are typically long, turnover is low and many revisions to the project brief common within Thorns culture. Therefore any dates recorded for the beginning and end of a project are open to wide interpretation. A discussion of the testing of H_1 and H_2 at Michell Bearings, and the reasons for not extending the study into the other firms is presented in sections 5.2.1, 5.2.2 and 5.2.3.

3.2.2. Data gathering

In order to test H_3 within Michell Bearings, a representative sample of project numbers was drawn from the 'Project File' - a ring-binder which contains brief details of each order in which the design department has a part. A selection was drawn at random by the researcher and checked by the design office manager to ensure that all project types were represented, and that any exceptional circumstances were noted. Details of each project included were noted, including the start, finish and estimated finish dates, along with a unique project number and a code internal to Mitchell Bearings which distinguishes the type of work to be completed. Initially the dates were only recorded to the week, but since a simple job may last only two days, which may be a Friday and Monday, the error could be as much as 400% of the true duration. The size of this error was pointed out to the design manager and, whilst it made no difference to the management of the design shop, he agreed to record the day along with the date of the start and completion. The estimated completion time remained recorded to the week only, since this was the detail to which the manager produced the estimate. The data originally collected had therefore to be disregarded, but the high project turnover allowed collection of the more accurately recorded information over the remaining period of study.

The testing of H_1 and H_2 required the recording of the numbers of new drawings and their sizes from the same random sample as used for the testing of H_3 at Mitchell Bearings. The major problem was with identifying which were new drawings and which were amended, particularly where the drawings had been produced on a CAD machine. The extent to which amendments had been made was also difficult to quantify. In order to gauge the degree of error present in the measurements made, the total number of drawings, and their area, required for each project were also noted. Only if there was a significantly better correlation between the estimate or completion time, and the number or area of new drawings, than between the estimate or completion time, and total number or area, could the way of measuring new drawings be said to be satisfactory, given that any degree of significance was apparent.

The project tracing requirement at Labman Automation, in terms of volume, is less of a problem than at Mitchell Bearings. For this reason there is no record of the start and finish of each project in one place, and the estimated completion is present in the tender documentation. In order to test H_3 at Labman Automation cut off points had to be identified from the project files for project start and finish points. These files are used to control and record a project's development. Since the estimated completion times quoted in the tender documents were relative to the date of order placement, this order placement was taken at the commencement date. Not all projects displayed a clear transition between the design and manufacture phase, the design quite often being on going until very late in manufacture. Also, estimated completion times were only quoted for the completion of the entire project, and not broken down to the level of just the design content. For these reasons the completion date was selected to be the date the project was signed off by the customer. The hypothesis tested therefore becomes:

$$H_{3'} \Rightarrow \left\{ \begin{array}{c} \text{The actual project completion time is related} \\ \text{to the estimated project completion time} \end{array} \right\}$$

It can be argued that the design time and project completion time may not be validly separated within this firm anyway (see section 5.2.3). However the hours spent by each employee with the firm were divided between design, and manufacture time. It was therefore possible that comparisons using total project completion time or just design time could be made.

3.3. Interviewing

During the early stages of the research the majority of the ten or so designers, managers and design managers approached expressed doubt that the subject was researchable. Whilst these people admitted, for the most part, that any new understanding in this subject would be valuable in the applied context, for improving accuracy, enhancing estimate credibility, and providing guidelines for estimators new to the task, they doubted that the phenomenon could be measured or the expertise gleaned. Estimators seemed never to have exposed themselves to any self-analysis of their methods, and regarded the estimation process as a 'black box', almost as if the specification for a new job would be presented to them, and after a certain length of time an estimate for the task duration would come to them in a flash of inspiration. However, if this was indeed the case the research must centre upon which features of the specification triggered a longer estimate, and which a shorter one. If this cause and effect behaviour was not observed then the research should uncover the more complex mechanisms beneath the surface of the specification and estimate. It was apparent that, in both these cases, the skill resided with the estimator, so the most direct way of revealing that skill was through investigating estimators themselves. The need to investigate the estimators suggested that interview and protocol techniques were appropriate.

3.3.1. Method selection and background

Research methods which use self reporting have been developed and used within the social sciences. Some concentrate on developing theory describing an individual's cognitive skills; some on both this and group interaction; and some on developing social theory - that is above the level of the individual. Different techniques can be seen as lying on a continuum somewhere between the description of cognitive processes of the individual at the fundamental level, and social theory describing large populations.

From the literature review (see section 2.3) the most appropriate methods were seen to be:

- Protocol analysis - training the subject to think aloud and then recording the verbalisations which may then be transcribed and analysed along with any written work to develop a model of the cognitive processes involved in the task undertaken.
- Grounded theorising - a combination of interviewing and observation used to develop theory grounded in the data collected, assisted by a framework of sensitising techniques and modelling paradigm

The problem with using protocol analysis was that, for best results, actual problems were needed for the recording sessions. The sites where fieldwork was undertaken were, on average, an hour's travelling away from the researcher's base. To travel to the site, set up the recording equipment, and undertake the warm-up exercises required to think aloud easily would delay the work of the estimator by more than an hour, or possibly two. Delays of this length would be unacceptable to the estimators and their colleagues.

Long travelling times the field sites delaying the production of estimates was unacceptable and produced several problems. In some firms an estimate may not be required for more than a month, and absences would amount to a considerable quantity of research time given that there were three collaborating firms. It was therefore not feasible for the researcher to spend all their time at the firms in the hope of being available when an estimate was about to be made.

An alternative to long placements at field sites was to use design briefs which did not originate from a new order or project. Briefs from historical data were considered, and hypothetical ones made up by the researcher. The problem with hypothetical briefs was one of validity. It was considered to be difficult to justify any fabricated design brief as being representative of actual design briefs, from the point of view of presenting the research. There was also the question of fabricating a design brief which was within the experience of the estimator. Without having a real problem to solve how could a fabricated brief be certain to include all appropriate specifications and parameters? Without considerable experience in the fields of each of the companies the specification of bogus problems for research purposes could not be justified. Using historical data circumvented this problem, but it became apparent from interviewing the estimators that they remembered an enormous number of projects from the past in quite considerable detail. It had therefore to be assumed that any design brief was likely to be familiar, along with the problems encountered by the designers and their possible effect on design time. The benefit of hindsight would have biased the results quite considerably and unacceptably. A further difficulty would have been in engaging the estimators interest. A historical brief could have been familiar and therefore not as interesting as a new problem. A hypothetical brief may have been unchallenging or, at the other extreme, impractically difficult. In of these cases interest may not be sparked as freely as with a new and real problem.

Both historical data and hypothetical briefs would have taken the estimator away from their everyday tasks, requiring even more of their time and delaying their work. There may have been other ways around these problems, but since a large part of the benefits of protocol analysis in this sort of situation accrued from observing the actual working practices, it was decided to avoid specific design estimation problems and use interviewing techniques to probe the general estimation method, with verbal protocol recorded from the examples introduced in the interview questions.

3.3.2. Data gathering

The interviewing sessions had three main objectives:

1: To provide information that would allow the case studies to be most effectively be undertaken.

2: To glean the expert knowledge used in the estimation process and capture verbal protocol of that process.

3: To corroborate the model developed from the information captured during the sessions designed achieve the second objective.

The interviews were tape recorded wherever possible and notes taken as a backup. Any notes made by the interviewee were copied when permitted. Some of the interviewees were uncomfortable at first with the thought of being recorded and so the data was recorded by detailed note taking. In later interviews trust had been established so recording was no longer a problem.

3.3.2.1. Achieving the case study interviews

An initial un-structured interview was set up with six firms to find out if their work was a suitable subject for this kind of research, if they were interested in collaboration, and a little about the type of work undertaken. The objective implies that a 'gate-keeper' to the design department had to be found. In all cases the person initially approached was not the design manager, but in the cases where collaboration was successful the person approached was either the gate-keeper or passed the inquiry on to the appropriate person.

Some firms would not have been appropriate for this type of research. For instance, if the firm does not have a mechanical design department, or if the work is confidential beyond the normal protection of competitive advantage - for example sensitive military applications. A judgement of whether the firm was appropriate for type of research project could be quickly made in the initial interview. Often the most difficult task at this early stage was persuading the gate keepers to allow the firm to collaborate with the project. Some could immediately see the value of such research, or were willing to participate out of good will or other reasons. Others needed to be informed of the likelihood and scope of benefits, or at least be assured that their expenditure of time would be kept below a maximum acceptable level. The process of 'selling' the research to potential collaborators could take sometimes three or four meetings with different levels of management. All firms were given assurances that information would not be passed to competitors, and that publication of information would not take place without their consent.

In order to perform the case studies effectively it was seen to be necessary to understand many aspects of the operations of each firm prior to the work, for instance:

- type of market the firm services

- the information given to the design department
- the way orders are won
- the degree of planning for price and delivery date which is required
- the accuracy of plans
- who produces the plans
- the consequences of slippage from the plan
- the way designs are delivered to the buyer, or subsequent manufacturing stage

Understanding the terminology used within the firm to describe the various phases and features of designs and the design process was also extremely useful. The above information was seen to be useful, and so was covered in the interview, thus providing a loose structure - there was an agenda of topics to be covered. However, the interviewer was not constrained by requiring particular categories of answer, or a particular order of questioning, and could be reactive in probing deeper into subjects which were not clear or of particular interest.

3.3.2.2. Achieving gleaning of expert knowledge

The researcher established a reasonable understanding of both the working practices of the firms' design departments, and the type of work undertaken by them, through the initial un-structured interviews and case studies. Later questioning could, therefore, be more specific, and examples given and requested with reasonable competence. Again this took the form of a largely unstructured interview, in the respect that the questions weren't set or certain types of responses required.

The agenda for these interviews was tightly focused on the estimation of time in the design planning phase. During the interview reference was made to a hypothetical estimation problem or part problem, with the intention of capturing verbal protocol describing the strategies used to produce an estimate, and any problems anticipated. These problems could include those encountered when forming the estimate, or the effect on the estimate of problems anticipated during the design phase. When verbal protocol was not forthcoming the problems were broken down further by the interviewer. In cases where verbal protocol could still not be encouraged, the subject was questioned on specific aspects of the estimation problem apparent from previous dialogue.

3.3.2.3. Achieving model corroboration

The final interview was in the form of a semi-structured interview, designed to explain the model developed to the interviewee, and establish, step by step, if the model matched his experience. Questions were also included to give information on the design estimator's subjective view of the usefulness of the model.

In order to maintain credibility with the interviewee the interview structure allowed questions to be skipped if the interviewer felt that they had been adequately answered in former responses. The model, explanation and examples were customised to suit the individual estimators interviewed, and the context of their company. For this reason a verbatim list of questions outside the contexts of these firms is not presented here. The issues investigated relating to individual steps of the estimation process model were:

- The form and extent of design solution knowledge prior to formal design work, required in order to produce an estimate of completion time.
- The consideration of alternative design solutions and scenarios during the estimation process.
- The disassembly of both the design specification, and possible solutions, undertaken during the estimation process.
- The consideration of design and manufacturing processes which may be anticipated, and their effect on the estimated design time.
- The degree to which the information present in the design brief communicates both the difficulty of the design problem, and the information required to produce an estimate.
- The consideration of factors external to the design problem and brief, and their effect on estimates. For example the brief could indicate in some way that a certain expert input will be required, which may not be available for a given time.
- The deduction of dependencies within the design problem from the brief, and the effect of those dependencies on the estimate.
- The integration of the individual estimates developed for the disassembled design problem into a single overall estimate.

- The consideration of dependencies during the integration of estimates into a overall estimate.

Issues relating to the model as a whole included were:

- Examples from there experience which relate to or illustrate the phenomena outlined in the estimation model.
- Strategies for undertaking the estimation process. For example undergoing an iterative process with looping, a serial process, a parallel process, or a combination of some or all of these.
- Strategies for controlling the estimation process. For example switching from one problem to the next in a sequential order, or when one problem becomes too dependent upon another, or when one problem becomes to complex to be tackled effectively, or undertaking problems in the order they arise when considering 'the core' of the brief.
- Strategies for the reintegration of the estimates, along similar themes to those of controlling the estimation process.
- The notes and sketches made during the estimation process.

Issues relating to the usefulness of the model included were:

- The degree to which the overall scheme matched the insights the estimators had into the estimation process.
- The degree of matching they saw between the model and the way someone may tackle general problems in time estimation for mechanical engineering design.
- Their opinion of the benefits available to experienced and novice estimators familiar with the model.

As with all self reporting, the interviews could only yield subjective judgements of the issues covered. A major problem with developing research methodologies was the subjective nature of the process and the quality of it's result. Whilst absolute comparisons can be made between estimate and achievement of design times, the estimates themselves may have the nature of a self fulfilling prophecy. The design work can expand to fill the time available. This issue is discussed further in chapter 8.

Whilst the problem is subjective in nature, methods of establishing the absolute truth of work based around it are going to pose an extreme difficulty. The estimators being the only available experts in their field, their opinion has to be relied upon for a large degree of corroboration of the model. At the beginning of the research all the estimators approached saw the problem as not amenable to research, and a majority of them could give no insights into the estimation methods they employed. When the work was complete, that the estimators recognised the findings at all implies that the research findings were well grounded in actual phenomena.

3.3.3. Data processing

All taped interviews were transcribed verbatim at the earliest opportunity. Where interviews could not be taped, brief notes and *aide memoirs* were made during the session. Detailed *post hoc* notes were then made, again at the earliest opportunity. It was important to record as text the interviews as soon as possible. Where tape recordings were not made information could be lost over time as the notes made were not exhaustive. The production of detailed reports relied on the notes cueing recall of information given during the interview from the interviewers memory. With taped sessions the problem was not so acute, since theoretically all the verbal information is recorded. However tapes were known to suffer from dropouts, and a quiet place to conduct the interview uninterrupted was not always available. Problems with recording occasionally caused single words or phrases to be indecipherable during transcription. These gaps could be filled by cueing memory of the exchange, if the transcription was completed soon enough after the interview. Memory was therefore important in ensuring a complete textural record of interviews, hence the need for prompt production of the textural record, and the need for the interviewer to produce all the reports personally.

3.3.3.1 Processing data for the case studies

Data for this objective was collected in two ways, interview recorded by the interviewer in the form of notes, and interview recorded on audio tape.

In the first instance, whilst the data recording may not capture every small detail of the interview, the information was easily presented in a coherent structured form. The notes were used to firstly divide the information gleaned into the subjects covered during the session. These were then used to outline a word processor document. The outline was then fleshed out using the notes and the memories they recalled in the interviewer. Where specific phrases were used by the subject to illustrate a point their inclusion is denoted by the use of single inverted apostrophes. See appendix A for an example of a report produced from an interview recorded in note form.

In the second instance the tapes produced a transcription rich in detail, but which often did not convey the information in a coherent or effective manner. A précis of the transcript was prepared. The précis reorganised the transcript into sections which followed logically from the research question and the information present. Detail which was seen to be at too fine a level, or irrelevant to the research was filtered, and the most salient points emphasised. Filtering and emphasis was based not only on the researchers perceptions of the requirements and goals of the interview, but also on the emphasis or otherwise of the interviewee. Any emphasis was demonstrated by the interviewee dwelling on a subject, or returning regularly to it. The intention was to report, in an effective way, two things. Firstly, what the interviewer saw as important to the research. Secondly, what the interviewee saw as important or interesting in their job, or important to the needs of the research as they perceived them. See appendix B for an example of a full transcript of a taped interview.

3.3.3.2 Processing data on expert knowledge

All interviews conducted for this part of the research were recorded on audio tape. The transcriptions were then reviewed to find key phenomena under which the particles information contained in the transcripts could be grouped. Strauss and Corben (1990, p96) define a phenomenon by:

> '*Phenomenon*: The central idea, event, happening, incident, about which a set of actions or interactions are directed at managing, handling, or to which the set of actions is related.'

The identification of these phenomena was a critical stage in the analysis. It was important to find a set which covered the observed information, in all the transcripts, without a great degree of overlap between phenomenon. Too much overlap would have created difficulty in coding the transcripts in a consistent, repeatable way. Including a 'catch all' category was seen to be unhelpful for this reason. In order to arrive at practical phenomenon it was important to be extremely familiar all the textural information. The transcription process, being time consuming for a poor typist and requiring many repetitions of some phrases, began this process of familiarisation. Further knowledge was gained from the proof reading and repeated re-reading of the transcripts. Possible phenomena were then tried by coding phrases of the transcripts into the phenomenon they relate to, and the context and actions to which they relate. Context, in this instance, is defined by Strauss and Corben (1990, p101) to be:

> '*Context*: ... the particular set of conditions within which the action/interaction strategies are taken to manage, handle, carry out, and respond to a specific phenomenon.'

The phenomenon to which a particular phrase related was noted, along with the elements of contextual information present and the action/interaction it caused. The discovery of the set of phenomena was not straightforward. Different ones were tried and rejected, modified or included during the early coding process until a satisfactory set was discovered. All transcriptions were then re-coded using the final set which were:

- co-ordinating tasks
- design method
- forming requirement
- production
- time management

See appendix E for an example of a transcript coded using this set of phenomena. The problem with this set was with eliminating any possible overlap between "co-ordinating tasks" and "time management", however when an attempt was made to unify these part of the benefit of coding was lost. The coded description resulting from unification did not differentiate between what were clearly two different phenomena, the large size of the group making it difficult to understand the small scale interactions present within it.

The coded elements were then mapped into a graphical representation. Bubble diagrams were drawn of each phenomenon, similar contexts or action/interactions being, as far as possible, adjacent. The bubble diagrams illustrated two aspects of the information. Firstly, similar interactions and contexts which had been disparate in the transcription became clearly linked. Secondly, some indication of the relative importance of the contexts and interactions present could be observed. More significant contexts or interactions had more entries on the diagram and therefore covered a larger or more densely populated area. See appendix C for an example of such a diagram.

The bubble diagrams were rationalised through removing successive levels of detail, either by rewording the interactions, or by discounting information not relevant to time estimation or of perceived insignificant effect. The process of rationalisation was repeated twice, at each stage referring back to the original data to ensure that the graph still represented the data, whilst not showing detail. The final result was a model of a generic time estimation process. See section 6.6.2 for a description of the generic model.

3.3.3.3 Processing data model corroboration

All interviews were again recorded on audio tape and transcribed verbatim. As the goal was to corroborate the estimation model discovered in the earlier work, the text of the interview could be taken largely at face value. There was no apparent need for complex coding or analysing inferences to any great depth.

The information contained in the transcriptions was sorted as it related to each of the issues of model fidelity and utility outlined in section 3.3.2.3. Sorting allowed the preparation of a short note of each estimators opinion on each issue. These could then be compared across the sample of three and inferences drawn on the fidelity of the model to the actual estimation process' employed. More tentative inferences could be drawn upon the different applications and emphases placed on the model in the different company contexts. Tentative because further work would be needed to show whether the firm specific models are typical of that market sector or not. However, it became apparent, within the three firms which participated to the highest degree, and in the firm who's involvement was much less, that, in the field of design management, there seems to be no such thing as a typical firm within a given market sector.

3.4. Case studies

In order to place time estimation in mechanical engineering design in its context, as an ongoing industrial practice, case studies were undertaken. All three firms participating to the greatest extent allowed an examination of the records relating to the development of one or more projects. One of these firms used the exercise to gain insight into what an outsider would perceive of its new product development operation. These studies also allowed the examination of company documentation, describing such things as quality procedures, management structures, best practice manuals, and some performance statistics. All this information provided a valuable background which served as a crude yardstick for the interview processes which followed.

3.4.1. Object of the case studies

The two objectives of the case studies were:

- to provide background information in order to facilitate the interview process
- to provide context and corroboration for the interviews conducted, and the conclusions drawn from them

The aim was to achieve both objectives with one study in each of the major participating firms. Initially the information collected would be entirely new and unfamiliar. The information would be compiled into a coherent form and used to prepare for interviews and understand the information resulting from them. With the completion of the interviewing, analysis and modelling, the information would then be returned to and the model compared with it in order to establish its validity.

3.4.2. Data collection

The first request made of any firm participating in the research was to allow the researcher access to documents relating to company procedures and project development. Mitchell Bearings, who have some military customers, were already accredited by some institutions, including Lloyds of London British Standards - in the form of BS5750 Part 2. During the fieldwork at Thorn Lighting the design office underwent an audit as a requirement for BS 5750 Part 2 accreditation in which they were successful. These companies operations had therefore been well documented as a requirement for accreditation. The detailed descriptions of design office practice and higher level documents describing operations and procedures within the larger context were examined.

At Labman Automation BS5750 Part 1 is a long term aim, but it became apparent that the firm relies heavily on its small size and flexibility to be reactive, so documents which truly represented the design process did not then exist. However common features of their work could be identified in the project documentation and through brief informal interviews with a significant proportion of the staff.

In Thorn Lighting and Mitchell Bearings the history of a representative project was examined. The particular project examined was suggested by the design manager in both cases as typical, not problem free, or particularly problematic, but was one which included most of the elements of the process to some degree. The survey amounted to examining the documents present in project files, including design briefs, specifications, change requests, test results, and the designs themselves. At Thorn a member of the design team was present to explain each item, and emphasise his perception of the way the process occurred. At both firms samples of documentation seen to represent significant stages were copied. For an example of such a record see appendix D.

At Labman automation a different approach was used, partly because process documentation comparable to Thorn and Mitchell was not available, and partly because a number of project files had to be examined in detail in order to get the information required for the statistical survey. Six projects in all were examined. Common features of the design process and problems with it were noted and compiled into a report. The projects ranged from the simple to the problematic, as can be seen in the design time data of the statistical survey (see section 5.5.2.2). The examination of a selection of projects illustrated the actual problems and procedures more satisfactorily than a single project, but was more time consuming by a factor of about four. However, the objective of this exercise was to gain an understanding of the context of time estimation and support later findings, rather than research the prescribed and actual design practices of these firms. For this reason a study of more projects in each firm was not seen to be profitable.

Upon completion of the model the reports and copies of original documents were re-examined and used as evidence either in support of, or contradicting the form and implications of the model.

3.5. Summary

This chapter has described in some detail the methods used to arrive at, and corroborate a model for expert methods of time estimation in mechanical engineering design. Not all the details are included. The design and commission of the few minor investigations which proved to be unhelpful or outright failures have been left out as not relevant to the thesis presented. The major investigation which proved a inconclusive (the testing of H_1 and H_2) is described in section 3.1. Also omitted from this section is a discussion of the fearsome problems of gaining access to sources of industrial data, and the co-operation of the busy experts on whom this work is based. The studies included are therefore provided by those few who see the value of the work, or at the very least deem it to have been a sound investment of their time for one reason or another.

The chapter has covered:

- the research strategy of combining quantitative and qualitative techniques
- the justification for, and method of, establishing the context within which time estimation takes place
- the method of reducing raw textural information into a model describing the features, context and interactions present within a generic estimation process
- the method by which the model was corroborated as being grounded in the data, and appropriate to the situation from which it is drawn

Further chapters will describe this model and the results of it's testing, the context within which it is operated, its possible implications and use, and further work which follows from its discovery.

4. Participating firms

This chapter describes the three firms involved in the research which were introduced in section 3.1. The descriptions which follow are based upon the initial interviews conducted at the three firms, and the project documentation examined for the case studies. They present some background about company size, markets and structure. The descriptions concentrate on the role and operation of the firms design departments, and the way design fits into the company as a whole.

Before the descriptions of the firms in particular, there first follows some discussion of the general issues of working with industrial collaboration. The chapter closes with brief comparisons of the firms.

4.1. Doing industrially based research

In order that industrial practice could be discovered and modelled, industrial collaboration was a prerequisite of the research.

4.1.1. Reasons of doing this type of research

There are two basic reasons for undertaking industrially based research. Firstly, performing the analysis on information gathered in the actual industrial environment, the likelihood of theory generated having a bearing on actual practice is vastly improved. Whilst it may be possible to generate theory in isolation of the industrial setting and then measure correspondence between this theory and practice, this approach has two disadvantages. Firstly, if the theory can not be found to match, the number of iterations of theorise and test required makes the process time consuming. The second disadvantage is in establishing credibility with the industrial collaborators. Being seen by the industrialists to listen and observe the process of interest before forming any theories can be more acceptable to them than appearing to arrive with pre-formed ideas.

The second reason for doing this type of research is one of application. Theory grounded in industrial practice draws not only its conclusions from the different firms, but also in some part its terminology and structure. It may therefore be more comprehensible to industrialists, and more likely to find application where it is intended, in the industries themselves.

4.1.2. Getting collaboration

It was extremely difficult to get industrial collaboration. Problems ranged from difficulty arranging meetings with busy managers, to the managers denying that estimation was anything more than a trivial problem.

Persistence was often repaid, either through finally selling the project as important, or convincing the manager concerned that the time taken to complete the work on their part would be extremely small. In some cases the managers were immediately responsive, but not all could be accommodated because the situation was not appropriate under the criteria presented in section 6.2.1.

The most important points in getting co-operation were found to be:

1. Convince the manager or 'gate-keeper' that the work was important and profitable to them.
2. Assure the participants that their time would not be wasted, and that the required involvement on their part would be minimised.
3. Maintain regular contact.

4.1.3. Managing the project

It was important to maintain a personal contact within a firm. Dealing with the same person at each visit or phone call meant that an understanding could be developed, and that breakdowns in communications were less likely. However, it was also important to ensure that there was someone else to go back to in a firm in case the contact was busy, ill, or unavailable for some other reason.

Diaries and note taking was also important, so that data were complete, and the current position in the research programme was clear. Contemporaneous notes were recorded in a more permanent format as soon as possible to minimise any loss of information. Since some of the information available to the researcher could have been of use to competitors of the firms involved, maintaining confidentiality was vital. Notes, case study data and reports were locked away where possible, and computer files were not left on public domain machines. Documents pertaining to one company were not circulated to the others, even though the firms involved could not be seen to be in competition. Where reports held particularly sensitive information confidentiality notices were clearly displayed. Because of these precautions the issue of confidentiality was only ever raised at the beginning of the collaboration, the firms being satisfied with this aspect of the project throughout.

4.2. The collaborating firms

Information required of the participating firms has been detailed in section 3.3.2.1. The information was used to understand the context within which the design estimation takes place, and to allow detailed, thorough and relevant investigation of the estimation process in particular. The data presented here has its sources in the staff interviews held, and company documentation, which is referenced when used. The eight points from section 3.3.2.1 form the headings under which the descriptions of the three firms involved are presented. In order to provide a complete picture of each firm, each is tackled in turn in the following sections.

4.2.1. Labman Automation

Labman Automation is a small firm which has undergone some considerable metamorphoses. Started over a decade ago as a one man operation, making small laboratory robots, they have twice undergone changes of ownership. Initially simply 'Labman', modest growth followed from the early days. A change of ownership meant the company traded as UMI Labman, and they were encumbered by a debt not their own. Receivership saved the original Labman core of the business, and new ownership sees them trading as Labman Automation.

The firm currently employs nine people, including a managing director, a technical director, two design engineers, skilled and semi skilled mechanical and electronic engineers, and secretarial staff. Typically they have turned over projects with an average value of £30,000 at just under one a month. However there has been some fluctuation in these numbers during the recent change of ownership. A large project for the firm would be one of over £40,000. The firm will also undertake service contracts and manufacture spares, although this forms only a small fraction of their work.

4.2.1.1. The market

Labman have virtually no competition in their field. No other firm services the bespoke laboratory robot market in the way Labman do. Labman have experience in automating handling intensive, light weight, low throughput tasks. The firm is not restricted to the laboratory robot niche, but the majority of the work-force's experience is with this type of work, and laboratory tasks largely fall within the throughput, weight and handling criteria. Labman will undertake to design, build, commission and maintain a robot to perform a given task given that it falls within these limits. The niche serviced is not therefore a volume manufacturing market, nor is it a competitive tendering situation. The task Labman have in order to win an order is to convince the enquirer that the task can be automated in a practical and cost effective way.

4.2.1.2. The order winning process

Work comes to Labman either through an agent, but most often by word of mouth. Any serious enquiry results in the completion of a design study of roughly 20 to 30 pages. The study typically costs the prospective customer £1000, depending upon the detail required in the proposal. The cost is pitched at such a level as to be a reasonable contribution to the cost of the work to Labman, and within the budget of a manager at the client firm. The fee ensures that only serious enquiries are dealt with, and that the go-ahead for design studies is not held up by the need for budget approval at the client firm. Much of the design study work is to simply fix a specification for the task required. The customer's specifications and preconceived ideas can vary greatly from detailed to almost non-existent. From dialogue with the customer, the designer is able to develop 90% of the 'architecture level' design work in the head. A large part of the 'architecture level' design goes into the design report, and on to the customer as arrangement drawings and critical specifications. The design report is only a proposal for a system and can be - and often is - negotiated. Labman quote short delivery dates, often because the machinery is being bought out of the residue of a year's budget, and overruns into the next year's budget are avoided if possible. However the deadlines from customers are not cast in stone.

The production of the design study is a balancing act between the functionality and cost of the finished robot. The study usually includes two or three options for the level of automation and flexibility of the robot, and their associated cost. These are not fixed and negotiation can produce a new specification and associated proposal for a solution before the contract is awarded.

4.2.1.3. Information used by the design department

The bulk of the information for a new design may come from the design study. However, oversights, changes in specification from both customers and suppliers can mean that further information is required. These changes cause delays and result in wasted design effort, and alterations to the completion date. Typically the later the changes are made, the more serious their impact on the schedule.

Much of the design work relies on the use of common elements. Most of the design problem solving is mechanical in nature, with some electrical and control elements. The use of common elements allows for the early release of drawings to manufacturing and subcontractors alike. The retrieval of the details of these common elements relies on the designer remembering what previous designs have the required part, so that records can be examined. These record are a recent innovation for the firm, so the body of data is as yet small. The records makes the task of finding information simpler, although the records do not cover a wide range of the common elements as yet.

4.2.1.4. Price and delivery date planning

Rough estimates of the project duration are made during the design study stage. These are for the purposes of preparing a quotation for price and delivery date. The delivery dates are often geared to the financial year, in order that projects can be completed without disturbing the customers budget for two years.

The firm time plans are not made until the contract is awarded, since this takes a great deal of effort. Time critical units are identified, for example long lead time out sourced parts, or sub-contract work, at the design study stage, but detailed planning of less time critical stages is left until the contract is won.

4.2.1.5. Plan accuracy

The plans take into account both design and manufacture. The boundary between the two stages is not as clearly defined as in most other companies. The manufacturing and design facilities are in very close proximity, and the design and manufacturing process are undertaken in parallel to some extent. The close proximity of design an manufacture allows for flexibility in the completion of the schedules, but also complicates the scheduling process. The flexibility of the work-force is also a double edged sword. There may be more than one person within the factory able to complete a task. For example, most of the manufacturing staff are competent mechanical fabricators, so scheduling a large fabrication job is simplified. However, only one of the staff is skilled in control systems, so it is important that this person is not employed doing a task which can be done by another person while there is some specialised control systems work to be done.

Much of the work undertaken is in the nature of a research and development problem. It is understood by the customers that progress with this sort of work can go in fits and starts. In order that the customer is aware of progress, stages are agreed when the contract is started for inspection of the work to that point. Slip does occur for the reasons outlined in section 4.2.1.3. These inspection of the stages ensures that the customer is fully aware of progress, problems, and any alteration to expected schedules.

4.2.1.6. Plan production

Where possible the planning for design and manufacture is all undertaken by the design engineer responsible for the design study. Once the order is won, the proposed architecture is examined to deduce its design, manufacture, sub-contract, and out-source requirements. Where the function of the element is familiar, the records of previous projects are used to calculate an estimate for time and cost. Where elements are unfamiliar experience has shown that in general design and testing are complex, so over estimates are made. These often prove to be inaccurate, coming in well under, or well over time. Lead times for out-sourced components and sub-contract work are checked with suppliers and contractors. All this information is combined with the dependencies evident in the architecture level design of the design study to produce a stage by stage schedule.

4.2.1.7. Consequences of slippage

The small size of the company allows good visibility of budget and schedule performance. The cost of mistakes can be seen to be disproportionately large. It is therefore important not to 'rock the boat'. The scheduling and budgeting systems are very sensitive to small change because of the relative sizes of the firm and the projects. For instance, one member of staff is 11% of the work force. Typically ten projects a year are produced, so only one needs to go slightly wrong for 10% of the years profits to be wiped out. For the same reasons of scale, scheduling for holidays is important, and the impact of illness can be very high. When estimating, it is important that these things are taken into account. The effect of holidays means that a seasonal fluctuation in project times can be observed. A month of production can be lost over Christmas through not only Labman staff holidays, but also those of suppliers. A similar number of man hours can be lost over the summer, over a longer period of time since the staff tend to spread their holidays over a longer interval.

Since penalty clauses are not used in the contracts between Labman and their customers, the effects of schedule slippage on the profitability of a project are indirect. As outlined above, any over-run in the completion times can cut into not only project profitability, but also company profitability. On the long run, the effect on the companies reputation of failure to deliver may minimised because of the regular inspection of progress by the customer.

4.2.1.8. Stages subsequent to design

The nature of the relationship between design and manufacture has been discussed in some part above. Because of the overlapping nature of the two functions, there is no formal handing over or signing off of completed design work, allowing a flexible approach to the early release of drawings. Early release may be needed for long lead time sub-contract work, or for complex manufacturing within Labman. It is also possible that the design of elements which have taken longer than expected can be brought back onto schedule within the manufacturing phase, on the condition that interdependencies with other elements of the project allow this. Flexibility in the transition from design to manufacturing introduces a further complication of the scheduling problem.

4.2.2. Michell Bearings

Michell Bearings are a medium sized firm which is part of the large Vickers engineering group. Their business takes two forms. The greatest proportion of their work is the design and manufacture of large or complex one off bearings. The other side to their operation is the repair and service of these items, and they will even work on bearings produced by other firms, for which the original specification is unknown. The bulk of the work is therefore of the Engineer to Order (E.T.O) type.

The design department divides into two sections, marine and land based bearings, with around thirty design office staff in total. Whilst there is no significant difference in the designs produced in the two sections, the volume of work produced in each section make the divisions convenient sizes to manage. For each section there is a design manager who is responsible for the allocation of work and preparing schedules for design projects. These managers undertake some design and design checking work, and also act as consultants for the less experienced designers, along with the organisational work. Each bearing design is completed by one designer, although a job requiring more than one bearing could be tackled either by one designer or one for each bearing, depending upon the delivery due date. The design office is responsible for authorising purchasing of material and sub-contracted work. It is also responsible for issuing drawings for repair work, although these require no new design work. The design function is therefore at the core of the firm.

4.2.2.1. The market

Much of the work undertaken by Michells is from regular customers. There are perhaps a handful of companies around the world capable of undertaking the majority of the work done at this firm. More specialised bearings may be possible by one other firm, or unique to Michell. The bearings themselves find applications in ship and submarine main bearings, gas- and steam- turbine generator sets, and other heavy engineering environments.

Most designs required by customers fall within a range of specifications that are extremely familiar to the experienced design staff of Michell. These therefore require the alteration of an existing design to fit the particular specifications of the new contract. These alterations can have a greater or lesser degree, depending upon the correspondence between the specification of the existing design and the new specification. For these types of work the dynamic design content is small relative to the static design content. Designs requiring new technology, or performance outside the normal range require consideration at a more fundamental level, and so contain a large proportion of dynamic design.

Michells typically receive enquiries for between 1000 and 1500 new bearings each year. Around 500 of these will become actual orders. The time between supplying the completed enquiry to the prospective customer can be as little as a few days or as much as six years.

Most orders are now fixed price contracts rather than cost plus, although for technically demanding or complex bearings, stage payments can be arranged. These payments may be to cover the cost of the design work, or the cost of research and development work. Stage payments are important in these projects since development times can be as long as three or four years. When compared with the typical duration of twelve days for all projects, there is a considerable difference in the design, and therefore order, turnover.

4.2.2.2. The order winning process

Orders are won through the sales staff. These people have technical backgrounds, and usually do not chase orders, but clarify the customers requirements, outline Michell's capabilities to customers, and provide an effective communications link between the customer and Michells design and estimating departments.

Each order comes to the design office in the first place as an enquiry. The enquiry may only require the designer to produce a rough arrangement sketch from which the estimating department can produce approximate figures for cost and delivery date. Only when the customer provides more information and requires hard and fast figures for price and delivery date will a detailed arrangement drawing and possibly sketches of more complex or expensive parts be produced. Higher levels of detail enable the estimating department to calculate accurate times and costs which can safely be written into a contract.

The estimating department are only responsible for producing figures for the time and cost of a contract. The managers themselves are responsible for the estimates of time requirements in their own departments. These estimates are circulated through the company on the 'work-to' document. Each order has an associated 'work-to' document, which originates in the design department and is passed from department to department in the sequence the order itself will follow. Each manager enters a start and finish date, depending upon the amount of work they estimate the order will take. If at the end of the sequence the estimated completion date does not match that of the due date on the contract, the managers bargain between themselves to ensure that the final work-to document matches the contract due date.

Michells have two pricing strategies they use to win orders, profit orders, and contribution orders.

The price of a bearing which is a profit order is calculated on the basis of:

material cost + overhead + profit margin = contract price

The price of a bearing which is a contribution order is calculated on the basis of

material cost + overhead + reduced profit margin = contract price

The profit margin for a 'profit' order is influenced by whether other firms are able to do the work, the budget of the customer, and how badly the customer needs the bearing.

The profit margin for a contribution order is set such that the final quote is an order winning price. Contribution orders are taken in order to complete the order book, offset the write-off cost of expensive machinery which would otherwise be idle, and to prevent the need to lay off expensive non - productive labour.

4.2.2.3. Information used by the design department

The information used by the design department to produce estimates for the amount of time and effort required for the design comes from a variety of sources. Once the contract is won the delivery date and price are fixed. The design manager uses the information contained in the enquiry documents, including the approximate material weights, special material requirements, any arrangement drawings available, the number of components required, and manufacturing processes required. If deadlines are tight, and the contract requires more than one bearing, more than one designer may be assigned to the project, perhaps one for each bearing.

All these sources of information are combined with the managers knowledge of past projects to form an estimate of the completion date which can be written into the work-to document. Whilst there is little formal writing up of past project performance details, information on start and finish dates in the design office is available. The records of project completion sometimes include comments, for instance if there was a late change to specification, or reviews of stages of the design work within the firm.

4.2.2.4. Price and delivery date planning

Price and delivery date planning is undertaken by the estimating department. The estimators use the same information as the design manager, but produce a price and date which can be written into a binding contract. These estimates are made prior to the preparation of the work-to document, and are the reference about which the rest of the firm schedules its work.

4.2.2.5. Plan accuracy

At the time of the first meetings and interviews the staff at Michell felt that the estimating for the actual design phase of the projects was extremely accurate. The major problem they perceived was the management of the enquiries. The majority of design projects themselves were said to fall either on the exact week planned, or one week either side. See sections 5.4.1 for comments on the accuracy of the Michell records, and section 5.5.1 for actual data on estimate and completion times.

4.2.2.6. Plan production

The only formal plan produced for each bearing which is used by the whole firm is the work-to document. As has been described above, this is produced by passing it from one department to the next, in the same sequence an order would follow. Once an estimate has been made by all the departments checks are made to ensure that the final time on the work-to sheet matches the delivery due date of the contract. If this is so the work commences as scheduled. If these dates do not coincide a bargaining process begins, whereby agreements are made on reduced times, or specific parts of the project are completed in one department for early release to the next. The system of releasing drawings early may be used where long lead time items are required, such as sub-contracted castings, or specialised materials. In this way factory wide agreement is reached on a way in which the delivery due date can be met.

4.2.2.7. Consequences of slippage

The consequences of slip from completion schedules are various in Michell Bearings. If slip occurs in the design office the effect knocks on to all subsequent processes in the firm. Since the design office is so central to the operation of the firm, the other departments are extremely dependent upon the smooth operation of the design facilities. Late completion of designs can cause the late ordering of materials, the late sub-contracting of work, and late commencement of in house manufacturing. In order to avoid this overtime can be worked in the design department, which in itself adds to the cost of the design work. Not only are more hours of work put into the project than planned, raising costs, but the hourly rate of overtime is higher than that of normal time, raising costs even more. The problem also arises that one project over-running impacts on other work in the design office through tying up shared resources. In extreme cases the designer of one project may be withdrawn to work on a more urgent one.

If the design work does over-run, the time may still be made up in the manufacturing stages, although again, this may be through using expensive overtime. If the time can not be made up, late delivery impacts profitability in several ways. Contracts can have penalty clauses which are triggered by late delivery. Penalty clauses have a very direct and visible impact on profitability. Overtime used to minimise late delivery is also a direct loss of profitability, although this may not be quite so visible as any penalties incurred. The third loss is in the effect of late delivery on the firms reputation. A firm with a reputation for failure to deliver on time will be less likely to win repeat orders if two tenders for a job are similar. In a market as small and specialised as the supply of large bespoke bearings, suppliers and customers are likely to be aware of each others reputation, so consistent failure to deliver not only affects the relationship with one customer, but with the whole market. Any loss of orders has an effect on profitability, but loss of reputation through word of mouth is very indirect, and very difficult to quantify.

4.2.2.8. Stages subsequent to design

The dependencies of purchasing and manufacturing have been introduced above. Whilst the design office is central to the firm, the focus for external correspondence is through the sales and purchasing departments. Whilst there may be many people within a firm working on a particular project, one person in the sales department will deal with the customer, and one person in purchasing will deal with all the material and sub-contract requirements of the project. This arrangement simplifies the co-ordination of all the information required, and improves the way information and responsibility for tasks can be traced.

The boundaries between the different departments are clearly defined. Whilst there may be little geographical distance between the departments, the departments are largely self contained and sequentially organised. The immediate path for a design project after the design office is towards manufacturing and purchasing. The hand over is formally achieved when the design manager responsible officially signs the drawings off as approved. Signing off would usually occur for all the drawings relating to a project simultaneously, however some overlap can occur when drawings are signed off early, or when the authorisation is given to purchase material before drawings are complete. That the design office gives puchasing authority is another manifestation of the central role of design at Michell.

4.2.3. Thorn Lighting

Thorn Lighting are part of an international group which, for many products, are a house hold name. When the research commenced the firm had several sites in England, including Enfield in Middlesex, Hereford, and Spennymoor Co. Durham. During the three years the Enfield site was sold. Upon this sale, the development and testing labs moved to Spennymoor, and the Marketing department to Borham Wood.

The company employs over 1000 people in the UK, with a very large manufacturing facility at Spennymoor. Most of the research was conducted at the Spennymoor site, although a two week research visit was made to the Enfield site whilst it was still in operation. The company has set itself the target of becoming a world class manufacturing firm in all areas, an admission what whilst the products are competitive, profitability can be, and is being, improved.

4.2.3.1. The market

The firm have two types of business. An expanding part of their operation is the design and manufacture of large bespoke lighting installations. Examples of this would range from external lighting for large public buildings, interior lighting for prestige offices, or lighting systems for new underground railway carriages. Maximum volumes for these types of product would be a few hundred. Business of the bespoke type is won through submitting tenders in a competitive environment.

The other type of business is a range of products which were manufactured in high volume at Enfield and Spennymoor, and is now based at Spennymoor. The product range divides into many families of different variants, totalling nearly 2000 distinct products. At one time there may be 300 projects under development, each with a level of urgency related to its strategic importance. During the interviews a basic assumption that the firm is market led was apparent. This is true where the development of variants on existing products is concerned, and the updating of existing product ranges. Having noted this, there is also a case for arguing that it is technology led in some areas. Often ideas for new products are generated in the Lighting Research Laboratories. These take the form of extensions to existing families, perhaps when a range of light sources is extended, or totally new families of products when a new type of light source is developed, or new technology can be applied to develop a new type of control gear.

The products manufactured in volume are not sold through retail, but through being specified by architects and interior designers when buildings are constructed or refitted. The most popular units may sell in millions over a year.

4.2.3.2. The order winning process

In the bespoke business the orders are won through a competitive tendering situation. The selling points are different for different types of project. For a prestige building cost may not be of particular importance, but aesthetic appeal may be most important. For an external lighting system technical performance, running costs, and then price may be most important. For transport system lighting, unit costs, reliability and functionality may be most important. Not only do the criteria change for the different projects, the way the designs are presented, deadlines, and the design briefs vary too. An architect may give the aesthetic designer a free hand, or the technical specifications for an external system may be very tight. The customer may only want drawings, or require mock-ups of the proposed article. It is therefore very rare that a project is approached the same way twice, even for the same customer. The approach of the bespoke design department is therefore flexible through necessity.

The volume manufacturing side of the business is in effect selling into an open market. It has therefore to beat the competition on a combination price, delivery, functionality, aesthetic appeal or marketing. Whilst it may not be possible to be leader in all five criteria, it is the company that puts together the best overall combination of these things that can win the order. Design can influence price, functionality and aesthetic appeal directly, and delivery indirectly.

4.2.3.3. Information used by the design department

The information available to the designers working on bespoke products varies form project to project. The amount and accuracy of the specifications and background material available is largely up to the customer. Technical information is available from British Standards, the specification of light sources, and general test data, but guidance on the particular problems of a project has to be provided by the customer, either by the supply of a specifications during the tendering process, or through a dialogue after the order is placed.

The same technical and standards information is used by the designers of volume products. The specification of the particular design under development come from within the firm. The market and technology leads of the company have been discussed in section 4.2.3.1, and the two strategies have a bearing on the sources of information available to the designer. In the market lead situation the market- or design-brief comes from the marketing department. This brief takes the form of a lengthy document detailing the range of products, their place in the companies strategy, the expected volumes, projected unit costs, launch date, and possibly information on the manufacturing facilities to be used. Often the design department need more information and this is obtained from the marketing department. The final specification of the finished product is usually a compromise between the design department and marketing, as a result of a dialogue between the two departments. Technology lead developments require a champion for the idea. The brief forms through dialogue between the technical, design and marketing departments, co-ordinated by this champion. The development process is like that for market lead products, but with more intangibles and deeper involvement form technical development people.

4.2.3.4. Price and delivery date planning

In the bespoke market the price and delivery date planning is undertaken in tendering for the job. Section 4.2.3.2 describes the different requirements of different types of bespoke project, and their affect on the tendering situation. This information, and the knowledge of the market and resources of Thorn, are used in developing plans for price and delivery date.

For volume products price and delivery date planning is decided by marketing. The marketing department plan the launch strategy for the product. Often the launch will take place at a favourable time of year, or at an international lighting show. Such considerations set a deadline for at least the completion of a working model. The design department have to plan and allocate resources to come within this target window wherever possible.

Price level is set by the market niche into which the product is placed. More specifically, the price is based on the known or anticipated price for a product with similar features in the same market. Price is volume dependent, as is the amount of design effort put into a design. Small volume production runs are not value engineered to a great extent, since the reduction in manufacturing costs does not justify the extra expenditure during the design phase. Larger production runs can recoup the extra design investment and more, even if the reductions in manufacturing cost and increased profits are small.

4.2.3.5. Plan accuracy

Plan accuracy for the bespoke products is easier to maintain than for volume manufacturing products. Development times are shorter, fewer parties are involved in the projects, and testing and tool-proofing requirements are less demanding. For these reasons the bespoke projects can be seen as fast track development.

The development process for volume manufacture products is more complex, requiring the involvement of more people of various expertise, extensive production engineering involvement, detailed testing of prototypes, and careful consideration of unit costs. The level of complexity means that small problems are more difficult to correct, and the possibility of unforeseen circumstances is higher. For this reason targets for completion time, cost and performance are more often than not missed.

4.2.3.6. Plan production

Detailed plans are made for the development of volume products. At the beginning of a new project schedules are produced in such a way as to lead up to the completion date. The times are fixed and then priorities and resources allocate in order that the times may be met. Detailed planning of this nature is not usually undertaken for the bespoke projects, unless the development time is long.

4.2.3.7. Consequences of slippage

Slippage from the bespoke projects causes the same problems for Thorn as it does for Michell Bearings. Penalty clauses, the need for overtime, clashing over resources with other projects and loss of reputation. Often the project is for a contract where numerous other parties are involved, so the late delivery of one item can cause disruption to the schedules of several companies. Late delivery in such a situation is extremely bad for a firms reputation.

In volume manufacturing the consequences are less visible. The most obvious is that delays in the introduction to the market mean loss of revenue for the time the product is late. More seriously the late introduction can mean alterations to marketing strategy, market position, missing of the market window, and in the worst cases the failure of a new product to cover its development costs. See section 1.6.1 for a fuller discussion of these issues.

4.2.3.8. Stages subsequent to design

The design process passes bespoke work straight on to manufacturing, with little need for feedback or refinement. Volume products need to be engineered for production. Jigs and specific tools may be needed, and these will have to be tested for process compliance over a sample run. Prototype products need to be tested for electrical safety and for compliance with standards which may have been part of the design brief. In all of these stages there is the possibility that minor or even major design changes will be required. The final design is therefore reached through a series of iterations, each time getting closer and closer to a final production specification.

4.3. Comparison of the firms

There are many points of similarity and contrast between the three firms. In order that they can be presented concisely they are arranged into a table (table 4.1).

It can be seen from the table that there are a great many points of similarity between the ETO (or bespoke) firms and the volume manufacturing firms. For example, some of the consequences of slip in schedules are the same. There are also points of contrast within the ETO firms. Getting a tender for a job from Thorns or Michell costs nothing, whereas there is a charge from Labman Automation.

Labman Automation	Michell Bearings	Thorn Lighting (Bespoke)	Thorn Lighting (Volume)
Nine staff in total, at one site.	Over one hundred staff in total, at one site.	Over a thousand staff in total, over several sites in the UK.	
Design and manufacture one-off products.	Design and manufacture one-off products	Design and manufacture products from one-off to a few hundred -off	Design and manufacture volume products, with volumes in many thousands.
The only firm operating in their particular market.	One of a handful of firms in the world operating in the large bearing market, with specialisation in some products which only they can undertake.	Open competition with a hand full of firms in Europe.	Open competition with many firms world wide.
Orders won through a production of a design report, which forms both a feasibility study and tender. This study carries a nominal charge.	Orders won through a tendering process.	Orders won through a tendering process, which can take several formats.	Orders won on the merits of a completed product.

Table 4.1 (continued over leaf)

Comparison of the characteristics of the firms involved.

Labman Automation	Michell Bearings	Thorn Lighting (Bespoke)	Thorn Lighting (Volume)
Specifications come through the design study and dialogue with the customer	Specifications come from the completed enquiry and dialogue with the customer, via the sales department	Specifications come through dialogue with the customer or his agent.	Specifications come from a brief prepared by the marketing department, and dialogue with marketing and technical staff.
Rough time plans made during the design study stage, details worked out after an order is placed.	Rough estimates for duration made by the estimating department, formal, factory wide details worked out after an order is placed	Plans are prepared during tendering.	Due dates are set by the marketing department. Plans are arranged in order to try and meet that date.
Indistinct boundary between design and manufacture	Distinct boundaries between design and other functions	Indistinct boundary between design and manufacture	Distinct boundaries between departments, but iteration required so the designs are passed back and forward.
Slip affects profitability mostly through increased labour costs and clashes with other projects over resources.	Labour costs, loss of reputation, penalty clauses and resource clashes affect profitability.	Labour costs, loss of reputation and penalty clauses affect profitability.	Labour costs, loss of production, missed market, wasted effort and resource clashes affect profitability.

Table 4.1 (continued from previous page)

Comparison of the characteristics of the firms involved.

4.4. Summary

This chapter covers some of the issues of doing industrially based research, including the reasons for undertaking such a project, and practical issues of getting collaboration. It briefly discusses a way of managing the relationship between industrial and academic partners.

The size and structure of the firms most closely involved in the research have been described. Also presented was some information on the markets the firms service and to some extent, the order winning strategies of the firms. The bulk of the information concentrates on the operation of the design office, and the use and generation of schedules. Subsequent chapters will present the results of further investigations into time estimation for design scheduling.

5. Results and discussion of the quantitative investigation

This chapter describes the aims, execution and analysis of the quantitative investigations carried out during the study. Whilst collaboration had been sought from around ten firms, only three were able to contribute in the fullest way to the project as a whole. It had been intended that the quantitative study take place in all these firms. Unfortunately, for reasons which will be detailed in section 5.2.2, this type of study turned out to be impractical in Thorn Lighting.

The remainder of the chapter describes the data gathering procedure, and the analysis performed. Discussions are included to explain some of the steps taken during the study, and where the issues remain within the bounds of the quantitative investigation. Discussion of issues arising from this investigation with consequences for the larger study are touched on, but are covered in more depth by chapter 8.

5.1. Object

The objective of this part of the study was primarily to establish whether there was any link between the times estimated for the completion of a new design and the actual time taken. A secondary objective was to identify, if possible, any link between design time and the number or area of new drawings required. If such a link could be uncovered it would provide a simple method for establishing a first estimate for design time. A link of this type could be compared to the calculation of weight of a component as a guide to its manufacture cost. More formally the three hypotheses to be tested using statistical methods were:

$$H_1 \Rightarrow \left\{ \begin{array}{c} \text{The time taken to complete a design is related} \\ \text{to the area of new drawings required} \end{array} \right\}$$

$$H_2 \Rightarrow \left\{ \begin{array}{c} \text{The time taken to complete a design task is related} \\ \text{to the number of new drawings required} \end{array} \right\}$$

$$H_3 \Rightarrow \left\{ \begin{array}{c} \text{The actual design time is related} \\ \text{to the estimated design time} \end{array} \right\} \text{ or } H_3\text{, as described on page 38}$$

The object of this investigation was therefore to gather data which would allow these hypotheses to be either accepted or rejected. It also revealed phenomena which could either be discussed simply on the basis of the statistics, or used as an item of interest for the qualitative survey to develop.

5.2. Scope

The scope of the investigation was largely dictated by three factors:

1) The access allowed to the researcher by the firms involved

2) The degree to which the appropriate data were extant and available at the firms involved

3) The capacity for implementing measures which would facilitate further data collection

The access allowed in the firms which participated in the statistical survey was the fullest of all the firms approached. Due date performance information could be sensitive in a market where delivery on time is increasingly becoming a market hygiene factor. Where profit margins on bespoke work are highly dependent upon meeting targets for resources and delivery dates, information of the type collected here could be of use to both customers and competitors. Access to this type of information was therefore the exception rather than the rule.

The existence and availability of data, and the capacity for implementing further data collection methods quickly become entangled when considering practical data collection. If data is unavailable, either through being present only in disparate sources, or simply not being recorded, the option of implementing a system where data can be recorded in one place and in the appropriate form may be taken up. Similarly, when data is present but at an inappropriate level of accuracy, or recorded for a similar but not identical phenomenon, revision of the data recording system may be possible. However, this new or revised data collection mechanism relies on there being sufficient projects subsequent to the mechanisms implementation to produce a usable sample.

5.2.1. Data collection at Michell Bearings

At Michell Bearings there initially seemed to be no problems with collecting data. However, following analysis of the first data set collected it was found that no significant trends were visible in the data collected to test any of the three hypotheses. Rather than reject the hypotheses based on a small negative sample an examination of the sources of the data, and the method of analysis, was made. The examination revealed that the way commencement and completion dates were recorded allowed the presence a large theoretical error. Only the start week, estimated finish week, and actual finish weeks were recorded. Some of the jobs undertaken in this firm have an extremely short duration. In the worst case of a job starting on Friday and finishing on Monday the error could be as much as 400% of the true duration. See section 5.2.2 for calculations of errors. The errors affected the data used to test all three hypotheses. In order to correct this the design office manager agreed to record the start week and day, and the end week and day, for each subsequent project. The estimated completion date was not calculated to the day and so could only be recorded as before. Because of the rapid turnover of projects, and the tendency for extremely large contracts to be broken down into phases, a significant quantity of data could be collected in the two years remaining.

5.2.2. Data collection at Thorn Lighting

At Thorn Lighting problems of the second and third types were encountered, to the most serious extent. Project briefs could originate from one of two sources, marketing, or from within new product development department itself. Until recently development could be undertaken at any of three sites in the UK. Project briefs can undergo frequent revisions. Frequent revisions and alterations to the brief mean that original estimates become invalid. Establishing where the revisions to a project cause it to become a new project, and what development can be carried over from the original project to the new influences the completion date. All these complications made it impractical to gather meaningful data from the existing project documentation. Meaningful in this context refers to data comparable with data sets from other firms. Assuming that a method whereby meaningful data could be collected from subsequent projects could be implemented, there would have been a further problem. With only two years remaining in the period of study, slow project turnover would have meant that the number of projects completed in that time would have been very small. In twenty four months it would be highly unusual to complete more than two projects. It would not have been exceptional for all projects undertaken in that time to take more than two years from original brief to full production. Even given three years for the study, the sample would be very small. For this reason the quantitative investigation was seen to be impractical in Thorn Lighting.

5.2.3. Data collection at Labman Automation

Labman Automation shared two problems with Thorn Lighting. Although the type of information required was present, and the design briefs were static within reason, the actual figures themselves were not in a form directly comparable with those from Michell Bearings. In a firm as small as Labman the distinction between design and manufacture becomes unclear. Whilst at Michell the drawings for long lead time items may be released from the design department before the design is entirely complete, to have the design and manufacture of a project operating concurrently is a matter of routine at Labman. For this reason separate estimates for design completion time and manufacturing completion time were almost meaningless and therefor not produced. Whilst it was possible to deduce the total design effort required from the time sheets completed each member of staff not covered in overheads, no comparison with estimated design time was possible since such an estimate is not produced. However, since the links between design and manufacture are so close in this situation it may be argued that the estimate for manufacture time mirrors an estimate for design time. In making this assumption it is important to be aware of when delays in project completion are due simply to hold ups in manufacture or procurement. In cases where this is so, the final completion time does not mirror the final design time. Such cases should therefore be excluded from the analysis.

The second problem Labman shared with Thorn Lighting was the slow turnover of new projects. When the firm is busy there may be two projects underway at one time, however for part of the time there may be no project underway, the work being confined to dealing with chasing new orders and dealing with enquiries. An order may take up to six months to fill. The method of recording the particulars of a project had undergone some changes, so historical records were of no use before a certain date. The changes meant that only six complete project records were available from the period of the study and from the historical records. To compound this problem the contact within Labman moved to a different firm, so access to subsequent project records was not possible. Because projects where problems with procurement or manufacturing must be excluded from the analysis the remaining sample is very small. However, since the record of each project's development is detailed, a high degree of confidence can be attached to the remaining data.

Data collection was therefore possible where it concerned H_3, but the small sample size inevitably affected the significance which could be attached to the results.

5.3. Sources of data

The documentary sources have already been mentioned in passing in sections 3.2.2 and 5.2. Explicit details of the sources used at the two firms where the quantitative investigation took place are given below.

5.3.1. Data sources at Michell Bearings

By far the largest quantitative investigation took place at Michell Bearings, both in terms of the number of cases examined, and the hypotheses tested.

Data concerning design time and project type were taken from the 'Project File'. The file is a ring binder which records, for each project within the drawing office:

Order number	A number unique to that project
Sign on date	The date at which the project enters the design office
Start day	The day (1-5) the designer first started work on the project
Start week	The week (1-52) the designer first started work on the project
End day	The day (1-5) the designer completed work on the project
End Week	The week (1-52) the designer completed work on the project
Estimated end week	The week (1-52) the design manager estimated work on the project would be completed

The file also records the draughtsman's initials, a description of the bearing type and number required, the customer, and other information relating to the project, such as if and when design review is required. Problems which may have occurred with a project are also recorded here, such as the customers late delivery of specifications, or approval of drawings, and also if the completion date has been revised.

Information relating to the number and area of drawings required to investigate H_1 and H_2 was taken directly from examining each of the drawings themselves. Although it was possible in the majority of cases, deducing the number, type, and new drawings from the arrangement drawing of each project could not always be done. All the approved master drawings for each project were therefore to be examined.

5.3.2. Data sources at Labman Automation

As described in section 5.2.3, the data from Labman Automation were recorded in a way different from Michell Bearings. Information came from the individual files relating to each project, and from time sheets. The time sheets are filled in by each employee who's wage was not entirely covered in overheads. Time has to be booked down against a specific project, and a specific operation, such as design work, manufacturing or software development. The project files included:

- A unique order code
- Order placement date
- The value of the project
- An estimated delivery date
- Actual delivery date

From these two sources of information it was possible to deduce:

- the total number of man-hours spent on a project
- the number of design man-hours spent on a project
- the duration of the project
- the estimated duration of the project

The project files also included documents regarding problems encountered during design and manufacture. Examples of such problems include late specification by customers, late delivery of bought out parts, and set-backs to planned design solutions. From this information it was possible to infer whether the delays were due to design problems or manufacture problems - vital information when interpreting the estimate and achievement comparisons.

5.4. Assessment of data integrity

This section presents some discussion and analysis of the quality and accuracy of the data collected in order to test the hypotheses detailed in section 5.1.

5.4.1. Data integrity assessment for Michell Bearings

At Michell bearings, all the data required had at some stage been approved by the Design Manager. It is the design manager who completes the information held in the 'Project File'. All drawings signed out of the design office are inspected by the design manager and are either approved by him, or revised before approval. Thus the recording of the information required was consistent. Drawings which were not valid could have been easily distinguished, since they would not bear the design managers mark of approval. Any sources of error in the recorded information therefore stem from mis-recording by the design manager - an unlikely occurrence since there is some redundancy present in the records. The quality of the figures used in the study can therefore be seen be to be high, especially compared with errors introduced due to the resolution of the recorded information.

Upon collection, the data sets were analysed using a spread-sheet program. Working in this way ensured that the results were analysed reasonably quickly and in a repeatable way. However, it was extremely important to spend some time considering the preparation of the spread-sheet, since a small fault with formulae used would be repeated over the whole data set, making it extremely difficult to trace. The remainder of this section presents consideration of errors in the data, and the formulae used to calculate the values eventually plotted. It may seem that the point is laboured since the values are in effect simply rounded up. However, it was important that this rounding was made explicit for the purposes of the spread-sheet, and therefore there is some justification for considering the implications of the rounding. It was this rounding which was responsible for the problems discussed in section 5.2.1, and without acknowledgement of the problems of using a spread-sheet, the trend present in the data may never have been spotted.

Changes in the resolution of the recorded start and finish dates for design have been discussed in section 5.2.1. Discussion of the errors possible both before and after these changes follows.

The design manager at Michell Bearings was prepared to record start and finish dates to the day. The 'day' therefore is taken as the smallest unit which can be used to measure design duration within this firm. The notation used for the analysis is presented below.

Variable	Symbol	Range
Actual duration in working days:	D^*_{days}	{1..}
Calculated duration in working days:	D_{days}	{1..}
Estimated duration in working days:	E_{days}	{1..}
Start day:	d_{start}	{1..5}
End day:	d_{end}	{1..5}
Start week:	w_{start}	{1..52}
End week:	w_{end}	{1..52}
Estimated completion week	w_{est}	{1..52}

An equation for calculating the duration of a project whose start and finish dates are recorded accurate to the week is:

$$\S 5.1 \quad D_{days} = \left(w_{end} - w_{start} + 1\right) \times 5$$

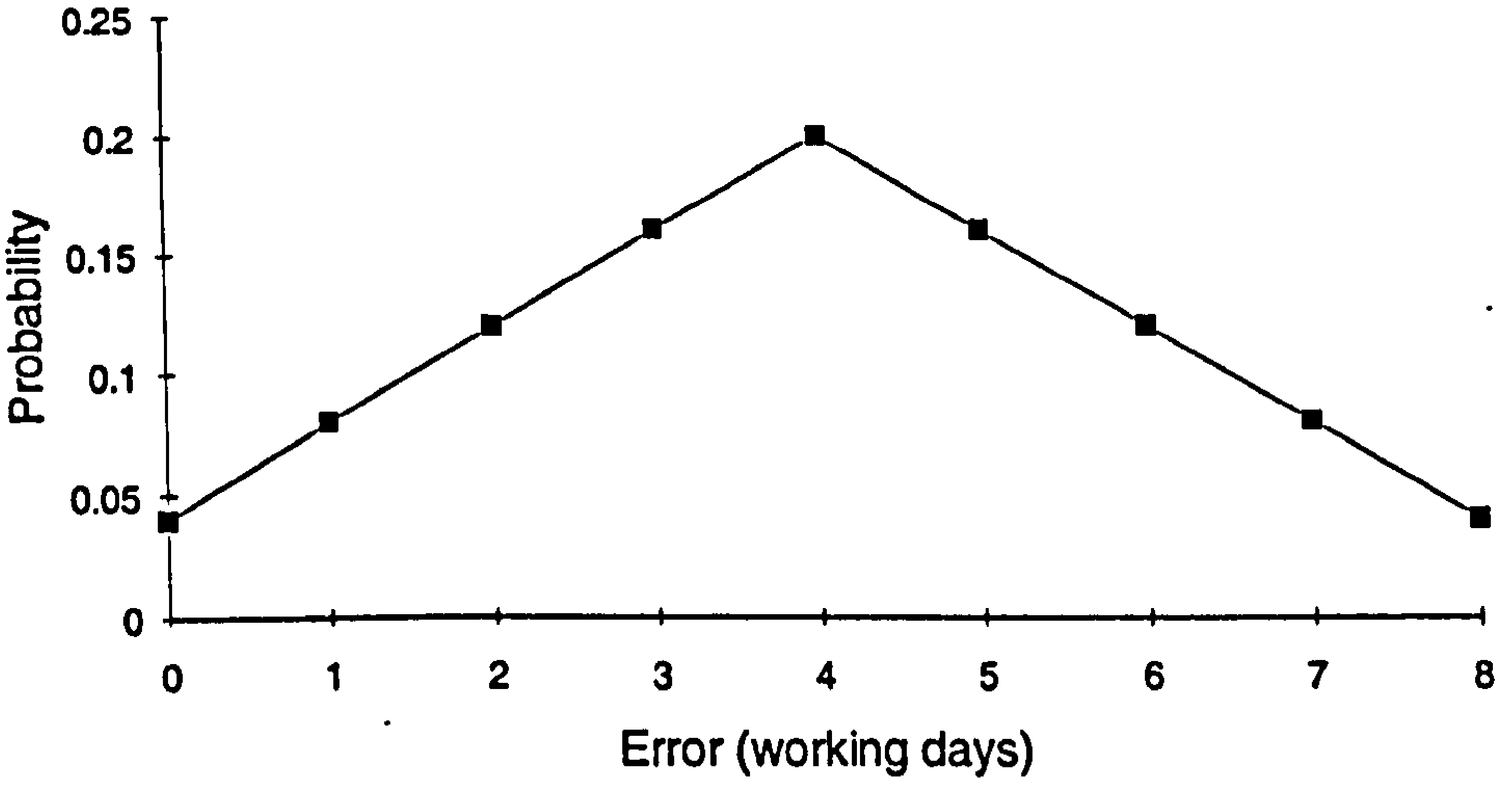
The [+1] term is introduced because a project starting and finishing in the same week may not have zero duration. The maximum duration of a project started in one week and completed in the next is 10 days - Monday of week one to Friday of week two.

Using these figures to calculate D_{days} with equation 5.1 gives the correct duration of 10 days.

However, the shortest duration of a project starting in one week and ending in the next is two days - Friday of one week to Monday of the next, two days. Using equation 5.1 the calculated duration remains 10. The error, as a percentage of the true duration is:

$$Error\% = \frac{D_{days} - D^*_{days}}{D^*_{days}} \times 100\%$$

This formula gives a maximum error between D_{days} and D^*_{days} to be 400%. The distribution of these errors is represented in figure 5.1. The analysis assumes that probability of project commencement and completion is uniformly distributed throughout the working week. There may not be uniform distribution, but the for the purposes of analysis it provides the simplest case.



Graph of probability of error against size of error $D_{days} - D^*_{days}$.

Figure 5.1

The errors are constant for a duration greater than one week, so as the actual duration increases the percentage error decreases. For a project of ten weeks duration the maximum error is +20%, with a likelihood of 4%. A typical error would be +10%. However, as can be seen in the graphs in section 5.5.1, many projects have a duration far shorter than this and hence, much larger percentage errors. It is for this reason that there was a need to record the start and finish times to the day.

By recording the start and finish day these errors can be eliminated. The equation for recording the duration becomes:

$$\S 5.2 \quad D_{days} = d_{end} - d_{start} + 1 + (w_{end} - w_{start}) \times 5$$

The [+1] term is included so that a project starting and finishing on the same day takes the value of the smallest unit used to measure duration at Michell Bearings. From equation 5.2 it can be seen that D_{days} and D^{*}_{days} have the same value when calculating the case which gave an error using equation 5.1.

Since the estimate was only made to the accuracy of one week, the calculation for estimated duration must take into account that a project may finish on a Monday or a Friday of the estimated week and still comply with the estimate. The equation for calculating estimated duration in working days therefore is:

$$\S 5.3 \quad E_{days} = 5 - d_{start} + (w_{end} - w_{start}) \times 5$$

If the estimation of duration were performed to any accuracy beyond that recorded it would be possible to perform error an analysis of the estimated duration data similar to that done for the start and completion times. However, since the finest detail at which the estimated completion time is ever known is one working week, analysis down to the resolution of one day would be meaningless.

Whilst there were initial difficulties with the low resolution provided by the system of recording start and completion times, it can be seen that the sources of data at Michell Bearings are reliable enough to test the hypotheses of section 5.1. The estimated completion time is only required by the planners at Michell Bearings to within one week, so attaching any significance to any day other than the Friday of the estimated completion week is meaningless.

5.4.2. Data integrity assessment of Labman Automation

Labman Automation operates different working practices to those used at Michell Bearings, so it is to expected that the way the start, finish and estimated finish times are recorded is different. Before a design is commissioned from Labman, the company produce a design study (see section 4.2.1). The study includes the following information:

- a description of the proposed machine's purpose
- specification of machine work load, critical components and appropriate limits
- discussion of basic design concepts, and possible options
- description of the type, value and supplier of major components
- a proposed arrangement drawing and drawings of some critical parts
- a variety of design, production, commissioning and payment options

The final item requires the estimation of design, manufacture and commissioning duration. Commissioning may be excluded when gathering data for the testing of H_3 since the commissioning is largely undertaken at the customer site. The delivery date having been taken as the completion of design and manufacture.

The notation used to denote the various items of information collected from Labman are listed below:

Variable	Symbol	Range
Estimated completion date:	E_{date}	{dd/mm/yy}
Start date	S_{date}	{dd/mm/yy}
Finish date	F_{date}	{dd/mm/yy}
Individual's hours of design time	h_{ind}^{design}	{0..}
Individual's hours of production time	h_{ind}^{prod}	{0..}
Total hours of design time	h_{total}^{design}	{0..}
Total hours of production time	h_{total}^{prod}	{0..}

The documentary sources of information were therefore:

E_{date}	taken as the quoted delivery date for the equipment appropriate to the option chosen by the customer from the design study.
S_{date}	taken as the date on the order notice, accompanied by an order number.

F_{date} taken as the date on the delivery note.

h_{ind}^{design} & h_{ind}^{prod} taken from time sheet information completed by each individual employee [*ind*].

Often E_{date} had to be found from the order notice date S_{date}, since the delivery date had been quoted in the design study as being a number of weeks from the order date. h_{total}^{design} and h_{total}^{prod} were calculated by addition of the h_{ind}^{design} and h_{ind}^{prod} for each individual working on a project:

$$§5.4 \quad h_{total}^{design} = \sum_{\text{all } ind} h_{ind}^{design}$$

$$§5.5 \quad h_{total}^{prod} = \sum_{\text{all } ind} h_{ind}^{prod}$$

The figures for E_{date}, S_{date} and F_{date} may be assessed to have a high degree of accuracy, since their documentary sources have legal significance. A degree of care will have therefore been taken with their preparation. h_{ind}^{design} and h_{ind}^{prod} may not be treated with the same degree of confidence, since the information is recorded purely for internal use. There is traditionally some resistance to the completion of time sheets and diaries, and whilst there was no evidence of this at Labman, it is possible that oversights or other factors may influence the accuracy of this information. There is also the possibility of differences, between one individual and another, of interpretation and conscientiousness when recording this information. However, the bulk of the analysis performed does not rely on the time sheet data.

5.5. Results

This section presents the data collected, and analysis performed to test the three hypotheses described in sections 3.2.1 and 5.1. Section 5.5.1 involves data used to investigate all three at Michell Bearings. Brief discussion of the significance of these results, and the appropriateness of the method of testing is included. The discussion has some bearing on the investigation completed at Labman Automation, the data and analysis of which are presented in section 5.5.2.

5.5.1. Data and analysis from the investigation at Michell Bearings

The information presented in this section was collected using the methods described in section 5.3. Some conditioning of the data was required before graphical representations and regression analyses could be prepared. Dates and week numbers were transformed into duration in days using formulas §5.2 and §5.3. In order to calculate the number and area of new drawings, the minimum unit of area was taken as the area of an A4 sheet of paper. A4 was the smallest size used at Michell for working drawings. The notation and formulae used for total number of new drawings; total number of drawings; area of new drawings; and total area of drawings were therefore:

Variable	Symbol	Range
Number of drawings of size A*n*	N_{An}	{0..}
New drawings of size A*n*	N^{new}_{An}	{0..}
Total number of drawings	$N_{A4..0}$	{1..}
Total number of new drawings	$N^{new}_{A4..0}$	{0..}
Area of new drawings	A_{new}	{0..}
Total area of drawings	A_{total}	{A4..}

$$N^{new}_{A4..0} = \sum_{n=4}^{0} N^{new}_{An}$$

§5.6 or

$$N^{new}_{A4..0} = \left(N^{new}_{A4} + N^{new}_{A3} + N^{new}_{A2} + N^{new}_{A1} + N^{new}_{A0}\right)$$

$$N_{A4..0} = \sum_{n=4}^{0} N_{An}$$

§5.7 or

$$N_{A4..0} = \left(N_{A4} + N_{A3} + N_{A2} + N_{A1} + N_{A0}\right)$$

$$A_{new} = \sum_{n=4}^{0} N^{new}_{An} \times 2^{4-n}$$

§5.8 or

$$A_{new} = \left(N^{new}_{A4} + N^{new}_{A3} \times 2 + N^{new}_{A2} \times 4 + N^{new}_{A1} \times 8 + N^{new}_{A0} \times 16\right)$$

$$A_{total} = \sum_{n=4}^{0} N_{An} \times 2^{4-n}$$

§5.9 or

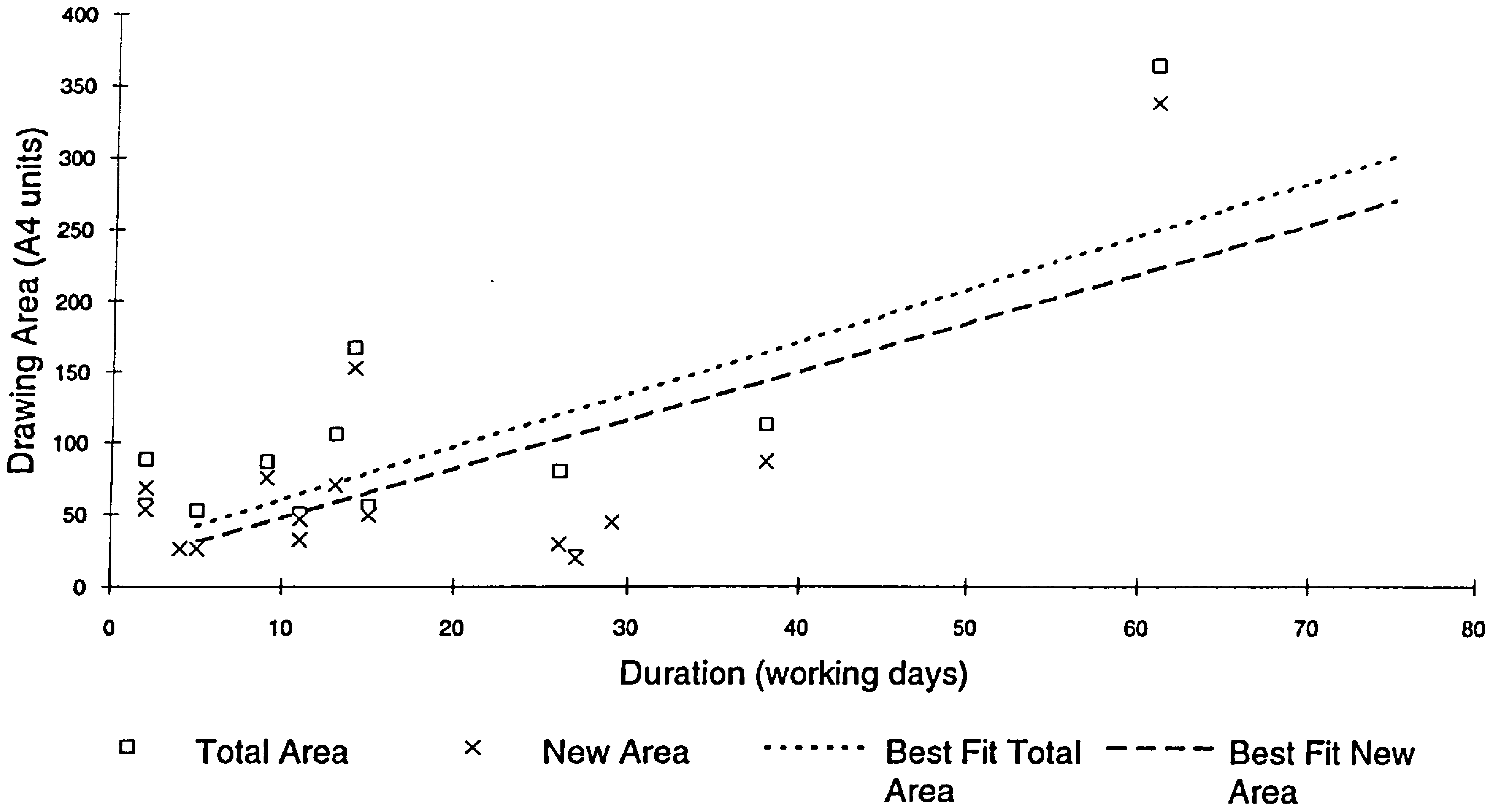
$$A_{total} = \left(N_{A4} + N_{A3} \times 2 + N_{A2} \times 4 + N_{A1} \times 8 + N_{A0} \times 16\right)$$

5.5.1.1. Graphical representations of data from Michell Bearings

Below are four graphs which represent five different data sets. Figure 5.2 shows two relationships, which are plotted together to emphasise their similarity. There is a positive correlation between both the area of new drawings produced for a project and the duration of its design phase, and the total area of drawings required for a project and the duration of its design phase. However, a high degree of scatter from the trend is apparent.

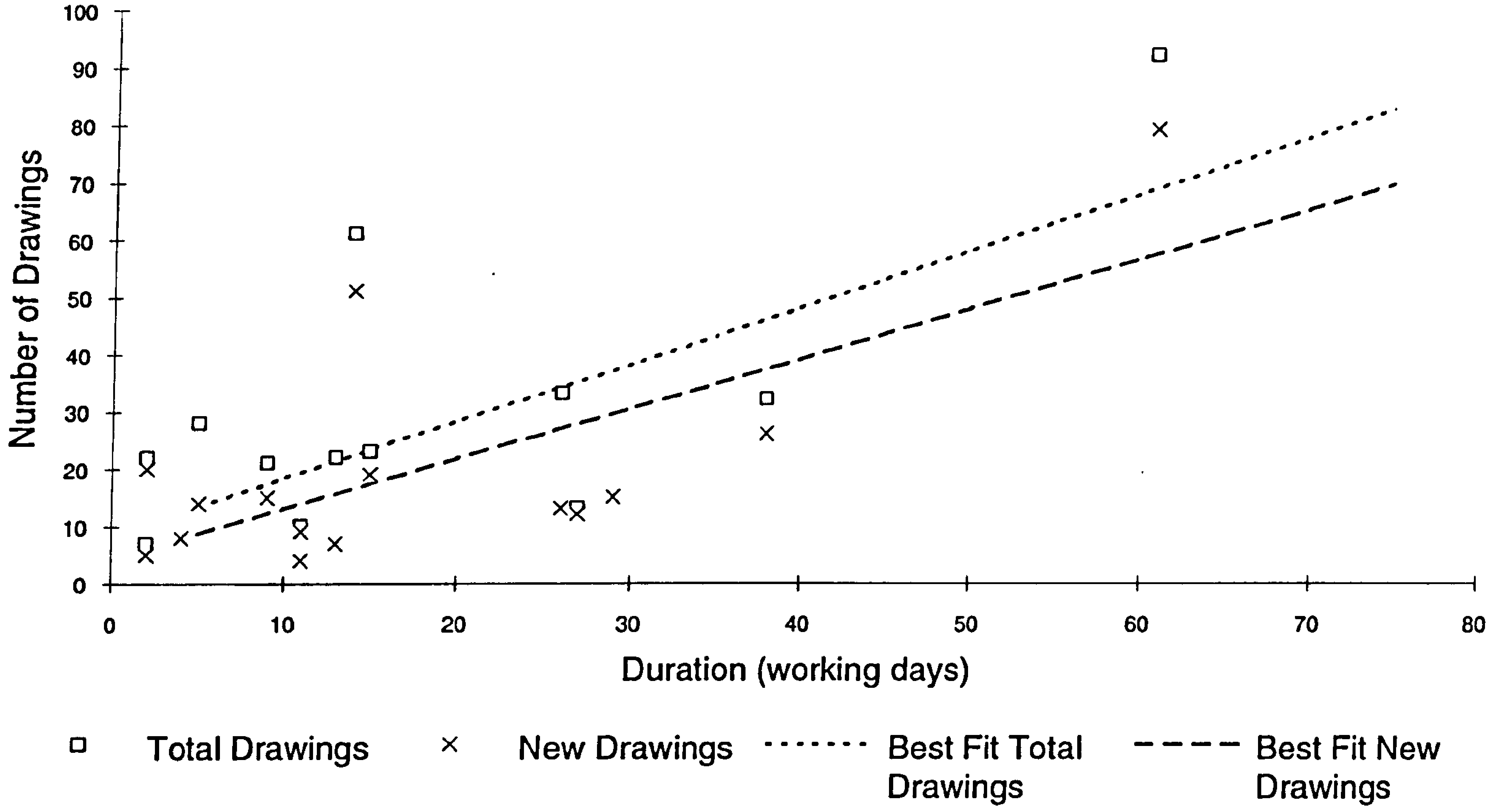
Figure 5.3 shows two similar relationships, which again are plotted together to emphasise this similarity. There is a positive correlation between both the number of new drawings produced for a project and the duration of its design phase, and the total number of drawings required for a project and the duration of its design phase. Again, a high degree of scatter from the trend can be observed.

Figures 5.4 and 5.5 both plot the estimated duration of projects against their actual duration. Both show a strong correlation between the estimated and actual duration of projects. The difference between the two graphs is in the way the regression lines are calculated. In the first instance the regression line is unconstrained in its intercept with the *y*-axis. The slope and *y*-intercept depend purely on the data points plotted. However, it may be argued that the best fit must pass through (0,0). When considering the null case - a project will no specifications, and requiring no solution, which presents no design problem, the estimated duration would be zero and the actual duration would be zero. When following this logic further assumption must be considered. For real cases the designer at Michell bearings does not start from a state of zero, or full project knowledge, and one would expect that some time would be required for understanding and drafting even the simplest problem. Issues of the level knowledge at the start of the project are discussed in sections 5.5.1.3 and 5.6.1. The two graphs are presented here as an illustration of the different cases. The graphs also carry a line representing total correspondence between estimated and actual duration. Points which fall above or on the line $y = x$ were completed within their estimated time. Points which fall below this line (the majority) took longer than estimated to complete.



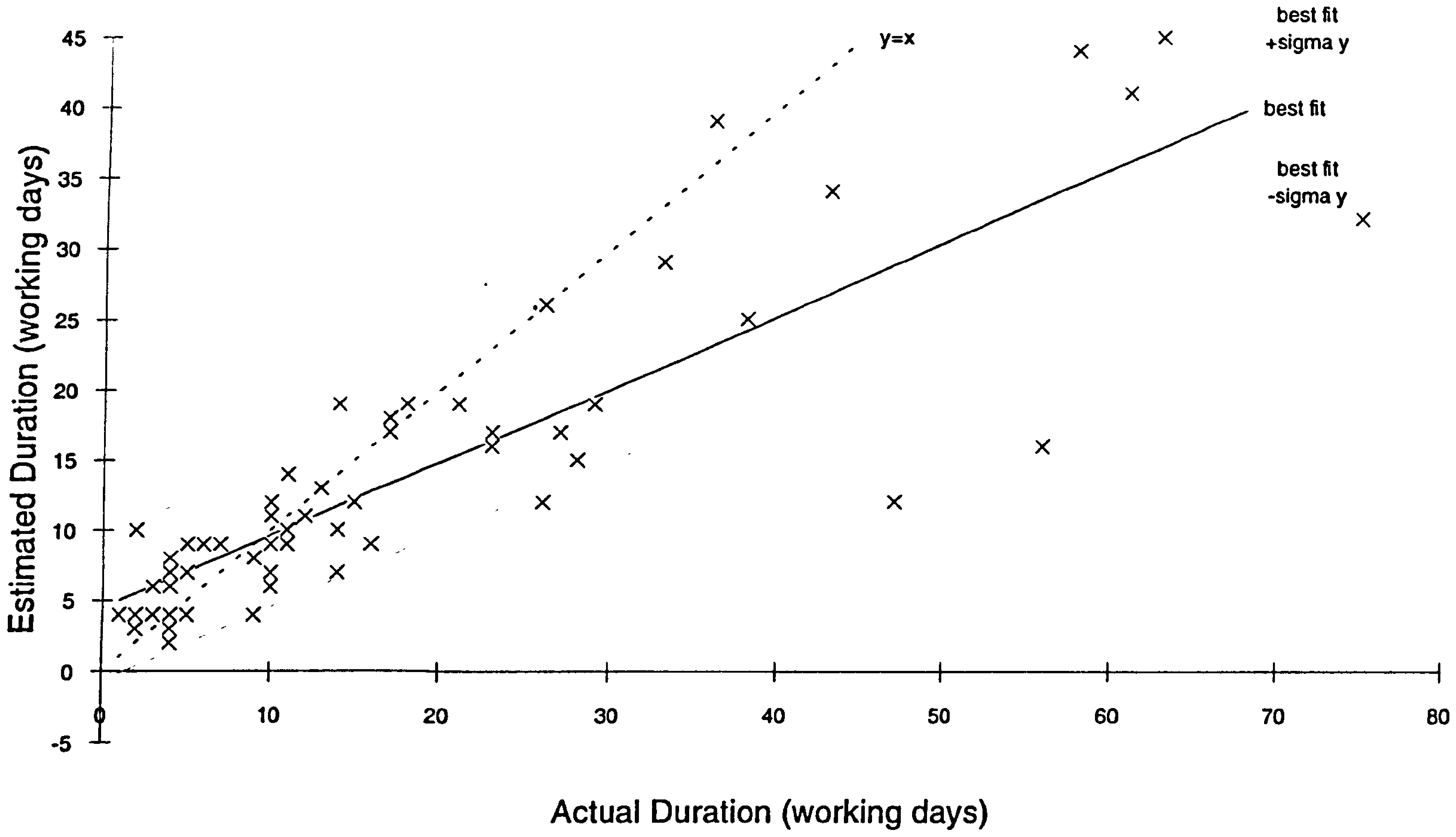
Graph of area of new drawings A_{new}, and total area of drawings A_{total}, against calculated design duration D_{days}.

Figure 5.2



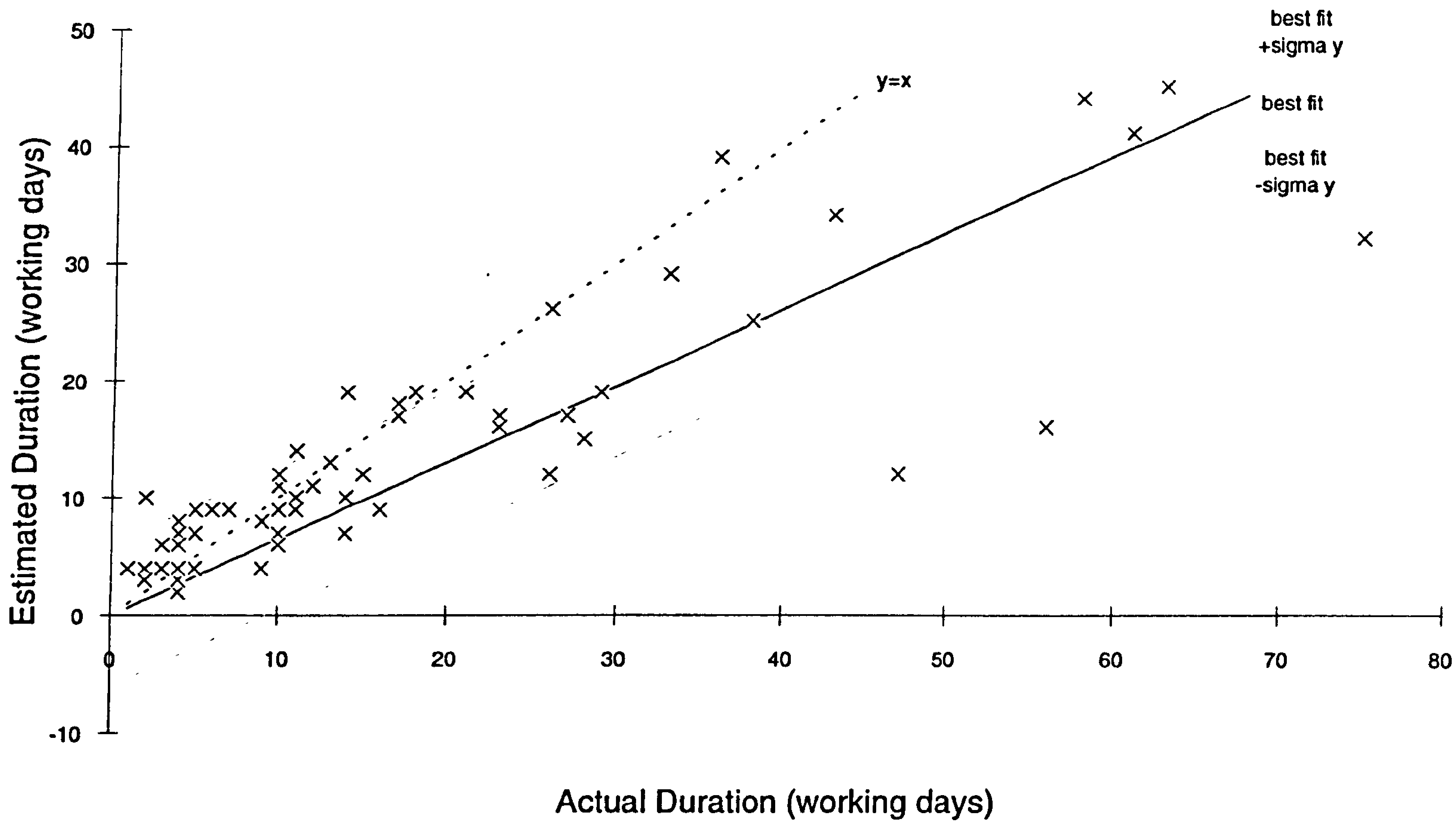
Graphs of new drawings $N_{A4..0}^{new}$, and total number of drawings $N_{A4..0}$, against calculated design duration D_{days}

Figure 5.3



Graph of estimated design duration E_{days} against calculated design duration D_{days}, with unconstrained least squares regression line.

Figure 5.4



Graph of estimated design duration E_{days} against calculated design duration D_{days}, with least squares regression line constrained to (0,0).

Figure 5.5

5.5.1.2. Regression analysis of data from Michell Bearings

Best fit lines are shown on the preceding graphs for each of the data sets represented. In order to test the correlation between the data sets and the best fit lines used to represent them, regression statistics were prepared and analysed. The regression statistics relating to the best fit lines on figures 5.2 and 5.3 are presented in tables 5.1-5.4.

m=	3.41	b=	13.38
σ_m=	1.00	σ_b=	23.72
r^2=	0.47	σ_y=	60.41
$F^{v_1}_{v_2}$=	11.55	v_2=	13

Table 5.1 - least squares linear regression statistics for new drawing area A_{new} (units of A4) against duration D_{days} (working days)

m=	3.69	b=	23.22
σ_m=	1.05	σ_b=	24.76
r^2=	0.49	σ_y=	63.06
$F^{v_1}_{v_2}$=	12.41	v_2=	13

Table 5.2 - least squares linear regression statistics for total drawing area A_{total} (units of A4) against duration D_{days} (working days)

m=	0.87	b=	4.37
σ_m=	0.25	σ_b=	5.84
r^2=	0.49	σ_y=	14.87
$F^{v_1}_{v_2}$=	12.30	v_2=	13

Table 5.3 - least squares linear regression statistics for number of new drawings $N^{new}_{A4..0}$ against duration D_{days} (working days)

m=	0.99	b=	8.51
σ_m=	0.29	σ_b=	6.83
r^2=	0.47	σ_y=	17.39
$F^{v_1}_{v_2}$=	11.65	v_2=	13

Table 5.4 - least squares linear regression statistics for total number of drawings $N_{\mathrm{A4..0}}$ against duration D_{days} (working days)

In each case the analysis is for a single least squares regression line with degrees of freedom v_1, v_2 of 1 and 13 respectively. Applying the F-test, the critical values of F are:

Degree of significance	F^1_{13}
0.05	4.7
0.25	6.2
0.01	9.1

Relationship	F	Significance Level
A_{new} against D_{days}	11.55	99%
A_{total} against D_{days}	12.41	99%
$N^{new}_{\mathrm{A4..0}}$ against D_{days}	12.30	99%
$N_{\mathrm{A4..0}}$ against D_{days}	11.65	99%

(Data from Halstead, 1960)

There is therefore less than a 1% chance that the regression is due to random variation in the data. However, a large amount of scatter is apparent on each of the graphs, as can be seen in the proportionately high values of σ_m, σ_b and σ_y. The results are interpreted more fully in section 5.5.1.3.

In the analysis of a single least squares regression line for the estimated and actual completion graphs, $v_1=1$ in both cases. Tables 5.5 and 5.6 present statistics relating to the regression analysis.

$m=$	0.52	$b=$	4.44
$\sigma_m=$	0.037	$\sigma_b=$	0.88
$r^2=$	0.75	$\sigma_y=$	5.14
$F^{v_1}_{v_2}=$	195.14	$v_2=$	66

Table 5.5 - least squares linear regression statistics for estimated duration against duration D_{days} (working days), unconstrained on *y*-intercept

$m=$	0.65	$b=$	0
$\sigma_m=$	0.031		
$r^2=$	0.65	$\sigma_y=$	6.01
$F^{v_1}_{v_2}=$	123.69	$v_2=$	69

Table 5.6 - least squares linear regression statistics for estimated duration against duration D_{days} (working days), constrained to zero on *y*-intercept

For the graphs of estimated duration against actual duration the degrees of freedom v_2 are 66 and 69 respectively. For a degree of significance of 99% the F critical value for v_2=60 is 7.08 (Halstead 1960). Examination of the values of observed F in tables 5.5 and 5.6 shows them much higher than this. The regression lines in both cases above are therefore significant to a much higher degree than 99%. There is a probability of less than 1% that the trends observed occurred through chance selection of data from a uniform sample. The values for σ_m,σ_b and σ_y are also proportionately smaller than in tables 5.1-4. The differences in σ_m,σ_b and σ_y may be observed in the reduced scatter apparent when comparing figures 5.4 and 5.5 with figures 5.2 and 5.3. The results are discussed more fully in the following section.

5.5.1.3. Discussion of results from Michell Bearings

The data presented in figures 5.2 and 5.3 was intended to test the hypotheses:

$$H_1 \Rightarrow \left\{\begin{matrix}\text{The time taken to complete a design is related}\\ \text{to the area of new drawings required}\end{matrix}\right\}$$

$$H_2 \Rightarrow \left\{\begin{matrix}\text{The time taken to complete a design task is related}\\ \text{to the number of new drawings required}\end{matrix}\right\}$$

In the discussion of section 3.2.2 a means of checking the validity of the measurements was presented. Since the hypotheses regard the *new* drawings and *new area* of drawings as critical, it was important to establish that the methods used to measure the number and area of new drawings were satisfactory before drawing any conclusions. Section 3.2.2 forwarded the argument that if H_1 and H_2 were true, and the method of measurement adequate, then there would be a significant difference between the new drawings or area of drawings, and the total number of drawings or total area of drawings. It may be observed from figures 5.2 and 5.3 that this is not the case. The similarities in these trends may be caused by a number of phenomena:

i) both the total number/area of drawings and the number/area of new drawings are independently related to the duration by the same amount

ii) the total number/area of drawings and the number/area of new drawings can not be distinguished using this method

iii) a third phenomena which is related to the duration of a project is indicated by the number/area of new/all drawings

It is stated in section 3.1 that the object of these two hypotheses was to establish a possible link between the duration of a project and the ratio of its static and dynamic content, as measured by the number or area of new drawings compared with the total number or area of drawings. If theory i) is accepted this ratio has no influence. If theory ii) or iii) is accepted the static and dynamic ratio can not be measured by this method. Whilst further work may establish that either the dynamic/static ratio does not affect duration, or that the dynamic/static ratio is not properly indicated by the ratio of new/total drawings, the limitations in the data available made this part of the study inconclusive. There are significant trends evident in the data set, but they can not be relied upon to indicate the phenomena of interest. For this reason it was not seen to be productive to extend the study to Labman Automation.

It can be seen in the analysis presented in section 5.5.2.1 that there is a significant trend present in figures 5.4 and 5.5. Where the regression line is not constrained to (0,0) there is a visibly better fit to the data points referring to projects of shorter duration. The fit at this point would suggest that an average minimum estimated duration for a project design time would be around four and a half days. The minimum may be interpreted as an average time needed for a designer to become familiar with the brief in preparation for solving the design problems. The designer will not be approaching the problem from a state of zero knowledge. The minimum time may be dependent upon the experience of the designer since, for the purposes of analysis, differences between designers are absorbed in statistical variation. Because the fidelity of the recorded data has been assessed to be good in section 5.4.1, and the regression analysis has proved to be significant, it may be asserted that H_3 is true. That is:

The actual design time is related to the estimated design time

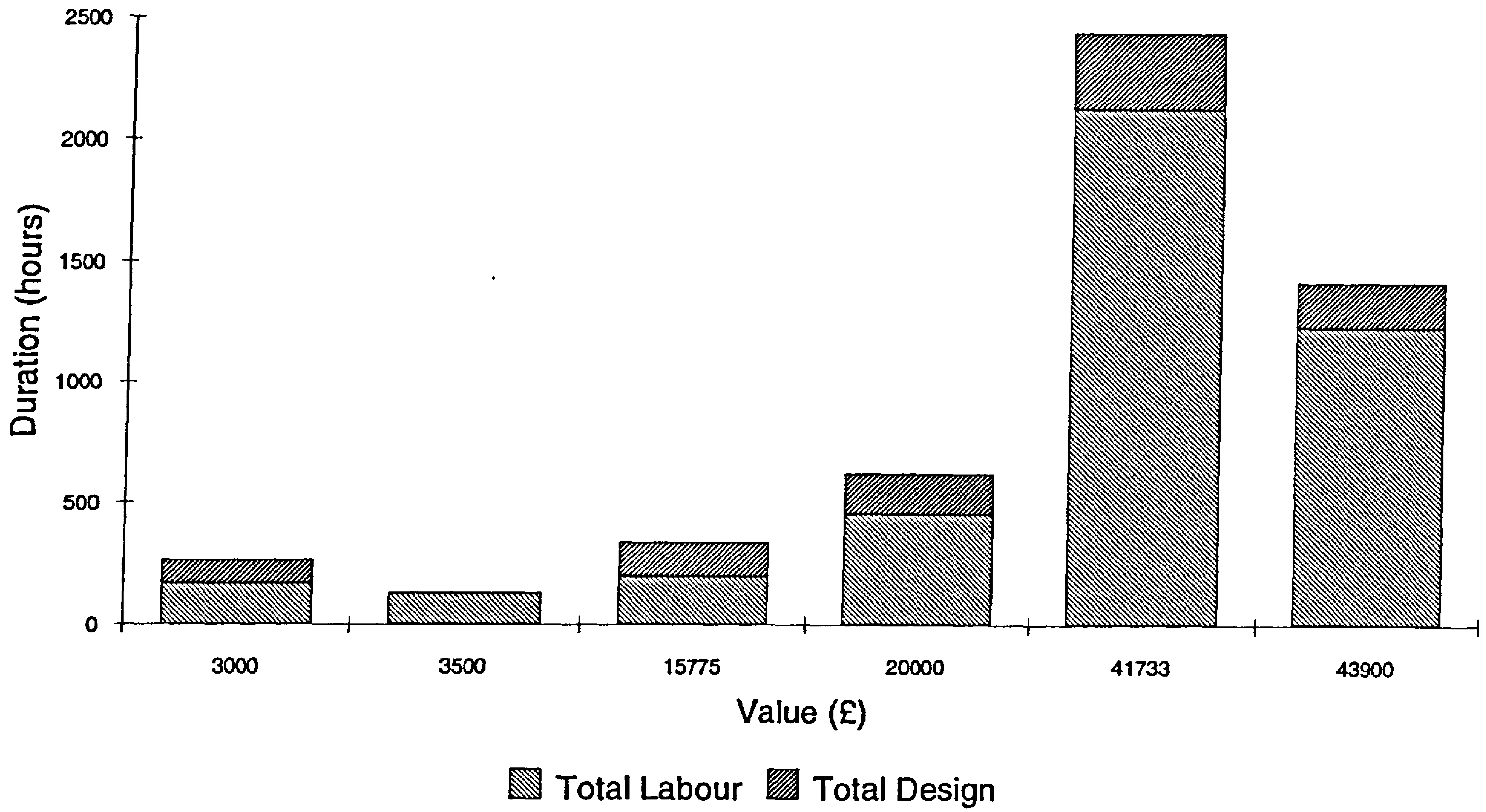
Whether this is due to the accuracy of the Design Managers prediction, or in the nature of a self fulfilling prophecy, or due to some other phenomenon will be discussed in chapter 8.

5.5.2. Data and analysis from the investigation at Labman Automation

The methods of testing H_1 and H_2 had proved to be in-reliable, so the study was restricted to the testing of H_3 at Labman Automation. See section 5.5.1.3 for the arguments leading to this conclusion. It has already been stated in sections 5.2.3, 5.3.2 and 5.2.4 that the problems with data collection at Labman took a different form from those of Michell Bearings. Collection methods could not be modified during the study, and there were a limited number of cases available, because of the slow project turnover. The study therefore had to make use of the information currently available at Labman, and historical records where possible.

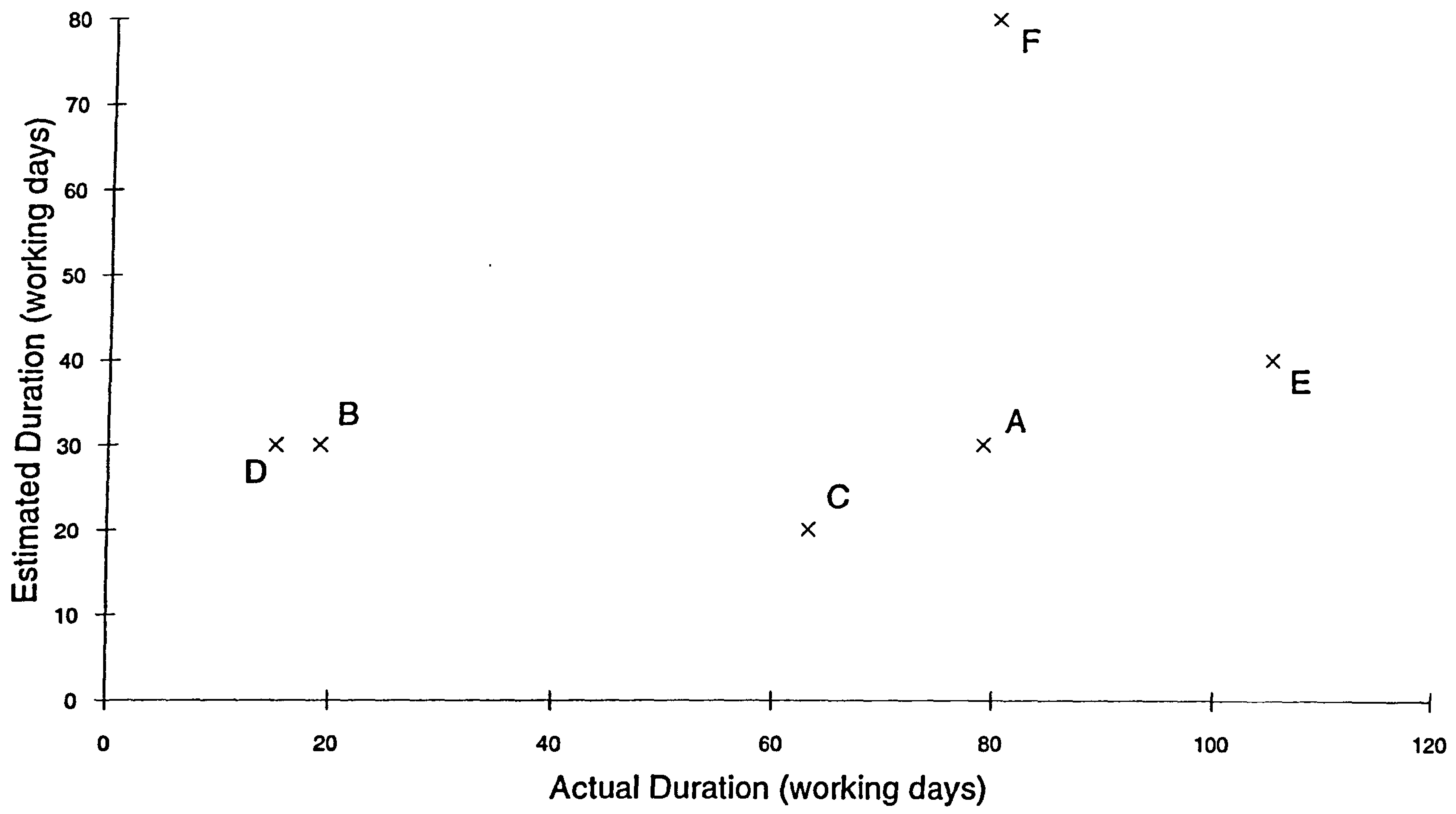
5.5.2.1. Graphical representation of the whole data set from Labman Automation

Six projects could be included in the data set. These six were projects where either the historical records were complete enough to recover the full amount of information required, or more modern projects where not only were the records complete, but a digest of the project development performance had been completed by the Design Manager. A break down of the contribution of design and manufacture was obtained by plotting hours of design work and manufacturing work against the value of the project. See figure 5.6.



Design duration h_{total}^{design}, and production duration h_{total}^{prod}, in hours, against project value.

Figure 5.6



Graph of estimated duration E_{days} against calculated actual duration D_{days}.

Figure 5.7

Some variation in the proportion of design time is evident. In examining the graph of estimated duration against actual duration it is useful to label each case, since the proportion of design content is, among other things, an important factor in the completion time of the whole project. The cases are labelled A..F starting with the smallest value. By labelling the points it is possible to relate them to the projects with low design content, or other factors present within the data. For a graph of estimated project completion time against actual project completion time see figure 5.7. There is a large amount of scatter apparent in the data, so each point is considered in turn to establish the reason for its particular position.

5.5.2.2. Description of individual cases from Labman Automation

Case A:

The brief was to produce a simple platform for a large pharmaceutical firm within the UK. The platform was then to be further developed by them.

Case B:

To produce a platform almost identical to that of case A, for the same customer.

Case C:

A collaborative project with another UK pharmaceutical firm. A high level of customer involvement was required in design, manufacture and commissioning of this system. A significant amount of novel design and develop/test work.

Case D:

Developed from an established system to fill an order for an Australian mining firm. System to be used was tried and tested, the item critical to the delivery date being the supply of a particular bought-out component. The component was delivered within the time allowed.

Case E:

Another collaborative project requiring considerable customer involvement. The system was to cope with a process with which neither the customer nor Labman had any prior experience. The project presented some development problems.

Case F:

Custom development of a system to perform a task with which Labman had experience. Dependent upon the customer for free issue of major parts. No problems experienced with deliveries or proposed design.

The cases divide into two groups. Firstly those which require fundamental development by Labman, and those which were largely familiar to them before design commenced. In the first group are A, C, and E, and in the second B, D and F. The design requirement in the second group, being more familiar, could be seen to be a smaller proportion of the total duration. Since this thesis concerns design estimation these will not be considered further, the bulk of the time for these projects being taken up by manufacture. A, C, and E will be considered in more detail in the next section.

5.5.2.3. Graphical representation of data sub-set from Labman Automation

Whilst the sample is very small, some trend can be seen in the estimate and achievement comparison of cases A, C, and E. Figure 5.8 shows these cases along with a least squares regression line, unconstrained on the *y*-axis.

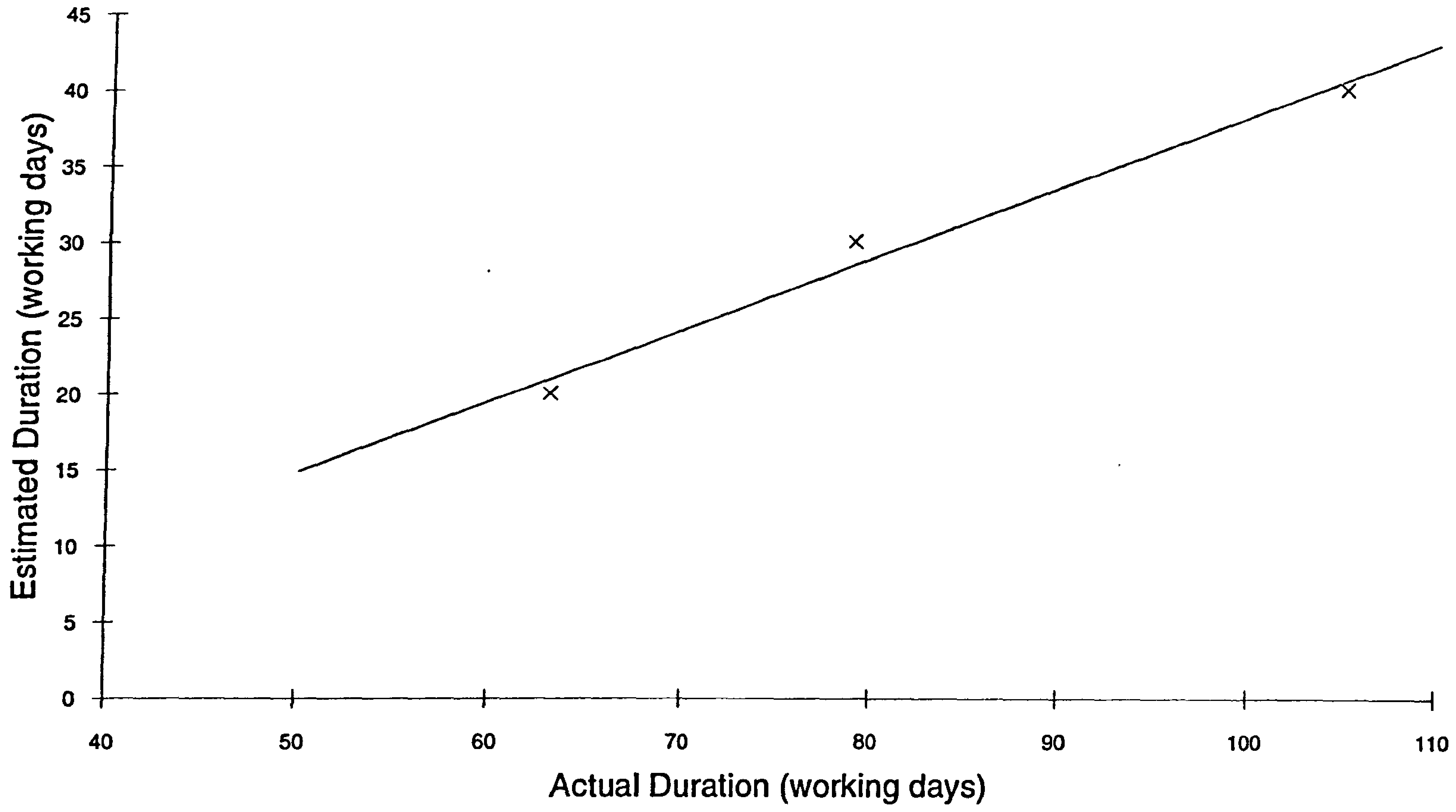
5.5.2.4. Regression Analysis of data sub-set from Labman Automation

Statistics for the best fit line on figure 5.8 are given in table 5.7

m=	0.47	b=	-8.48
σ_m=	0.064	σ_b=	5.41
r^2=	0.98	σ_y=	1.93
$F^{\nu_1}_{\nu_2}$=	52.92	ν_2=	1

Table 5.7 - least squares linear regression statistics for estimated duration against duration for the cases A, C and E.

Because there are so few data points $\nu_2=1$, so $F_1^1=161$ for a level of significance of 5%. The small number of points means that there is more than a 5% chance that the trend has occurred through random selection of data points from a uniformly distributed population.



Graph of estimated duration E_{days} against calculated actual duration D_{days}, for cases A, C and E.

Figure 5.8

5.5.2.5. Discussion of results from Labman Automation

Were it possible to get more data points, through longer observation, or to eliminate the effect of estimating both the manufacturing and design times together, it could well emerge that estimated design times are related to actual design times. However, to assert this would require a study of much longer duration. It is possible to see a trend in this data, although no high degree of statistical significance can be attached to it.

It emerged that two types of project were undertaken at Labman. Those which involved a purely manufacturing problem, or a design task which was very familiar, and those which required innovation by the designers. In order to separate manufacture from design times only the innovative projects were considered here. Such a division may provide a useful tool for Labman in assessing the likely accuracy of a delivery estimate.

5.6. Comparison of data sets

It is difficult to compare data sets when the method of recording and analysis is so different, but some features of similarity and difference can be observed. This section outlines these and discusses their implications for the qualitative study.

5.6.1. Similarities and differences of the two data sets

In both firms the data indicated that a positive trend does exist linking the estimated design/project completion time to the actual design/project completion time. Cases where the Design Manager was absolutely correct could be observed, as could optimistic and pessimistic estimates. There were cases of the design running late through the late issue of drawings, specifications, or parts by the customer. There were also cases of designs over-running because of unforeseen technical problems to be overcome.

One difference occurs in the intercept each regression line has with the *y*-axis. The data from Michell bearings has a positive intercept, suggesting that there is a minimum time greater zero for even the simplest project. At Labman automation the intersect is negative, (although this is not statistically significant, it is outside 1 standard deviation of being positive). Following the same logic as for Michell would suggest that the design could be completed before it is even known, which is clearly absurd. One explanation for this with the Labman 'Design Study' system (see section 4.2.1.2). Before each order is undertaken, a design study is undertaken, usually by the person who will undertake the bulk of the design proper. The use of such a method means that the designer will be familiar with the problem and have formed a conceptual solution before the design time as measured here has even started. Having pre-formed ideas of this type could be seen as the designer being some way along the learning curve before starting to measure time to completion.

Another difference is in the amount of scatter present in the graphs. Scatter in Michell data is much smaller than that in the Labman data considered as a whole. The scatter is probably due to the large variety of work undertaken by Labman. Michell work largely on a set familiar systems with a variety of parameters. The solutions they produce range from relatively simple to extraordinarily complex. In most cases though, the behaviour of the systems with which they deal is understood in great detail. Labman undertake to automate jobs which deal with a large range of substances and processes. Whilst the 'weight' -in terms of throughput and bulk, of the tasks to be automated may be limited, the range of industries which form their customers is some indication of the different demands made of their expertise.

5.7. Implications for the qualitative study

The quantitative study has established that there is a link between the estimated and actual design time, and that this is highly significant in the case of Michell Bearings. The link may be present for one of two reasons. Firstly that any estimate the Design Manager makes has the nature of a self fulfilling prophecy. It is the task of the Design Manager to ensure that projects do not over-run whilst they are his responsibility. Therefore any estimate made by him has an investment of his reputation, and he will make provision for keeping the project on schedule by the means at his disposal. Methods available to the manager may include the allocation on further resources, provision for technical help, verbal encouragement or even menaces. The second reason for this link is simply that the Design Manager can estimate the time required a design through examination of the project brief, and the resources at his disposal. A decision on which of these cases may be correct can not be reached based on the data from the quantitative study. The question of which of the above explanations for the link is more correct could be addressed in the qualitative study. It was possible that there are aspects of both cases in the real process.

A larger amount of scatter from the best fit was apparent in both the longer duration Michell projects, and the Labman data, when taken as a whole. The qualitative study should theorise about the possible reasons for this scatter, and the essential differences which allow shorter projects to be estimated with more accuracy.

The effects of starting a design on the time it takes to complete should be investigated. It was hypothesised that the designers at Labman Automation had a head start on the design process through necessity of completing a 'Design Study' for the customer before the project could be commissioned. Analogues for this head start should be sought at Michell and Thorn Lighting, and through their presence or absence, their effect on the design process assessed.

The issues outlined in this section are addressed directly and indirectly in the next chapter. The chapter also includes detailed descriptions of the object of the study, its sources, and an discussion of the data quality.

6. Modelling time estimation in design

This chapter describes the process of generating models of the way time estimation for scheduling is performed. It details the specific methods used to gather and analyse information from Thorn Lighting, Michell Bearings and Labman Automation. It also describes in detail the models finally produced, and introduces some discussion of issues of model accuracy and the implications the models have for design management

6.1. The modelling process

This section briefly reiterates the description of the modelling process in general terms which was first introduced in sections 3.3.2.2. and 3.3.3.2. It describes the process of generating a model from data collected from practitioners of design time estimation, given that the link between the planners estimates and the actual times achieved had been established (see section 5.5.1.3).

6.1.1. Objectives

The objectives were:

1: To generate a model which could explain the observed phenomena of a link between estimated design time, and actual design time.

2: To generate a model which could be interpreted and applied to the situations prevailing in the collaborating companies.

3: To generate a model which would provide insights into the process of time estimation in design in general.

Whilst the objectives do not divide the work up into distinct phases, they do provide criteria by which the completion of the required tasks may be gauged.

6.1.2. Description

The modelling process started from a initial knowledge of the collaborating firms operations. Background knowledge had been established through the case studies undertaken in each firm. Information within this context was .therefore required regarding:

- the operation of the design process in particular
- the factors influencing design estimates

- the process used by the estimator to reconcile the above into a design time estimate

Gathering information regarding the influencing factors and reconciling processes proved the greatest challenge of this modelling process. Often information of this type was only present in the data in oblique references. Much of the models structure was therefore deduced from indirect questions when direct questioning resulted in steps being missed or unclear in descriptions, or issues were not described in sufficient detail. The 'think aloud' protocols gathered when asking the interviewee to consider an actual example were particularly useful for both highlighting missing steps, and deducing their operation.

In terms of the stages undergone to produce the models the work divided into two phases. First data collection. This broke down further into identifying the interviewee; conception of the interview structure and content; taping and taking notes whilst posing questions during the interview, and transcribing the notes in full. Second, analysis. This entailed; familiarisation with the data (the transcripts, notes, and any other material used during the interview); categorising of the transcripts; revision and re-categorisation of the transcripts; presentation of the categories in graphical form; simplification of the graphs; validation of the maps, and generation of the model.

From the stage of having a completed general model, the model was then placed into the context of the individual firms by reference to the interviews, case studies and other material relating to the specific firms. These models were to be used for the purposes of corroboration (see chapter 7).

6.1.3. Scope

The remainder of the chapter will describe each of the stages described in section 6.1.2 for each firm in turn. The process undergone, problems experienced, and examples of intermediate and completed results included. Some brief discussion and conclusions complete the chapter.

6.2. Data collection

Interviews had already been conducted during the case study phase, as part of work done to establish the background to design time estimation in each firm (see section 4.2). The case studies allowed the subject, or subjects, responsible for the estimation of design time to be identified in each firm. It also provided some guide to the terminology and abbreviations used in each firm, an introduction to processes routinely undertaken in the design phase, the design philosophy employed, and a source of hypothetical examples and actual illustrations useful in directing and explaining questions.

6.2.1. The interviewee

In each firm the interviewees had to satisfy three criteria:

1. A willingness to be interviewed
2. Availability
3. Routinely responsible for the estimation of design times

The criteria are listed in no particular order, since to fail on any of these criteria would discount their appropriateness to this study. Were the subject not willing to be interviewed, the interview may not be arranged, or if conducted the data would hold very little meaning since the interviewee may give, or even choose to give, incomplete or misleading answers. Availability may be a problem for a number of reasons. One set of interviews was conducted by 'phone for a number of reasons, including the subject moving to a new job on short notice, being unable to guarantee availability in the foreseeable future, and the author being some hours travelling away. Another reason was the pressure of work on one prospective interviewee, who could genuinely not afford to take the hour or so required away from his firms work. The interviewee had also to be responsible for the routine estimation of design times. In order to produce relevant, current and accurate models the data had to be gathered from practising experts.

6.2.1.1. The interviewees at Thorn Lighting

Two people were interviewed at Thorn Lighting. The first was Chief Designer - Special Projects, who was responsible for custom designed lighting for such things as new offices and transport systems. The job involved participation in and supervision of liaison with customers, conceptual design, tendering and completion of orders. He also undertook some in-house consultancy for the volume manufacturing side of the business. The practice of estimation of design time is part of the tendering process, so this subject was very familiar with the estimation problem. The other interviewee was a senior designer for the volume manufacturing side of the business, again responsible for estimates and various stages of design.

6.2.1.2. The interviewees at Michell Bearings

Two people were also interviewed at Michell Bearings. As described in section 4.2.2 the design office was divided between marine bearings, and land based bearings, with one manager for each division. The managers responsibilities included the management of the resources within the offices, and hence the estimation of design times, for both the tendering of new work, and scheduling of incoming orders.

6.2.1.3. The interviewee at Labman Automation

The subject at Labman Automation was a Design Manager. Responsible for the completion of design studies, tenders and some proportion of mechanical design of contracts, this subject was very close to estimating, scheduling and design problems.

6.2.2. Interview setting

Interview settings were decided through negotiation with the interviewees. The desirable characteristics from the interviewers point of view were:

- Quiet, undisturbed setting, conducive to audio recording
- The setting within which the estimation takes place
- Comfortable for a prolonged meeting

The first requirement was necessary in order to ensure that the recording of data was complete, and could be transcribed accurately upon completion of the interview. The equipment used had a device which automatically set the recording level. Automatic level correction ensured good recordings of spoken words in different settings. However, in the event of sudden loud noises (such as might come from a factory), the level was reduced to such an extent that it made deciphering the tapes difficult in transcription. Such a reduction could last for several seconds before the level was restored to normal. Therefore some settings which might be quite adequate for conversation between people were not appropriate for taping a meeting.

In order that the information gleaned in the meeting described the estimation process, and design office organisation as closely as possible, it was important to conduct the meeting in an environment familiar to the interviewee. A familiar environment allowed the interviewee to feel as comfortable as possible during the session, and afforded some feeling of control. It also ensured that they were not far from any reference material they might use during the estimation process. A further benefit of the actual surroundings was to provide queues to recall, which could be used both during the interview, and which may be used during the estimation process. For example, a pile of enquiry notices may remind the estimator of the offices current work load, or an empty desk of a designers illness or holiday. With these queues present it was more likely that the influences they signalled would be verbalised.

Maintaining concentration levels beyond half an hour was difficult, and where meetings went on beyond this it was made even more difficult by uncomfortable surroundings. One meeting was conducted in a new conference suite, with plush seating, good lighting and sound-proofing. After some time the room became extremely hot and airless due to a problem with commissioning the air conditioning. Towards the end of the meeting there was a perceptible slowing in discussion and general weariness evident.

6.2.2.1. The interview setting at Thorn Lighting

Whilst one of the experts concerned was based in south east England, all the interviews were undertaken at Thorn's site at Spennymoor County Durham. The drawing office was busy and open plan, so a meeting within the usual estimating environment could not be kept free of interruption. The interviews were therefore undertaken in a quiet, enclosed conference room adjacent to the office. Some support was given to the descriptions and explanations through reference to documents and drawings relating to example projects which had been taken in to the interview. The documents were later copied for purposes of completeness.

6.2.2.2. The interview setting at Michell Bearings

Both divisions of the business - land based and marine - operated in the same open plan office. Again a meeting held in the environment usual to the estimation process could not be guaranteed to be free of interruption. The meetings were held in a glass sided office of a senior manager away on business, which was adjacent to the drawing office. Thus some visual queues were present, and the setting was not completely sound proofed.

6.2.2.3. The interview setting at Labman Automation

Many interviews with the Design Manager at Labman Automation were conducted by telephone. Such an arrangement allowed the interview to be interruption free, and conducted at the desk of the interviewee, the place where design time estimation took place. The major problem with this technique was the inability to gather secondary notes on such things as posture and body language. Inability to record gestures meant that notes on emphasis could not be as complete as in a face to face interview. The difficulty was overcome in some part by the immediate transcription of the tapes, whilst the mood and tone of the conversation was still fresh in the interviewers mind.

6.2.3. Structure and subject of the interviews

The interviews were largely unstructured in the sense that there was not strict set of questions, or even a fixed order for tackling an agenda. The intention was to allow for full exploration of one issue before moving on the next, leaving the interviewer and interviewee free to pursue a point where information was seemingly incomplete. It also meant that the interviewer could pursue another tack if information was not forthcoming. The general principles are discussed in section 3.3.2.2, but the case studies had revealed considerable differences between the three firms, and the effect of these differences on the strategies of the three firms could only be explored through lines of questioning particular to each one. The issues covered in each interview with each firm are covered below.

6.2.3.1. Interview structure and subject at Thorn Lighting

The volume manufacturing business of Thorn Lighting was of most interest to this study, and since both experts had knowledge of this area, and only one had knowledge of the bespoke business, design estimation in the volume manufacturing business was the theme explored in the interviews. It had been established in the case study that although the bespoke design work was undertaken within tight schedules, the design work undertaken for volume products was more flexible and open ended (see section 4.3). Whilst the Marketing department may set firm deadlines for volume product launches, these often didn't fully account for the scope of the project undertaken. It was therefore seen as necessary to cover the following issues in the interviews:

- the extent to which time was estimated for volume product design
- the influence different design requirements had on design time
- the influence and type of external factors, unrelated to design which typically affected design time

The information gathered on these subjects was used to guide direct questions on the estimation steps and strategy. 'Verbal protocol' of stages of the estimation process was also sought through the use of examples.

6.2.3.2. Interview structure and subject at Michell Bearings

The work done in Michell Bearings design office is all engineered to order. Whilst the technology and methods used in the design and manufacture of land and marine bearings is largely the same, the design department is split between marine and land based.

Despite this division, and because of the similarities, the working practices and problems experienced by the two pat of the design office are extremely similar. It was therefore possible to take the interviewees comments as relevant to the whole of the design office, and not just the particular section managed by the interviewee making the comment. The issues covered in the interviews with both managers were:

- the interviewees' jobs and duties
- the tendering situation - in particular:
    how jobs come in to be tendered upon
    what work a tender requires
    who works on them
    what decides who works on the tenders
    who sets the deadlines
- the order process
- the path the order takes
- the 'work to' document
- how the 'work to' estimate is developed, in particular:
    sources of data
    influencing factors
    unknowns and unknowables
- what goes wrong with estimates
- ways round the problems with estimates

As with the interviewees at Thorn Lighting the steps and stages the estimation processes were approached through both direct questioning and the capture of 'think aloud' verbal protocol. The verbal protocol was recorded whilst the interviewees were undertaking examples of estimation in stages.

6.2.3.3. Interview structure and subject at Labman Automation

Because of the bespoke nature of the work undertaken at Labman much of the questioning followed the lines of that described for Michell Bearings. Where questioning did differ was in the investigation of the tendering process. The processes described in sections 4.2.1.2 and 4.2.2.2 can be seen to be quite different methods for the production of a tender and the winning of an order. Since these stages produced a central part of the data which could be used in the estimation process, and could form part of the estimation process itself, the differences had to be explored. Another difference between the two firms was the apparent closeness between the design and manufacturing facilities at Labman. The design office at Michell could be seen to be a specific department, whereas at Labman, the boundary between the manufacture and design function was extremely blurred. A corollary of this was the possible effect of the small and flexible work force on the consideration of the estimates. The issues discussed in the interviews were therefore:

- the interviewees job and duties
- the design studies - in particular:
    - how a design study comes to be commissioned
    - what work a design study contains
    - who works on them
    - what deadlines exist for the design studies
- the order process
- how the tender estimate is developed, in particular:
    - sources of data
    - influencing factors
    - unknowns and unknowables
- what goes wrong with estimates
- ways round the problems with estimates, in particular:
    - the effects of flexibility and multi-skilling
    - staged design work

Again, the steps and stages the estimation processes were approached through both direct questioning and the capture of 'think aloud' verbal protocol. Verbal protocol was recorded whilst the interviewee was undertaking examples of estimation in stages.

6.3. Examination of transcriptions

Not only were the transcriptions themselves important as artefacts of the research, the process of transferring the information from verbal reports to written ones, and checking those written reports fidelity, was vital. Transcription was an extended and detailed task, and meant that the author became extremely familiar with the content of the recordings. Familiarity with the transcripts was important to enable the efficient coding of the information, ensuring that small but important details were not neglected in the coding. The following section describes the processes of preparation and checking of the first written record of the interview data. Some further discussion of the issue of familiarity is also included.

6.3.1. Preparation of the transcripts

The transcripts were all prepared to a standard format, with a simple coding system. The coding system was intended to allow the layout of the document to read, as far as possible, like a piece of prose, but also to convey the way the conversation flowed. Information on times of pauses had originally been included, but these added little to the analysis and subtracted from the legibility of the transcript as a whole. Conveying information about pauses was simplified. Sentences were punctuated with commas between phrases, full stops where there was some change in subject between phrases and a space and three full stops where a sentence trailed off or was interrupted. Specific durations of pauses, breath marks and emphasis where not conveyed in phrasing were not found to be particularly valuable. Mood, where not conveyed in the text, was expressed by including comments in square brackets. The coding system eventually used evolved from some pilot sessions undertaken with academics at the university, so the actual data collection sessions could be transcribed and analysed in the final format from the first.

6.3.2. Quality of the data recording

All the recordings were made with a hand held tape recorder with separate microphone. There was therefore no problem with motor noise degrading the recordings. The microphone was best attached to a solid object such as a table or wall, equidistant between the speakers. A problem with using a table to mount the microphone was the risk of loosing some of the speech. If the table were knocked, or something dropped on to it, the resulting bang would cause the tape machine to drastically lower the recording level, and then slowly increase it in the ensuing silence. In the same way, loud noises both from inside and outside the interview room could cause the loss of some speech. See section 6.2.2 for a description of the interview settings. Despite the occasional loss of recording quality, contemporaneous notes and repeated attempts with the transcription machine to decipher missing words mean that there are very few instances where a phrase could not be transcribed. See appendix E.

6.3.3. Familiarity with transcript content

The intention of the work was to generate theory relating to the way the time taken to complete engineering design projects is estimated. The theory generated was to be grounded in observed phenomena. Works by Glasser and Strauss (1967) and Strauss and Corbin (1990) emphasise the need for complete familiarity with the observations before attempting to analyse them. The generation of grounded theory is only recommended once some analysis is complete. Particular reference is made to the need for the complete transcription of tapes. The advantages of the researcher being responsible for this transcription are described (Strauss & Corbin 1990 pp 30,31). In the case of this research , the recorded conversations do not constitute the only record of the observed phenomena. Observations were being made from the very outset - well before the formal interviews started - are reported in the descriptions of the three firms included in chapter 4. However, the tapes of these conversations form the part of the data which relates most closely to the phenomena of specific interest. The other observations can only supply contextual and corroborating information. It was therefore important to the quality of the theories produced that the researcher was most familiar with the content of the taped conversations. To this end, the author undertook to transcribe and annotate all the tapes of the interviews.

6.4. Preliminary transcript analysis

Each interview was transcribed, checked and coded before the next was undertaken. The preliminary transcript analysis involved the interpretation of the transcriptions into sets of concepts, and the sorting of these concepts into different groups, and the linking of the different concepts.. In terms of grounded theorising, this interpretation into concepts is the identification of actions, events and ideas. The sorting into groups provides for both the identification of the phenomena (the subject of the group), and some understanding of it. A general description of this process is given in section 3.3.3.2, the remainder of this section will deal with specific cases tackled.

6.4.1. Interpreting the transcripts as concepts

The object of interpretation was to change prose into shorter phrases which could be understood when taken away from the particular context used when they were spoken. The context of the interview is implied through the description of this research work, and the context of the particular passage is implied in the title given to the group the concepts are placed in, so some simplification is possible whilst retaining the proper sense. Therefore, within the context of the coded transcription, and map, the concepts can stand alone. An example illustrates this simplification process:

From I12405SD (see appendix E for the full transcript):

69 R: Say if you've got a casing which has never been made before, that would influence the time
70 you would put down on the work-to document, ...

71 S1: Yes.

72 R: What other sorts of things ...

73 S1: Availability of labour, certain people are more reliable than others, obviously some people
74 have been here a lot longer than others so they can do jobs more quickly, more efficiently.
75 Depending on who I would want to do a particular job ... when a certain kind of bearing came in
76 I would have in mind, who, ideally I would want to put onto that.

77 R: Right. So you know ...

78 S1: I know roughly how long it will take when some people can do the job quicker than other
79 people, and it's really that sort of thing.

Coded into concepts and groups this becomes:

No.	Line No.'s	Group	Concepts
28	68..71	time management	need for long lead times apparent in order
			influences the date given by design on the work-to document
29	72..77	time management	availability of labour
			experience of each designer
			designers area of expertise
			affect the time put on the work-to document
30	79,80	time management	designers known personally
			work rates known

Because the context of the concepts is dependent upon their group classification the interpretation of the concepts and their classification had to be done simultaneously. The close connection between concept and its group meant that possible classification groups had to be generated as the transcripts were coded. In turn this would dictate the phenomena which emerged from the study. So that the discussions at the beginning of the interview did not influence the coding more than any other part of the discussion three, sometimes four, passes of alteration, simplification and re-coding were done over each transcript.

Each transcript was treated as a separate set of phenomena to be discovered. What happened in practice was that there was considerable overlap between the phenomena emergent from the discussions held with each of the estimators. Since the preliminary analysis was done in its entirety for each transcript before the next was started, many of the emergent phenomena had already been encountered and tried when later transcripts were analysed. The coding process was speeded since rejection of invalid phenomena could be done more rapidly in the knowledge of previously coded concepts and groupings. The knowledge of which groups were successful, and which not, considerably aided the generation of universal groups.

6.4.2. Generation of the universal groups

In order to compare the phenomena emergent from all three transcripts, the coding had to be made uniform across the whole set. The need for uniformity prompted the generation of a set of universal groups which could encompass all the groups generated in the preliminary analysis. The process had already begun through the rejection of some groupings during the preliminary analysis. The universal groups had to satisfy the following criteria:

- describe a logical connection between a set of concepts
- retain the contextual information required for interpretation of the concepts
- simplify the representation of the interconnected concepts

It was also desirable that groups were mutually exclusive whilst covering the whole set of concepts. However, as has been described in section 3.3.3.2, it proved impossible to satisfy the three primary criteria and maintain this exclusivity. The final group groups developed were:

- co-ordinating tasks
- design method
- forming requirement
- production
- time management

The transcripts were all then re-coded using these groups. Re-coding ensured that the data was in a format where the interviews with the different estimators could be compared, and allowed a check that the contextual information required by the concepts had been retained.

6.5. Arrangement of groups

Section 3.3.3.2 outlines the way the concepts within the groups were arranged and simplified. Arrangement and simplification was initially done by drawing the maps out by hand. Writing the groups out by hand gave some difficulty, because of the shear number of concepts to be represented in early stages. Some of the groups contain as many as 106 concepts. Since this time a program called 'Graphics Cope' has become available for dealing with this type of information, so subsequent diagrams and analyses were done using this package. It allows for the automatic arrangement of concepts and links, and for moving groups of concepts *en masse*. It also has a text finding capability which was of great assistance in identifying similar concepts by the use of keywords. The text moving and finding facilities were used to simplify the maps, cutting out information not relevant to the estimation of design times, and re-wording some of the concepts to ensure the context and sense of them are retained. Cutting and re-wording was done with repeated reference to the original transcripts to ensure validity and continuity.

6.5.1. Mapping of the universal groups

The concepts gleaned from the transcripts were not all mapped onto the same graph, for reasons of clarity. Because of the huge number of concepts their arrangement on one page would have been incomprehensible. Links between concepts would have crossed many times and been very long. It would have been impossible to group like concepts together. The high level of complexity present in the diagrams would have made satisfactory analysis impossible.

In order to keep the diagrams manageable, each interview was mapped separately into its universal groups. Because the interviews with managers from Michell Bearings and Labman automation remained more focused on design and organisational issues, there are no concepts which fall into the 'Production' universal group, nor does this map have any connections to the concepts central to time estimation. The group 'Production' was therefore one area where simplification could take place.

All the maps were examined in this way - removing concepts which did not relate to the central topic of time estimation, and merging and rewording concepts where possible to simplify them and reduce their number. Reducing the number of concepts was vital for two reasons. Firstly, to make verification of the findings possible with the interviewees, and secondly to make them practical and useful. The actual process of simplification, and some of the major steps in the process are described in further detail in section 6.5.2.

It would not be useful to include all of the groups in this thesis. In all there are 13 universal groups, an average group covering four pages, and when rationalised there would be a further 12 groups of around two pages. However, the process used to deduce the model presented in section 6.6.2 the results are illustrated by an example set - the maps obtained from interviews at Labman Automation - included in appendix G.

6.5.2. Rationalisation of the maps

The purpose of the rationalisation was to focus on the relevant points of the data so that a clear model of time estimation for mechanical engineering design could be deduced. The first step for each of the maps was to remove the irrelevant concepts. Such concepts had been included for completeness during the analysis of the transcripts. They described the transcription when the interview had strayed from the topic of time estimation. It can be seen in the later interviews that the focus remains fairly tight and fewer concepts are removed. Tight focus on the estimation issue implies evolution in the interview style. The first interview was with the estimators from Thorn Lighting, so not only does this have the largest number of discarded concepts, it also has the highest total number of concepts, so the time estimation problem is covered in good detail, but the information has to be carefully extracted. In the case of the 'production', no concepts were relevant and so the whole group was discarded. Other groups were simplified to a greater or lesser extent. The groups most relevant to the estimation problem were 'time management' and 'co-ordinating tasks'. However most groups yielded some relevant information for the estimation model, indicating the complexity of the task, and the impact the different disciplines have on it.

6.5.2.1. Rationalised maps from Thorn Lighting

In the original maps of the groups the total number of concepts gleaned from the transcriptions was 221. These maps give an extremely detailed picture, not only of the estimation problem, but also the way the design process is organised; what impacts upon the final quality of a design; how designs are put into production, and what makes a good design from the marketing point of view. All these things not relating to the estimation problem were removed. The remaining concepts numbered 76 - around a third of the content of the transcript.

6.5.2.2. Rationalised maps from Michell Bearings

The refining of the interview technique has been discussed in section 6.5.2. One effect of this can be seen by the relative numbers of concepts discarded. The first interview retains only one third of the concepts gleaned from the transcripts. Subsequent ones retain at least two thirds. The transcript resulted in 168 concepts, 107 of which remained after focusing on time estimation. More concepts are retained from the Michell data than from either of the others. However, the information from the other sources is not less detailed. The reason for the disparity is the different procedures used at Michell Bearings. Many of the concepts refer to the documented processes used to control the use of time during product design and manufacture. There is rigorous control of the time, and it can be seen that in some respects the estimation problem at Michell is more tractable than at either of the other firms, due to the repeat nature of much of the work, and the rapid turn over of new designs. For these reasons, information from the transcript is more verbose, rather than of greater depth.

6.5.2.3. Rationalised maps from Labman Automation

The transcript from Labman Automation was considerably shorter than that from Thorns, yielding 106 concepts. Of these 70 were retained after rationalisation - a comparable number to Thorns. In some ways their design problems are very similar. The designs can involve a significant amount of dynamic design, and the technical demands of a project are often not entirely understood before it is undertaken. These conditions can occur at Michell Bearings, but are rare in their routine work. For maps of the revised groups see appendix H.

6.6. The design estimation models

The groups having been honed to the point of referring to time estimation and closely related issues, two tasks remained to complete the generation of a model of the time estimation process grounded in actual observed data. The first of these was to further simplify the collections of concepts by re-wording clusters of related concepts to create a single one which could encompass all the meanings expressed within them. Representing several closely related concepts by one re-worded concept was done for all of the interviews. The other step required was to integrate into one model the threads drawn out of the specific interviews. Integration was achieved by comparing the collections of these final concepts. An explanation of the model was then prepared which was based on its derivation. Such an explanation was needed in order that the model could be corroborated with the estimators originally interviewed.

6.6.1. Generation of the final concepts

The final concepts were created through the manual examination of the rationalised group maps, with reference to the actual transcription. The reference to the transcription was used to maintain a direct relationship between the information presented in the final concepts, and the information gathered from the interview.

6.6.1.1. The concepts for Thorn Lighting

The final concepts were:

1. identify requirements
2. identify market type
3. identify projected volumes influence on design method
4. identify requirements influence on the design method
5. identify the markets restrictions on time and specification
6. identify units and features of the design
7. identification of possible sources of interference with design
8. integrate estimates for unit completion times with projected interference
9. ensure compatibility of the estimate with the requirements

Some of these concepts can not match with those taken from Michell and Labman until made more general, since they include consideration of the product's volume, and the characteristics of the market. This issue is discussed further in section 6.6.2.

6.6.1.2. The concepts for Michell Bearings

The final concepts were:

1. identify units and features of the design
2. identify time influencing processes of each feature
3. compare resource requirements with those available
4. identification of possible sources of interference with design
5. integrate estimates for unit completion times with projected interference
6. ensure compatibility of the estimate with the requirements

Many of these are comparable with those resulting from the Thorn transcript. However some concepts are revealed which are not explicitly stated in the analysis of the Thorn data.

6.6.1.3. The concepts for Labman Automation

The final concepts were:

1. identify requirements
2. form pre-design concept
3. identify units and features of the design
4. identify units previously recognised
5. examine at increasing levels of detail to estimate from first principles
6. identification of possible sources of interference with design
7. compare resource requirements with those available
8. integrate estimates for unit completion times with projected interference

Again, some concepts are comparable with one or both of the other sets of final concepts, and there are further additions to the concepts explicitly stated in the transcript analysis for the firms.

6.6.2. Generation of the universal model

The object of the universal model was to integrate the knowledge gleaned from the analysis into a description which covered all the methods used by the estimators interviewed. The model could then be appraised by the estimators themselves. The comments from this appraisal could then be used to decide which parts of the model were most relevant in particular design environments, and which may not be applied. The comments would also perform the vital function of checking the validity of the findings, indicating whether more information needed to be gathered, analysis performed, or experiments undertaken. It was very important therefore that the model represented the final groups accurately, and that the model's presentation was comprehensible to each estimator.

Because of this need for clarity the presentation format chosen was a graphical layout of different functions, placed in the sequence they are undertaken. Another decision taken on this basis was to restrict the number of stages to seven. The major stages were deduced from the whole set of final concepts from all the interviews, these being:

1. identify requirements
2. identify market type
3. identify projected volume's influence on design method
4. identify requirements' influence on the design method
5. identify the market's restrictions on time and specification
6. form pre-design concept

7. identify units and features of the design
8. identify units previously recognised
9. examine at increasing levels of detail to estimate from first principles
10. identify time influencing processes of each feature
11. compare resource requirements with those available
12. identification of possible sources of interference with design
13. integrate estimates for unit completion times with projected interference
14. ensure compatibility of the estimate with the requirements

With a simple one-to-one correspondence between concepts and stages there would be more than the maximum seven major stages to be presented. A two level model was therefore developed, with concepts grouped or extended to allow a logical flow from one stage to the next at the highest level, and where the primary stages did not provide all the detail available, they were broken down into a number of secondary stages which could be hidden or revealed as required.

It was not anticipated that the divisions between the different stages were well defined or rigid. The model was also not intended to convey a serial nature to the estimators. It was intended to be possible, within the scope of the model, to progress with one part of the estimation problem through many stages, whilst leaving other areas of the problem to be tackled later. Looping around was also anticipated, the estimator refining and correcting estimates through the different stages continually, as the process went on. All these requirements for the model were found to be to be difficult to convey graphically, so it was decided to give a verbal explanation of this, and other aspects of the model during the corroboration interviews. The stages of the model are described below.

The first primary stage identified was '**identify the problem**', this encompassed final concepts one to five in the above list. This stage was broken down into five secondary stages directly corresponding to the five final concepts included.

The second primary stage was '**decompose into estimable features**' encompassing concepts six to nine. The three concepts were re-worded into three secondary stages, '**examination of pre-design concept and categorisation into interconnected features**', '**features recognised as previously used, or of sufficient detail to allow consideration from first principles**', and '**feed back features not yet detailed enough for either of the prior courses**'.

The third primary stage was '**identify factors which influence the design time for each feature**' which corresponds directly to concept ten, but which is further explained by secondary stages '**processes needed for the completion of each feature identified**', '**time influencing processes identified for each feature**' and '**important factors influencing time sensitive processes identified for each feature**'.

The fourth primary stage was '**identify degree of constraint for each factor**' which corresponds to concept 11, but which is further explained by secondary stages '**properties of features which are time sensitive compared with resource capability and availability**' and '**synthesis from feature properties, context and expertise to anticipate new constraints**'.

The fifth primary stage was '**identify sources of interference with degree of constraint from other features and factors**', which corresponds to concept 12.

The sixth primary stage was '**integrate the degrees of constraint for each factor to estimate for each feature**', which corresponds to concept 13.

The seventh primary stage was '**integrate feature estimates into a total project completion time**', which corresponds to concept 14.

Some of the secondary stages may appear to show greater detail than the final concepts present. The extra detail is present because, in order to achieve continuity between the primary stages, reference was made back through all steps of analysis, to the transcripts in order to elicit missing stages. For example '**synthesis from feature properties, context and expertise to anticipate new constraints**' can be traced back to lines 180 to 199 of the Labman Automation transcript (appendix E), among other places.

Some of the model stages would clearly not apply to some of the firms involved in the project. Any stages referring to the volume of a product would clearly not apply to Michell or Labman since they only produce one off designs. Some of the stages were less clear. Since relative amount of dynamic design content at Michells was known to be low, it was possible that the '**features recognised as previously used, or of sufficient detail to allow consideration from first principles**', and '**feed back features not yet detailed enough for either of the prior courses**' stages may simply not include estimation of an engineering problem from first principles. However, it was included in the model presented to Michell, since it was possible it formed part of the estimation process there. Two separate models were therefore prepared, one for the volume manufacturing environment of Thorns, and one for the ETO environments of Labman and Michell. Figures 6.1 and 6.2 show the models tested at volume manufacturing sites and ETO sites respectively.

For volume manufacturing the model tested was:

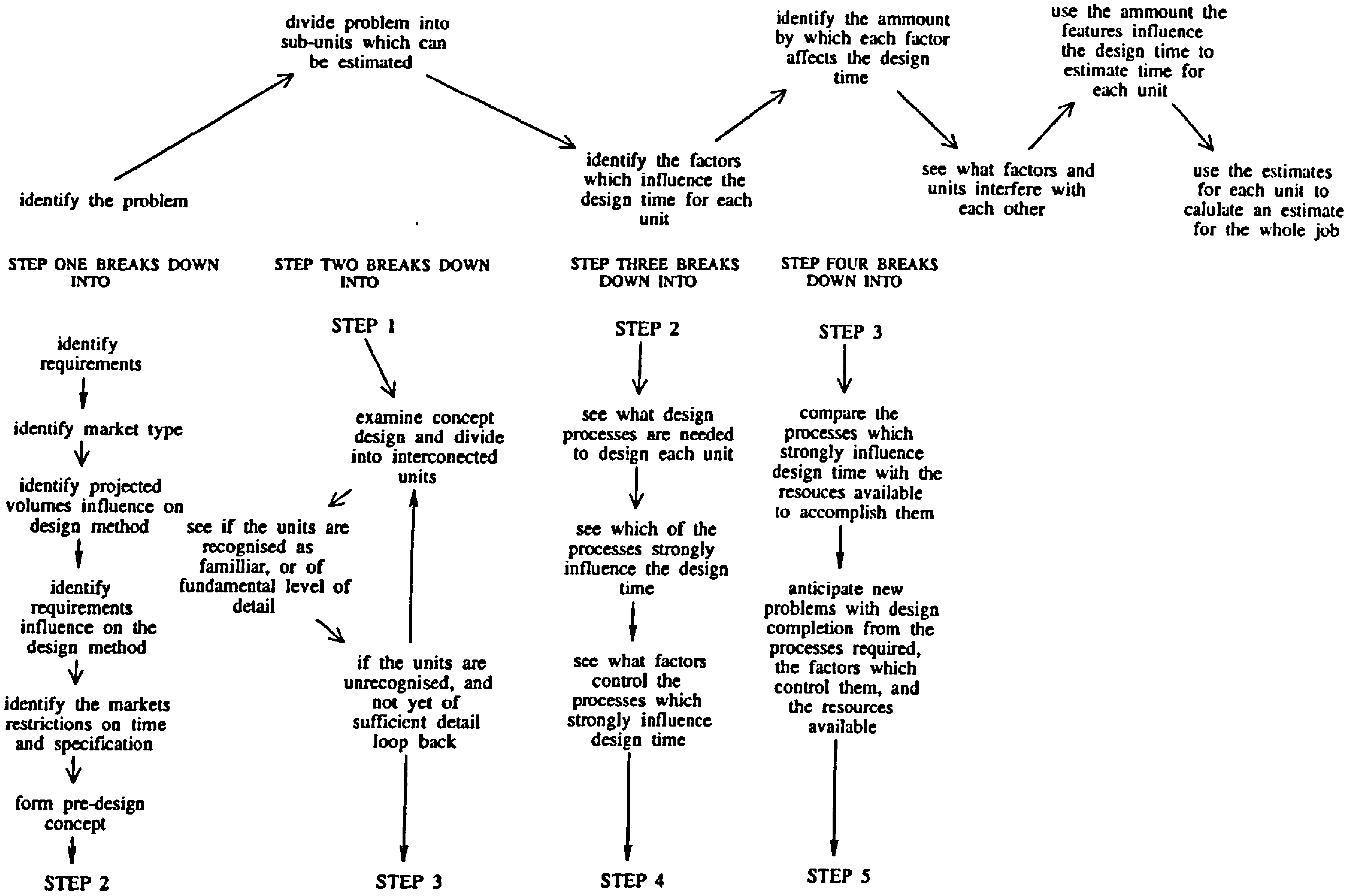


Figure 6.1

For ETO firms the model tested was:

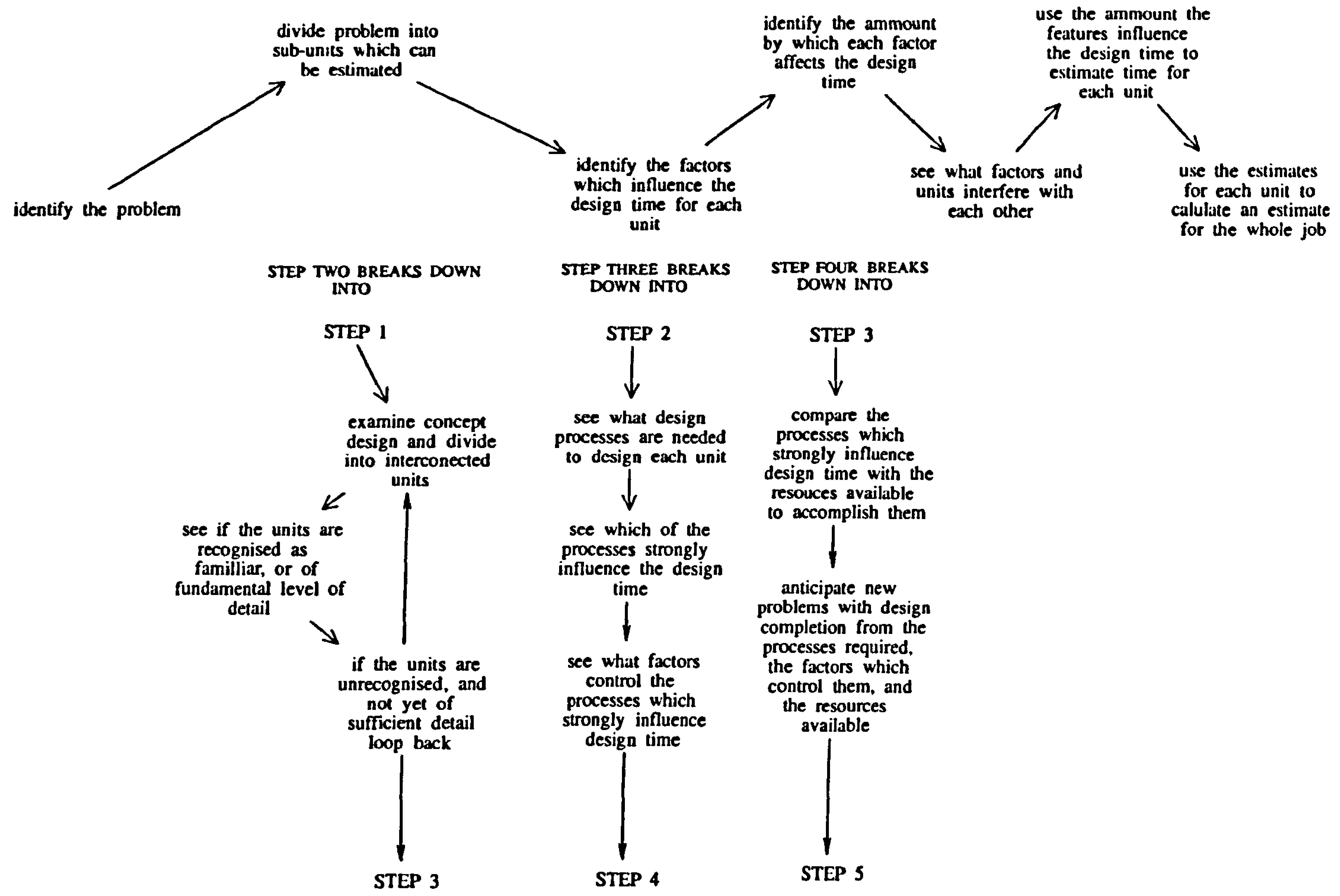


Figure 6.2

6.7. Conclusions

This chapter has described how a general model of the estimation of design times was developed. The method used to do this developed a model grounded in observations made of the process, and the expertise of the estimators themselves.

The model describes the process used to integrate the available information into an estimate for the duration of future design work. The sources of information used can be traced through examination of the maps developed at the different stages of analysis towards the model.

The model explains how an estimate may be reached from incomplete information about the requirements of a project. It is possible, through the application of the method described by this model, that given the information available to the estimators (both contextual and project related) an estimate for a design time could be produced.

The model is general in character, and so needed to be customised to suit the different environments prevailing in the firms involved in the research. The major difference apparent between these firms is the difference in the volume of production. Labman and Michell are both ETO firms, and Thorns volume manufacturing. The customisation therefore done, before the models could be presented to the firms, was to ensure that the references in the models, to product volume and market, were appropriate. Two customised models were therefore prepared for presentation, to test their validity in each of the firms.

The modelling process provides insights into the sorts of issues and information present in the estimation problem. It reveals the types of information required to produce an estimate, and the way in which that information can be combined. The model itself, if proven to be valid, may be used to provide self knowledge for experienced estimators, or as a tool in assisting the education and expertise acquisition of novice estimators.

7. Model corroboration and refinement

Whilst the model had been generated from systematically recorded observations and interviews, with rigorous checking back to original sources throughout, the model required corroboration. This final stage of the research involved both checking with the principle experts responsible for the subjective information integrated into the development of the model, and external corroboration for the model. External corroboration was intended to establish the validity of the model as a description of the design time estimation process in situations similar to those from which the model was developed. An ETO firm agreed to give up the time and information required to do this. It may therefore be argued that the model is most closely corroborated for this situation.

The following sections describe the method, introduced in sections 3.3.2.3 and 3.3.3.3, used to corroborate the model. Brief descriptions of the four interview sessions are presented, describing the general content in the case of the interviews of the principle participating experts, and including a description of the firm, subject and setting of the external corroboration interview. Specific responses are also included in these sections, both as evidence for the acceptance or rejection of a specific facet of the model, and as guides to the interviewees opinion of the overall quality of the model. The implications from all the interviews are considered for the model as a whole, and for each element of it. Modifications are proposed and finally a revised version of the model presented.

7.1. Corroboration method

The need for corroboration is acknowledged in section 3.3.2 as the final objective of the qualitative study. A quantitative approach was considered, and two approaches seemed to be applicable. Firstly, metrication of the estimation process with the intention of collecting data which could support or reject the different facets of the model. The metrication approach comes up against almost the same problems as the earlier quantitative study. The problems included:

- Inability to change the systems and documentation used in estimation, both because it alters the situation which is the object of study, and because this would be unacceptable to the participating firms.

- Difficulties with the collection of data from disparate sources.

- Small turn over of required estimates in some of the participating firms meaning extended delays before a statistically significant sample can be assembled.

The other possible approach for a quantitative study would have been to produce a questionnaire to be filled in by the participating firms, or others. Methodologically, problems exist with the apparent objectivity of such a survey. Whilst simple yes/no responses to questions can be quantified, it is very difficult to remove the influence of the question phrasing, mood of the respondent, and level of respondent understanding. A questionnaire type study could only answer very simple questions. Ranking systems and open questions allow for richer range of expression by the subject, but create problems with questionnaire design and response analysis. More practically, in order to explain and test fully what is a complex model, the questionnaire would have to be extremely lengthy. Getting respondents to complete such a questionnaire was believed to be difficult and time consuming. Finally the author felt that lack of previous experience in questionnaire design would be a considerable problem, whist a similar study could be achieved by using interviewing skills already developed.

The interview itself had a more closely defined structure than the interviews conducted in the earlier work. Each one started with comments by the interviewer to explain the way the model was presented. The presentation was then followed by the interviewer explaining each step in turn, with direct questions concerning the acceptability of the step, and more general discussion of related issues. Related discussion sometimes pre-empted questions relevant to later stages so these later questions were omitted. The interview closed with discussion of the estimation and design processes in general, and invited comments on the overall quality and applications of the model.

7.2. Labman Automation interview

The subject felt that both steps one and two were accurate descriptions of his method of preparing an estimate, and that the shape of the expected solution was known at the planning stage:

> R: [...] The first two boxes imply that you have some idea of the form of the design solution before you can go on and estimate how long it will take to design. Is that reasonable?
>
> S: That's absolutely true. The prerequisite to starting any planning is to understand the parameters, you can't really do anything until you have that. That's absolutely central, so that's fine.
>
> Appendix F(iii) lines 12-16

However, no alternative designs are explicitly considered in the estimate. The consideration of contingencies is not done explicitly, and this could be the cause of some of the problems of late completion:

R: So would you perhaps go through the estimation process, taking on board a couple of design variations? So for instance, you think 'I might be able to solve this problem in this method, and I'll estimate how long it will take to produce an solution in this way, but if that doesn't come off or it turns out that this design might be nicer I'll just work out how long it takes to do it a different way.'

S: I think when it comes down to problem solving, what we tend do is we'll do the synthesis of getting a design that is optimum in terms of whether it will work, or whether its compatible with what the customer wants, etc. before we embark on going down to numbers. When it comes to the point of estimating, it's already quite likely that the system is already 99% there. Now it has happened in the past that we've gone down a route and found that actually the costs of creating it are prohibitive, and we've had to go back and make a compromise solution, but I think that happens a little bit later than the planning you require when you come to do the estimating.

Appendix F(iii) lines 17-29

Lines 34 and 35 establish that the design work is broken down into sub-problems. However, consideration from first principles is not really done for time estimation purposes, but for the purpose of actually solving the design problem itself (lines 37-44). The subject felt that designs which had to be broken down into many levels of detail provided the most challenging estimation problems, with the largest scope for inaccuracy (lines 44-47).

Parts of the design and design process which affect the design time are identified (step 3):

R: What sort of indicators do you find in the project brief that say 'ah we're going to have a critical stage there'?

S: Ah ...

R: I suppose it comes down to your pre-concept design.

S: That's right. It's the experience of past projects. Certainly every area, every sub-division of the project you can pick out the most important factors which will relate to the system as a whole. It's experience that helps that I'm afraid.

Appendix F(iii) lines 72-78

Previous experience is cited as the source of information for design times for critical processes and sub-units. Experience in this context is not the same 'experience' as was cited for the preparation of a complete design time estimate during the earlier phases of this research, but measurable and recordable statistics. The statistics would be process lead times and 'repeated unit' design times, as is made apparent in lines 79-82.

Consideration of resources (step 4) plays a major part in the estimation process at Labman, as can be see but the discussions in lines 99-105 and the following:

> R: [...] Say you've only got one person who can do the electrical design work, so if they're busy that's going to be a critical part of the design process.
>
> S: There is a certain amount of critical pathing goes on through the process, and it is largely dependent on what is the major resource requirement at the time. For the electronics we've only got one chap so if his element of time has got to be compromised then we can work around that. In terms on physically designing something, the place where you start is the place where it has the greatest effect, so you leave the peripherals. For instance if you're designing a de-capper you design its footprint first, and then go to the peripherals of holes in place and bits and pieces which are just kind of ancillary to getting the major part of the project going.
>
> Appendix F(iii) lines 56-65

The step five describes the identification of interdependencies between the sub-units, and the subject agreed that this is undertaken (lines 106-110). Evidence as to the way the estimation problem is approached is also offered:

> R: How do you cope with the problem with interdependency, do you work on both things at the same time or do you work on one as far as you can go and then move on the next one and so on?
>
> S: I try to avoid switching from one to the other too much, the problem is you can loose the thread and it's not a good idea. What I try to do is work on the elements which have to most links. It can be difficult from the outset to resolve the interrelations, and quite often as the manufacture goes through, you can see other relationships that weren't apparent in the design synthesis, so what may happen at that point is that you have to re-shuffle the end of the design process to take into account that new relationship. You've got to have flexibility at the end of the day.
>
> Appendix F(iii) lines 111-117

The quote would imply that estimation for each unit is not undertaken in an *ad hoc* way, but that the order of consideration is structured, the unit with the most apparent dependencies being tackled first. However, the order remains flexible (lines 121-123).

Step six, describing the preparation of time estimates for the design of the sub-units gets agreement from the subject (lines 124-125). The subject barely draws any distinction between deciding where interdependencies affect the design time, and preparing the unit design times. The subject may be indicating that steps five and six are closely related, or that their order should be reversed, or that the steps should be regarded as simultaneous.

The importance of the effect of interference on unit design time can be seen in the passage below:

> R: So this step implies that you look at those times you've got and you consider them against any interference, at the level of the factor of the design for each unit for instance the footprint which are going to be critical ...
>
> S: Interference as you call it, we call it integration, and that has to be accounted for.
>
> R: Yes.
>
> S: What we tend to do is to look at these number of linkages which leads directly to the amount of integration time that we need. So that's a way of accounting for interference.
>
> R: Right, and then you come up with a time for each unit?
>
> S: That's right.
>
> Appendix F(iii) lines 126-136

The final step, regarding the preparation of an overall estimate from the unit estimates, gains agreement from the subject. Emphasis is placed on it not being a simple addition (lines 140-156).

More general discussions cover the way the estimate is approached. For instance whether the estimation is approached a stage at a time for the whole design problem, all stages in turn for each sub-unit, or a compromise method. The response describes an iterative heuristic algorithm:

> [R:] Would you do it all at once or all in sections?
>
> S: It feels like we do it all at once, but no you're quite right, I start off going down the route and then perhaps I have to double back or start another bit off, or scrap it and try something completely different. It's very dependent on how it falls together, and each project is different unfortunately.
>
> Appendix F(iii) lines 163-167

Notes are used during the process, although formal reporting is limited, and a final check on the estimate produced is based on 'if it makes sense' (lines 172-173). The value of what makes sense might be based on completion times for previous projects, commercial considerations or pragmatism (lines 175-184). The subject sees the major problem of the model as being one of presentation:

> R: [...] Do you think the overall scheme describe what goes on?

S: It does yes, its pretty good. As you say though, those arrows do imply its a step by step approach, and there are elements of each that coalesce into each other.

Appendix F(iii) lines 196-199

The subject also sees a use for the model in improving methods of documentation of estimates, although improving the estimates themselves through the rigorous application of the method described was seen to be more doubtful.

7.3. Michell Bearings interview

The assumption of stages one and two, that the form of the design solution was known before an estimate of design time was made, was again seen to be the case with this subject. The design solution would be based upon the work done for previous jobs:

So steps one and two imply that you've got some idea of what form the design solution will take when you've seen the design problem. Would that be reasonable?

S: Yes, because when we start estimating time it means that we've got at least a drawing or a basis that you've got to have to produce detailed drawings.

R: Right. So not only have you got the arrangement drawing you did for the enquiry, but you've also got some idea when you get the job in.

S: Generally you've done similar things before so you can relate to those.

Appendix F(i) lines 11-17

In lines 18-20 is again noted by the subject that the most unfamiliar projects present the most difficult estimation problems (c.f. appendix F(iii) lines 44-47). No alternative designs are considered for the purposes of estimating, at this stage (lines 21-25), the general design solution having being selected at the tender stage. The tender stage is more flexible in its deadline, allowing for consideration of the alternatives:

R: So you're down to detail work after the tender stage?

S: Generally speaking yes.

R: Right.

S: So the new design problem would have a tender stage when you have a deadline to meet, but that's certainly not as strict as trying to get work out of the door in sixteen weeks or twelve weeks or whatever.

Appendix F(i) lines 26-31

The concept solution which is produced during the tender stage is divided into sub-units for the purposes of estimation (step 2). In particular the most convenient units appear to be those which are represented on their own drawing:

> R: [...] Assuming you break the design down into manageable units, say perhaps you've got the casing design, the oil ways ... would you break the design down into manageable sections in order to estimate?
>
> S: Yes. At the enquiry stage we would have an assessment of how many new patterns we would have to make, you would know whether something was already drawn, or whether the pattern existed or not. The unit you would divide it into would be how much you knew, complicated drawings which have to be done from scratch, how many are quite similar to what we've done before, we may only have to alter part of an existing drawing to satisfy it, and probably an overall assessment of how many drawings have to be made in total. So the units would be what's brand new, what can we crib from somewhere else, what do I not have to do anything at all with.
>
> Appendix F(i) lines 34-44

The quote above emphasises the variant nature of the design problems tackled at Michell Bearings. Further sub-division is not undertaken for the purposes of estimation. Information regarding the specification of unfamiliar units would have been calculated during tender, although there would be no detail. The time estimator would therefore consider how many drawings would be needed to convey the anticipated solution to the manufacturing facilities (lines 51-57).

Consideration of time critical design processes (step 3) is presented as a consideration of the resources available, and the length of work queues in the design office:

> R: [...] If you've seen the drawings before but you need to alter something that's going to affect how long its going to take, so you would look how different it is from the previous work. Are there any other things that would influence the design processes that take the time for these familiar parts?
>
> S: Generally speaking not many. Most of that we probably know already, so if something is as simple as that then the greatest time that it spends in our office is the time that it's in the queue waiting for someone to do the work. It may be three weeks waiting, and then only three days on the board.

> R: So its actual drawing time, putting the lines on the paper, and checking that nothing interferes with it?
>
> S: Yes.
>
> Appendix F(i) lines 65-75

The above quote is relevant to step 4, as if there were only one time influencing process (the work rate of the draughtsman) so explicit identification of it is not needed, thus skipping over step 3 (lines 73-75). Reallocation of resources is also described as an option, when the deadline for completion is the limiting factor, rather than the level of resource (lines 76-84):

> R: You try and allow yourself as much time as possible, you perhaps find that whoever you went to in the drawing office with it didn't have such a problem with it and you were left with quite a comfortable margin?
>
> S: Not often.
>
> R: If you were running late that person would work longer hours?
>
> S: Yes.
>
> R: So it's a matter of altering the amount of resources to solve the problem in time, rather than estimating accurately.
>
> S: That's right yes. I can put two men on one job if I need to, which I've done just recently. Generally speaking we're not too bad at the moment.
>
> Appendix F(i) lines 90-99

As with the Labman Automation expert, step five is explicitly undertaken, particularly for long lead time items:

> R: So you identify where the interference comes between the two parts?
>
> S: Generally speaking long lead items are forgings, castings because you might have to make the pattern, but even if you have got the pattern it still takes four weeks to get them from the foundry, and fabrications. I would consult the other department to see what he wanted first. That's the way we would work in the office, if its going to take them weeks to get a forging then make sure that's the thing that gets done first.

R: If you had to do some other design work before you could complete the forging, that would have to be done as well?

S: Yes.

Appendix F(i) lines 107-115

As with the Labman expert, these dependencies guide the production of an estimate for the critical design units (step six):

R: [... do] you work out what the total time for designing the forging and the parts it is dependent upon?

S: Yes, it would have take into consideration everything that affected that component before you could release the information.

R: So you would be able to produce an estimate for how long its going to take to produce a drawing for the forging, so you can produce a rough time for each new part you've got to design?

S: Yes.

Appendix F(i) lines 131-138

The emphasis is placed on these long lead time items being critical to the design time. Such items have priority and the design is completed in order of reducing priority, down finally to fixtures. Detailed estimation is not therefore done outside these high priority parts, the time required for completion being present in the factors of safety allowed in the time estimates (lines 144-149). Estimating for only high priority parts simplifies step seven.

The overall fit of the model does not appear to be as good for Michell Bearings as it is for Labman Automation. Each of the stages can be seen in some form or another, but because the design work undertaken at Michell is simpler (in terms or organisational requirements, not technical requirements) than at any of the other sites, the simplification of the detail of the model may be expected.

7.4. Thorn Lighting interview

Much of the discussion at Thorn Lighting was related to explaining the format of the model and the meaning of each stage for Thorn in particular (lines 1-61). Of particular interest to the interviewees was the application of the model (lines 62-167) and problems it highlights with the systematic estimation of design times. The interviewee almost accepted the model as accurate without modification, although criticism of the layout and wording of the steps was made. The problem of wording is tackled by the interviewee in lines 207-292, where each stage is examined for its relevance to Thorns operations, and re-worded using company terminology. Each stage was found to have meaning for the firm. One modification was to allow the estimation of resource level to match a deadline, as well as produce an estimated completion date from a known resource capability:

> S: This scheme does not relate to working backwards, does it?
>
> R: It is not laid out in the format of being able to work backwards, it assumes that you are going to work forwards. The same points for give and take are still there, so you can work backwards all you do is change the emphasis from estimating the time to working out what the resources are you are going to need.
>
> Appendix F(ii) lines 163-167

The interviewee not only expressed the belief that the model was a good representation of Thorns estimation task, but also that the designers would each claim to recognise the model with the modified wording and perform each step. However he expressed doubt that each estimator would approach each step with rigor.

> S: [...] So looking back over my comments, you give that to a designer and he'll say,' oh we do that anyway' but they don't. As it is it's extremely unfriendly.
>
> Appendix F(ii) lines 293-294

He had earlier expressed the opinion that one of the sources of inaccuracy in estimates was the failure of the estimators to approach the problem systematically:

> R: No it's not. One of the major criticisms I've had from other estimators is that it is laid out in sequence when it is not actually done as a strict sequence. It's a lot more flexible than the lay out of the scheme suggests.
>
> S: That's why it is done incorrectly mostly as it is not done as a logical sequence.
>
> Appendix F(ii) lines 173-176

The experts overall verdict of the model was favourable, although it relates more to the applications of the work, rather than its fidelity:

> R: Would you find it of some use?

> S: I think so, it was produced in a more comprehensible form. And its got to be something that can be done in a matter of minutes, and a logical sequence that they can understand, with all the options, without having to think about. Like any check list its so you don't forget things. It makes you think.

Appendix F(ii) lines 295-299

7.5. Brown Brothers interview

Brown Brothers in Edinburgh sell heavy mechanical engineering equipment into the marine industry. Their main products are the folding fin stabiliser with applications on ships, and high pressure fluid swivels with applications in the off-shore oil industry. Although the majority of the projects are bespoke in nature, requirement for design also extends to the development of new products, both to keep the firm competitive in their core markets, and to enter new markets which can employ their expertise in heavy engineering, hydraulics and control systems. The firm wins orders through submitting tenders, the products all requiring some customisation to fit the individual needs of the contracts. The firms development programme means that it has to cope with some of the problems of a volume manufacturing firm - the development costs are not covered by sale to one customer; the point at which further development is uneconomic has to be estimated; the market requirements are not fixed before development is commenced.

The expert interviewed was a design manager, with responsibility for estimating times and resource requirements for design work. The interview was conducted in the same way as at the three other firms, although further introduction was needed to establish the purpose of the research, and the field of Brown Brothers operations. The setting for the interview was an open plan conference area, which whilst not entirely silent, was a comfortable and semi-formal environment familiar to the subject.

Steps one and two are undertaken by the person planning the project. The steps involve not only conceptual knowledge of the anticipated solution, but also (as with Michell Bearings) some technical detail too:

> R: First step: Identify problem, what constraints there are and have a rough idea of the end product.
>
> S: We call this proposal engineering and do a few calculations to see if it's actually feasible and then perhaps an arrangement drawing.
>
> R: So then you would divide this into separate units that you can work on, as many at one time that can be handled.

> S: This is done not so much for the stages of assembly but for the different phases of the project that can be estimated.

Appendix F(iv) lines 116-123

Not only are the major units identified, further levels of detail are identified in the unfamiliar sub-divisions:

> R: So in more detail you examine your proposed design or arrangement drawing and see what the interconnected areas of work there are. If you recognise these as been approached before that's fine but if you don't then perhaps brake it down a little more. Would this be reasonable?
>
> S: Yes.

Appendix F(iv) lines 124-128

The problem for the estimator however, is not to estimate the completion date, but to establish the amount of resources that will be required to finish the project within the previously agreed time (lines 131-141). The need to set resource level is similar to the problem faced by Thorn Lighting, and occasionally the problem faced by estimators at Michell Bearings.

Step three of identifying what design processes are needed to complete the various units, and then seeing what factors influence how long those processes take was seen with some scepticism (lines 149-150). Whist it was identified as a good methodology, it was not seen as a direct representation of the process undertaken by the estimators at Brown Brothers. The expert raised the issue of interconnected units influencing the completion of each other as more important.

Step four, the comparison of time sensitive processes with the resources available to perform then was identified with. The matching of delivery date with work requirements to come up with resources required was seen to be an obvious skill required of the estimator:

> R: So you've worked out the processes which strongly affect the design times and compare these with the resources that you have available. Perhaps in your case because you are trying to work out how much resource your going to have to apply to get it done in the time, you'd be almost doing a reverse of that process. So you wouldn't be comparing the work you've got to do with the resources that you have and coming up with a time, you would be comparing the work that you have got to do with the time that you have to do it in and coming up with the resources needed.

> S: I'm sure that must be common isn't it? As whether it's a customer or a board of directors that is setting what you have to do, someone always wants things done by a certain date.
>
> Appendix F(iv) lines 159-169

The identification of dependencies between the sub-units of the design (step five) had already been flagged as important by the expert (lines 156-157). Further discussion of this revealed the way in which these dependencies can influence design time through then need for iteration:

> R: This interference of what's a predecessor and what's a successor, the time affecting processes and how they interfere with other time influencing processes and how they also affect the units, these would be your predecessors and successors. So perhaps say that you can't design certain parts of the job until you've worked out tolerances for something or the pressure for something else so you would have to do those first. You would have to perhaps go around in a loop and iterate.
>
> S: Yes.
>
> Appendix F(iv) lines 171-178

When discussing the preparation of design times for sub-units and their integration into an overall estimate for design time (steps six and seven) it was not only established that such an operation is performed, but also that an element of time estimation rather than resource level setting is required from the planning process:

> R: If you were perhaps producing a gant chart, putting all that information for your sub-units onto the chart you can say which areas will overlap, then you can get a start and finish date. But in your case you would get a result telling you what resources you need for each stage.
>
> S: As you have said it works both ways as by the time you have you've gone through this process you realise that the time scale is a year not six months as you first thought when you started, and even by putting extra resources on it you can reduce the time to perhaps eight months because of maybe some of the factor things that you've actually got to go through.
>
> Appendix F(iv) lines 181-189

The interview tends to agree with most of the model for time estimation, whether it is for the planning of time schedules, or for the setting of resource levels. Where disagreement does come is in the identification of time influencing design processes, and the factors in the design problem which influence the degree of their effect. The disagreement is not with the method of doing this stage, but with the performance of this stage at Brown Brothers. The expert believed that this stage could be a good way of approaching the particular facet of the estimation problem, but that it was not currently applied by their estimators.

7.6. The implications of the interviews for the model

Each of the four interviews supported most of the model. The model had been presented as the method for estimating design times given knowledge of the resources available.

It was apparent that in some of the firms it would be more representative if it described the estimation of the resources required given the deadlines, rather than the estimation of the time required given the resources. Representing resource estimation rather than time estimation requires very little in the way of alterations to the model. The most significant change would have to come in stage four where work requirements are compared with resources available to come up with time constraints. The wording would need to be altered such that work requirements and time deadlines were compared to come up with resource requirements.

Many of the interviewees observed that the model was not as well presented as it might be. The main criticisms were:

- the phraseology used to describe the various stages was not entirely transparent
- the sequential nature of the model, using arrows to link stages, implied a rigid structure and order to the process which does not represent actual practice
- the stages were not immediately applicable to the particular firms since the vocabulary used in the model was different to that used in each firm

In some ways the first and last criticisms militate against each other. Each firm uses its own terms to describe parts, stages and processes. It would therefore be impossible to present a general model which would entirely satisfy the need to use accurate terminology with each firm. For the most complete understanding it would therefore be most useful for each firm to develop a model specific to its needs, using its own internal language, perhaps illustrating the various stages with examples from its own historical data. However, this was beyond the scope of this research project, since the actual implementation of changes brought about by the model had not been considered during the researches design. The problem with the sequential nature of the model is more serious, since it mis-represents the process which it is the object to describe. An attempt to rectify this problem is made in the final model presented.

7.7. Proposed modifications

Two modifications are made. The minor one is to adjust the phrasing of some of the steps to make their meanings more transparent. Adjustments are also made to the parts of step four to allow for the estimation of resource requirements given a deadline, as well as the estimation of completion times given the resources available.

The major modification is to the way in which the model is laid out. It was suggested by one of the interviewees that the boundaries between the stages be removed or blurred. Another suggested that iteration be allowed for. One also suggested that the model is too mechanistic altogether and the description should convey the nature of each step influencing the estimate, rather than the steps, followed one by one leading to the estimate. The final form chosen is one therefore of each step standing independently with its detailed breakdown grouped around it, with a connection to the time estimate, and each other stage. The steps are laid out in a clockwise manner with a spiral indicating that the further clockwise one proceeds, the nearer one is to a total design time estimate. However, this clockwise spiral does not restrict the estimator from hopping about from one step to another as and when the problem requires - the interconnecting lines imply that the estimator may move from one stage to any other.

The final model, including these adjustments, is presented in the following section.

7.8. The final model

The model (figure 7.1) represents both the engineer to order and volume manufacturing markets. Since many firms have aspects of both type of operation it is most useful not to draw too strong a distinction between them. Because, of this the general model will have some redundant elements when compared with a specific firms operations. For instance identification of the market type would have no meaning in an engineer to order firm which services only one market. Redundancy is, however, in the nature of a general model.

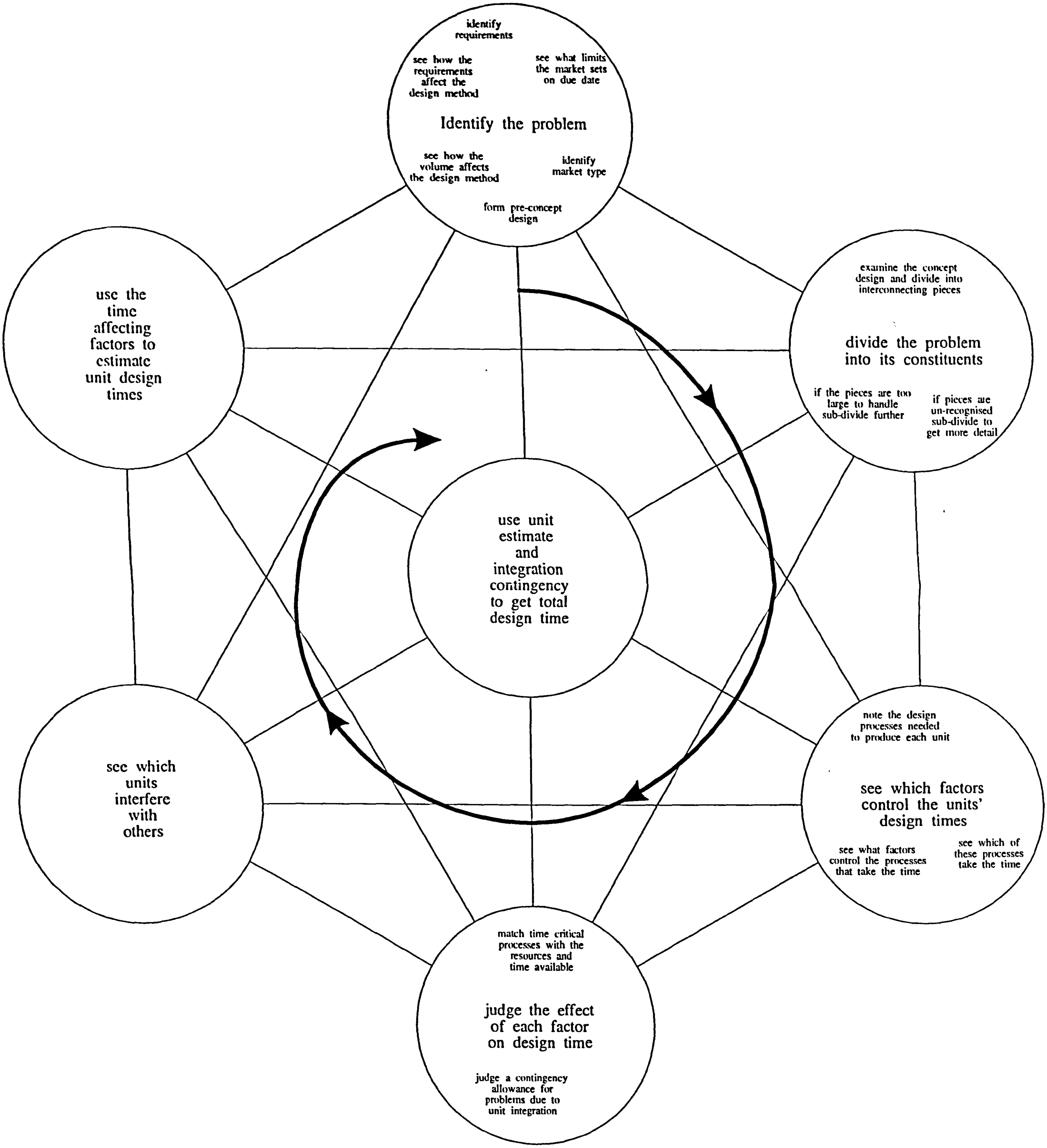

identify requirements
see how the requirements affect the design method
see what limits the market sets on due date
Identify the problem
see how the volume affects the design method
identify market type
form pre-concept design
examine the concept design and divide into interconnecting pieces
divide the problem into its constituents
if the pieces are too large to handle sub-divide further
if pieces are un-recognised sub-divide to get more detail
note the design processes needed to produce each unit
see which factors control the units' design times
see what factors control the processes that take the time
see which of these processes take the time
match time critical processes with the resources and time available
judge the effect of each factor on design time
judge a contingency allowance for problems due to unit integration
see which units interfere with others
use the time affecting factors to estimate unit design times
use unit estimate and integration contingency to get total design time

Figure 7.1

8. Conclusions and recommendations

This chapter summarises the discussion of the results which have been presented in chapters 4-7. The discussion is divided into two parts, as the research involved two distinct methodologies. After the discussions of the individual components of the research, the implications of the study as a whole are explored. The thesis closes with a set of recommendations which are not only suggestions for further research, but suggestions of how the work may be carried on for the firms collaborating with the project.

8.1. Discussion of the quantitative study

The quantitative study formed only a small part of the research, being possible in two of the three major collaborating firms. It performs, however, useful function in helping to establish the case for the research.

8.1.1. Findings of the quantitative study

When collaborators were initially sought for the project, the managers approached raised a number of objections to the project. One manager at Michell Bearings claimed that the estimates were already accurate, so no improvements could be made, and therefore participation in the research would bring no benefit to the firm. However, the quantitative survey has revealed that the difference between the estimated and actual completion times is statistically significant.

A graph was plotted of estimated completion times against actual completion times. In the situation where estimates were accurate one would expect the gradient of a best fit line trough the point on this graph to be 1.0. However, gradient of the least squares best fit line was found to be 0.52. For a project estimated to take twenty days (which is not unusual) the expected duration would be over thirty-eight days. The trend is statistically significant; there is less than a 1% chance that the scatter of the point is due to random fluctuation. It is significant in more tangible terms. It is a 90% overrun, a three and a half weeks delay, one hundred and thirty man hours per designer.

Despite this difference between the estimated and actual completion times, the trend indicated can be interpreted in a more positive way. It indicates that the estimates produced have a systematic relationship to the actual completion time. That is, a longer time estimate would be associated with a longer actual completion time. The estimates reflect the actual completion time, therefore actual project completion times can be estimated to a statistically significant degree.

8.1.2. Limitations of the quantitative study

As discussed in section 5.2.2, a formal study could not be conducted at Thorn Lighting. The trend obtained from Labman Automation was not significant because of the small sample size. The reasons for a restricted sample are discussed in section 5.2.3. In order to establish the degree of accuracy and significance of the estimation process at these firms a longer duration study would be needed. A study of four or five times the duration may yield some more significant results at Labman. In addition to the longer study time, any investigation at Thorns would have to take in to account the evolution of the design problem during the design process. Changes to specification and functionality would have either to be frozen or accounted for. Since freezing specifications would be impractical, a system of measurement of functionality and resourcing change would be required. Whilst measuring resourcing level would present some problems, finding a method of quantifying the level of functionality for this type of product would be a complex research problem in itself. Were such measurements possible, the statistical analysis would then take the form of multiple regression, which would itself require a larger sample size to produce statistically significant results.

8.1.3. Implications of the quantitative study

Even though the link between design time and estimate time has been proven statistically, this may be interpreted either as accuracy of the estimation process, or as a sign that the design time estimate affects the duration. The second case could be due to the designer taking as much time to complete a job as there is available. Such a strategy would affect the data by making completion before the due date exceptional. Examination of the data reveals a number of projects which are completed before they are due, making this explanation unlikely. Design time could also affect duration because projects running late are given priority, either through resource allocation or management expediency. The effect of this strategy on the comparison of actual and estimated design times is difficult to predict. Awareness of the possibility of this strategy is therefore important when interpreting the qualitative results.

By way of a summary, the two major results of the quantitative study were:

- the significant difference between estimated and actual design times, indicating that estimation was not accurate
- estimates have a systematic relationship to the actual design durations, indicating that either the estimators could predict design time to some degree,

or that design managers altered the level of resources to ensure that actual duration was related to the estimate, or a combination of the two

8.2. Discussion of the qualitative study

This section summarises the results from both the case studies and interview work. The link between estimated design time and actual design time having been established in at least one case during the quantitative study, most of the qualitative study was designed to investigate the way in which the estimates were produced. The model of the estimation process produced during the research is only part of the results of the study. The work also revealed the context within which the model is operated. The contextual information includes what each firm requires of the estimate, what constrains the estimate, and what variables may be adjusted to achieve the constraints.

8.2.1. Findings of the qualitative study

The interviewing and case study parts of the research established that each firm has its own requirements and constraints where design time estimates are needed. In most firms the requirements and constraints can be different for different projects. In order to fit within the constraints the firms adjust three variables, delivery date, resource levels and functionality. The flexibility of these variables is dependent upon the firm's market type, and project requirements. In the ETO environment the functionality of a product is almost entirely inflexible, whereas in volume manufacturing some considerable degree of adjustment may be possible. The relationship between the three variables is not a simple one. In a simple case, if resource levels to be reduced one would expect that estimated duration would go up. The duration could be kept static if the project were made simpler, i.e. functionality reduced.

The general design time estimation model was initially intended to use constraint of resource and functionality to establish an estimated duration. During the corroboration phase of the project there was some criticism, from both the internal and external corroborators, of the model's apparent emphasis on estimating duration rather than resource level. The final model is re-worked in order to reflect this. Variation of resources to fit in with deadlines is now more explicitly stated in the model. However, the emphasis remains on time estimation because of another phenomenon which became apparent during corroboration. The phenomenon in question reflects a situation where the required due date is un-attainable, either because of inadequate resources, or because of a lead time over which the estimators have no control. Given limited time the situation can often arise that no amount of resource will allow the project to be completed. Given limited resource a solution will usually reached after some time. In practice, the situation where a target can not be met means that targets are reassessed. Reassessment means a time estimate has to be made in combination with an estimate of resource level. It is therefore the time estimate which is more common, and the resource level which follows from that.

8.2.2. Limitations of the qualitative study

Throughout the research design, data collection and analysis there was great attention paid to ensuring that the findings would be valid, in terms of the quality of the academic research, and its application to industrial situations. Methods were selected which would generate theories grounded in actual observations. These observations focused on people responsible for the actual practice of the phenomena of interest. The observations were recorded in their entirety and complete permanent records made. Analysis methods were identical for each of the records. At each stage conclusions and theories were checked with the original records to establish their validity and any supporting evidence. The methods described above produced the model of the time estimation process detailed in chapter 6.

The model was corroborated by presenting it to each of the subjects involved, stage by stage, and getting their opinions and suggestions for improvement. These opinions provided internal corroboration. External corroboration was achieved by presenting the model to a design time estimator employed by a firm uninvolved with the generation of the model. The comments from each of the four corroboration interviews were used to prepare a final model which should be the most representative and practical.

It may be argued that the model is most representative of the ETO environment since two of the three firms involved in its generation are of this nature, and the firm from which external corroboration was gained was also predominantly of this type. However, throughout the thesis it has been argued that the division between ETO and volume manufacture types of company is a blurred one. In each of the firms involved there may be recognised features of both type of operation. Michell Bearings and Thorn Lighting represent the extremes of this sample, but neither can be said to be archetypal ETO or archetypal volume manufacturer, whatever the archetypes may be. The model is general because has been generated from a selection of firms with a selection of characteristics from both ETO and volume manufacturing. It therefore applies firms with a selection of characteristics from both ETO and volume manufacturing.

8.2.3. Implications of the qualitative study

When collaboration was sought as the project was just beginning, estimators and managers were approached. All agreed that time estimation is a difficult task both to perform and investigate. Some asserted that it could not be researched. A couple of estimators believed that they did not have a method whereby an estimate was produced, but relied on inspiration or a lucky guess. The study presented in this thesis has revealed that there is a systematic method employed, and some of the factors that influence that method.

The qualitative studies have uncovered the method by which time and resource estimates can be generated from project briefs. The method has been found to have discrete parts which interact together. It has been established that the method is not followed with rigour by the estimators, but that each part of the method is used by estimators to influence the design time estimate. The method still involves the application of judgement to some degree. The method is affected by the market within which the estimator is operating. An estimator in a predominantly volume manufacturing firm will not be concerned with covering development costs through a fixed number of sales, an estimator in a predominantly ETO environment will not be concerned with the volume of sales requiring value engineering to be performed. Each firm has a unique set of requirements and constraints which relate to the estimation method.

8.3. Conclusions

This research offers the following findings:

- that estimates for the time and resource requirements of design tasks are prepared in many firms as a matter of routine
- that there can be a statistically significant link between the estimated and actual design time
- a general model representing methods used by estimators in industrial settings
- that although some stages may not apply in some firms, the general model applies in both volume manufacturing and ETO situations

8.4. Recommendations for further work

Because the research was industrially based, recommendations are presented in two parts. In order that the industrial partners may gain more benefit from the research there are a set of recommendations which relate specifically to the industrial applications of the work presented in this thesis. No further research would be required before the development of these applications could commence.

Further avenues for research are also suggested. These avenues relate to more detailed questions about the estimation process for engineering design, questions about estimation in other disciplines and the development of applications of the estimation model.

8.4.1. Recommendations for industrial application

The obvious application for the research findings is in the improvement of estimation techniques. Such improvements could be achieved through three approaches. Firstly tools such as check lists and *pro-forma* work sheets could be devised to ensure the systematic consideration of the factors which influence design time. Generating these check lists and record sheets would have to be done for each specific firm, since it has already been observed that the characteristics of each estimation problem vary from firm to firm. A simple check list of this type was prepared with Thorn Lighting (see appendix I). Checklists and record sheets would allow:

- more rigour to be applied to the estimation
- clearer presentation of an estimate's justification
- formal recording of the calculations and figures required to produce an estimate

The last consequence above would be another application of the estimation model. Were the figures used to calculate an estimate recorded two benefits might accrue. First, historical records would be generated which could speed the estimation process through removing the necessity to repeat work. Second, comparison of estimated targets and achieved results would be possible in more detail. Comparing estimate and achievement on a more detailed level would allow the pinpointing of the inaccurate parts of the estimation process, or from another perspective, the parts of the design process which cause most slip from estimates.

The estimation model, when combined with the historical records, would also be a useful tool in training novice estimators. The model would provide them with framework of tasks which are performed to produce an estimate. The historical records would provide examples of solutions to various design scenarios, and guidance for the application of judgement to new estimation problems.

8.4.2. Recommendations for further research

It was noted in chapter two that although there is now a quantity of descriptive work on design methodologies, there has been little by way of independent checking, acceptance or rejection of theories (see Popper, 1959 pp 78,92 for discussion on the testing and testability of theories). Since there has been no other work in the field of time estimation in mechanical engineering design, and the validity of this work has been checked both with its sources and externally, there would be small benefit from testing this model in more and more firms. What would strengthen or weaken the model more effectively would be to study the phenomena by some other means, and then test the findings of the studies using the methods proposed by Bloor (in Silverman 1985). These being:

> i) The attempted prediction of members' descriptions in actual field settings (e.g. how they would diagnose disease in a particular case).
>
> ii) The attempted prediction of members' reactions to hypothetical cases constructed by the observer.
>
> iii) The attempt by the researcher to 'pass' as a member in a particular setting or situation.
>
> iv) Seeing whether 'collectively members recognise and endorse the sociologist's account of their social world'.
>
> From Silverman (1985) p44

Although this last method has been used to corroborate the findings of this research, no comparison was possible with existing models, since none exist. Performing one or a selection of these tests on more than one theory would give an even clearer indication of the quality of 'fit' of this theory.

The model as it stands still allows some scope for the judgement of the estimator to influence the result. More detailed studies might break the process down further and focus on these steps in order to understand more fully the application of this judgement. Such detailed work might also reveal the order the steps are undertaken and greater detail about the performance of estimation in action. The study of estimation in action would present a difficult research problem, but one which might be solved by using video protocol analysis sessions in staged settings. Such work has been undertaken for other disciplines with some success (Laws & Barber 1989).

Detail which might be forthcoming from such a study would be useful in assessing what makes an estimator particularly good or bad. A study of a variety of estimators, perhaps all in one large firm, would provide a basis for meaningful comparisons. Such knowledge would be useful in guiding teaching of good estimation practices. Although this might not guarantee such practices were used (c.f. Frike, 1993).

The development of tools which might aide the process of estimation would also be possible. The tools could be the simple paper based systems proposed in the previous section, or sophisticated computer software which would allow for the automated searching of a historical data base; rigorous and rapid application of the method; the representation of estimates as probability distributions; fuzzy logic, and 'what if' analyses.

The logical progression from computerised estimation tools is the automation of the estimation process itself. Where new designs are variant in nature the system could possibly be parametric, based on the customers specifications. Where the design problem has more unknowns the method would have to be much more complex, requiring the consideration of not just the customers requirements but contextual information; knowledge of the state of technologies; and many other variables.

Finally, the research could be extended out of the mechanical engineering domain, into other types of engineering, including civil, electrical, electronic, plant and software. Indeed, some work in the latter field is already underway with support from the EPSRC (grant number GR/J 57568). Outside engineering altogether estimates for project completion times are made in areas as diverse as scientific research and marketing. The process that marketing people use estimate that a new product will be needed in fourteen months may provide equally interesting and useful research findings.

Appendix A

Final report of an interview recorded in note form.
Interview with the Design Manager at Michell Bearings,
Part of the Vickers Group.
17 October 1990.

Introduction

Michell Bearing's business takes two forms. The greatest proportion of their work is the design and manufacture of large or complex one off bearings. The other side to their operation is the repair and service of these items, and they will even work on bearings produced by other firms, for which the original specification is unknown. The bulk of the work is therefore of the Engineer - to - Order (E.T.O) type.

Interests at the beginning of the meeting were:

- The type of market within which their business interests lie.
- The order winning process.
- Design procedures favoured.
- The cost controls placed upon the design procedure.
- The communications links within the development function.

In the E.T.O environment products have a high design content because the design effort is shared between a much shorter run length than in mass production, where design effort of the same scale would be divided between a run length four or five orders of magnitude greater. The designers at Michell Bearings may therefore be expected to have a great deal of experience and have a vast pool of previous work to draw upon.

Discussion.

The meeting took place largely with Mr ********, and also to some extent with the senior marine bearing designer. The information gathered with regard to the E.T.O. work divides conveniently into five categories. These are enquiries, design, estimation, communications and commercial considerations.

Enquiries:

Each order comes to the design office in the first place as an enquiry. This may only require the designer to produce a vague arrangement sketch from which the estimating department can produce rough figures for cost and delivery date. Only when the customer provides more information and requires hard and fast figures for price and delivery date will a detailed arrangement drawing and possibly sketches of more complex or expensive parts be produced. This enables the estimating department to calculate accurate times and costs which can safely be written into a contract.

The estimation process can be an iterative process, with specifications, revised designs and estimates bouncing around between customer, designer and estimating department many times. Even so, sometimes a customer will have a detailed specification which will allow a sufficiently detailed arrangement drawing to be produced and in turn an accurate estimate of price and delivery date, without the need for repeated revisions. This depends very much upon the customer and the type of application for the bearing.

Some more general points were thrown up:

- Michell Bearings receive 1000 to 1500 enquiries every year.
- An enquiry may only require a ball park figure.
- The average enquiry takes one week to respond to.
- Orders are only taken from exactly agreed price and date information.
- Roughly 500 enquiries become orders and reach the design stage.
- Enquiry design time is included as an overhead.

Enquiries may take from as little as a few days to perhaps six years before a contract is agreed. This disparity highlights the diversity of work and customer the firm deals with, and the flexibility required of the whole organisation.

Design:

The design facilities at Michell bearings are split into two sections, the Marine section, and a section that deals with all other E.T.O. work. The tree diagram in figure 1 outlines the company structure, with the emphasis upon design.

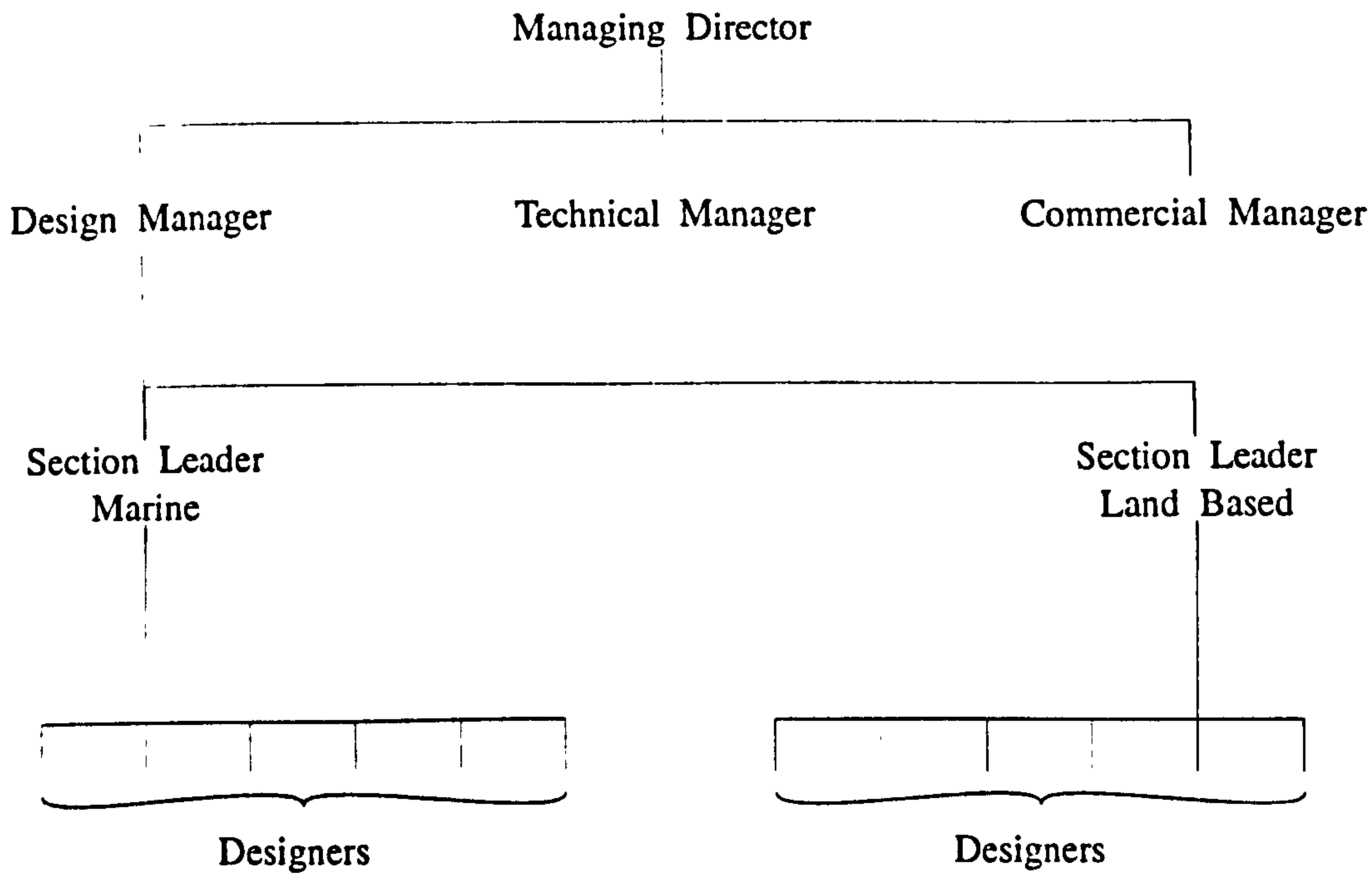


Figure 1

Each bearing design is completed by one designer, although a job requiring more than one bearing could be tackled either by one designer or one for each bearing, depending upon the delivery due date. The section managers are working designers, but they also co-ordinate the work of the other designers in their sections and act as consultants for the less experienced members of their section.

To be eligible to compete for Ministry of Defence orders, and the American Department of Defence, Michell's have had to become a company of assessed quality under various International, British and American standards. One of the requirements for this assessment is the production of a document detailing design office procedure. Within this document the process of design is described in the form of a flow diagram, and the design review procedure set out.

Estimation:

As would be expected, it is the estimation department which predicts final values for most of the variable factors of a project, but it is the design managers job to predict the time a design will take to produce from the completion of the enquiry to the completion of the working and assembly drawings. He does this from the same information the estimation department uses, this being:

- The arrangement drawing.
- Pricing information from the enquiry sheet which includes:
    - Approximate material weights.
    - Special material requirements.
- Previous similar designs.
- The number of components involved.
- The processes involved in manufacture.
- Patterns required which do not already exist.
- Special test requirements.
- Other special requirements, such as translation of technical literature.

The estimate for times and costs of work are passed to the sales department as outlined in the enquiries and communication sections. There is no official communication channel between the design and estimation department.

Communications:

The only formal means of communication available to all departments is the 'work to' document which is prepared after the order has been won. To this the design manager has to add the time it will take for the design to be produced. Some 'horse trading' can take place during this preparation stage, and often the design manager may be forced to cut time safety margins so that this 'work to' document matches the delivery due date. There exists a more informal communications structure on a person to person basis.

The design and estimation department are situated in the same large open plan office, and people are encouraged to communicate person to person where dialogue is necessary.

Orders are won through the sales staff. These people have technical backgrounds, and usually do not chase orders, but clarify the customers requirements, outline Michell's capabilities to customers, and provide an effective communications link between the customer, the design department and the estimating department.

The route an enquiry takes is outlined in figure 2. As explained earlier in the enquiries section, the enquiry may make several passes through the system, each time the customer modifying the requirements until the performance, price and due date are acceptable to all parties.

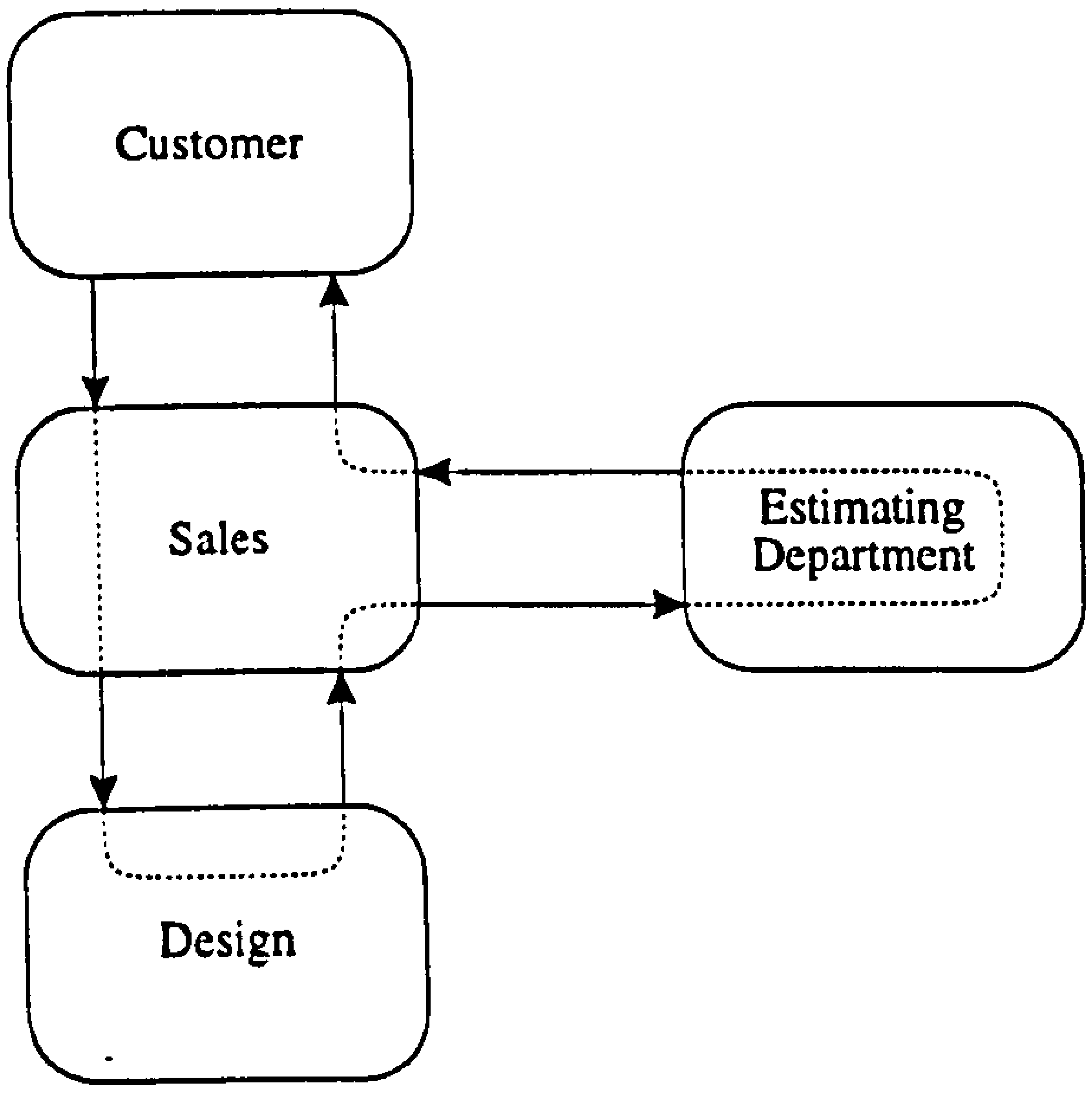


Figure 2.

Once work on the contract is underway there are both inter- and intra- company communications. Within Michell bearings there are regular review meetings to discuss large contracts. The people present include:

- The technical director.
- The commercial director.
- The designer involved with the contract.

Communications with the customer are not always channelled through the sales department. Often there is direct dialogue between:

- Michell's designer and the customers designer.
- Customers buying department and Michell's sales department.
- The customer's quality manager and Michell's quality manager.

Commercial Considerations:

Time booking is not practised a Michell Bearings. Design time is estimated during the enquiry stage and included in the quoted price, but design undertaken during the estimation phase is regarded as overhead, unless the project is particularly large. In this case, say for an estimate put together over several years, money is required in advance for the investigation work.

Once the order is placed, if large changes in specification are needed requiring major redesign, the customer has to pay for effort previously put into design at a standard rate. The design manager estimates the approximate design time taken when working to the original specifications.

Two types of orders are taken at Michell Bearings, profit orders, and contribution orders.

The price of a bearing which is a profit order is calculated on the basis of:

material cost + overhead + profit margin

The price of a bearing which is a contribution order is calculated on the basis of

material cost + overhead + reduced profit margin

Factors which influence the size of the profit margin for a profit order are:

- Whether other firms are able to do the work.
- The budget of the customer.
- How badly the customer needs the bearing.

The profit margin for a contribution order is set such that the final quote is an order winning price. Contribution orders are taken to:

- Complete the order book.
- To offset the write-off cost of expensive machinery which would otherwise be idle.
- To prevent the need to lay off expensive non - productive labour.

Conclusions.

The organisation at Michell Bearings needs to be very flexible because of the shear range of work and customer they have dealings with. To this end it seems a heuristic approach to management is taken, particularly where communications are concerned. Another consequence of this need for flexibility are the loose controls placed upon the design process. The hours spent on each job are not recorded so final total design times can not be accurately calculated, nor can the cost of design. This results in all design work, whether during the enquiry stage or in preparing an order for manufacture, being included as overhead. When the design problem is open ended as with the enquiry stage, a simple system of tight design control is difficult to envision., but without controls on the rest of the design cycle Michell's may be creating problems for themselves. For instance - it must be difficult to keep accurate records of the cost of previous design work and therefore difficult to estimate the design cost for prospective work. Measuring the designers ability in terms of productivity versus quality is also a vague and subjective task.

It may not be practical or popular to implement rigid time booking whilst still retaining the flexibility needed in this organisation. This though, may not be necessary when each designer works on one job only at a time. If the section leader were to keep detailed records of job allocations and progress, including how his own hours are occupied, controls would be tighter. This may result in the section leader having less time to give to design work, but would increase the accuracy of the estimating departments work and reduce the safety margins needed to cope with the unexpected. This reduction in safety margins would enable profit orders to become more profitable, and contribution orders to become more viable.

Appendix B

Transcription From:

Meeting with designers at Thorn Lighting.

Date: 7th April 1992

Time: 2.30pm

S1: Bespoke projects designer

S2: Volume projects designer

R: Interviewer

Transcript follows:

S1: Right, lets start at the beginning, listed you've got the market, market segment, range of competitors, market shares, key range revisions, and price. This is an existing product, going to be revised, this is if you like, the guide lines that we have decided through the corporate process of several meetings, is the way we want to go.

R: So this is going to be the shape of the mark two.

S1: Yes Derek is in fact working on it now. One of the reasons I'm up here is that we have a meeting tomorrow on this very thing, so it's still an ongoing thing. We haven't totally finalised the design yet. We're broadly following the guide topics here.

R: There is a lot of detail here.

S1: There is actually, because its a bit like - how can I put it - in that segment of the light fitting business it's a bit like a ... like a Vauxhall Cavalier if you like, or that type of car, where you want to ... you have a basic model, but you try and pitch it so that you have very simple versions to deluxe versions. That's the intention.

R: What I'd like to do is just go through each part of the brief bit by bit, and talk about what bearing that would have on how long it's going to take to complete the design work.

S2: Okay, fire away, let's see where we get to.

R: We've just said that there is a lot of detail in this brief, I suppose that's because you've already done one, it's an existing product range, you get a lot of the background from the first model.

S2: Well, there's a fair bit of flannel in it I think isn't there Brian, that's probably the word. You've got to read it and read it for the bits that you're looking for.

S1: Yes, not every word in there is an instruction to design the thing, obviously there are statements of reason for why a thing is thought the right and wrong way to carry on.

S2: In that it is an existing product that we're trying to attain it probably is a little different.

S1: As you see item two here says it divides into three sectors, you've got the base low, cheap type of thing, and then the more middle ranges, and what perhaps one would call the upmarket versions, which would be the sort of thing you would have in the more expensively furnished VDU environment. There is a range of attachments to go with a series of produced bodies and so on, for different ceilings.

R: So this is actually aimed at the medium to high market, or is this product going to address all three of these areas in its different forms?

S1: I think really the idea is to try and get it to address as wide a band as possible,

S2: I would say we're trying to address the two top ranges there,

S1: We have another product which does the bottom range, called the 'pop pack' so when it's called Quatro it's the middle tier upwards if you like, albeit there will be dearer and cheaper ranges and version of that one, but essentially it picks up where the other one leaves off and carries on upwards.

R: So from a design point of view you are looking at a more quality feel of materials, and more quality feel of manufacturing. The market you are planning on will impose some restriction on your finishing design?

S2: Yes that's true.

R: You say the options have a bearing on how long the design is going to take, with more options you are going to have more design work to do. Lest go through and you pick out what things you think will affect the design stage from this design brief. Go through section by section.

S1: Well if we start of with the louvers, essentially this type of fitting has two types of attachments to it. One is called a louver, which you can see hear has various versions to it. The other on would be a prismatic panel, a perspex sheet with a pattern which has optical properties. There a simpler or fancy ways of holding that panel. Probably the biggest demand of this range is going to be louvers, that tends to be the sort of attachment which is sought after. This is obviously a time element here, working the body to fit the various different ceilings, and that sort of thing, that has quite an input.

R: These eight things are all restrictions on the final design ...

S2: They are either restrictions or instructions really, in the louver, this is what the marketing people are looking for. Again, these things are based on the existing product, a lot of these things are different from the existing product.

R: Are they problems they have picked up from the previous product, or nice features which have been seen to be worthwhile adding.

S1: They are features we should incorporate or modify. These increase the versatility of it, or the appearance of it, or the ease with which you are able to install it.

S2: Apart from the bottom two, the existing range of fittings doesn't have those features which are listed above.

R: So you would be starting with this new design, were you starting with the original thing as the basis, or were you starting from scratch?

S2: What we started with was the ceiling, because the ceiling is imposed on us, we then move on the louver, were told that 80% of quantities would be louver, and 20% would be plastic attachments. Because of money restraints on this particular project, we were looking for a louver where we could use the existing tooling, so that placed quite a restraint on us. We were looking at existing curves.

S1: That's tooling the louver, for your first question, starting at the top, the body really is a totally new concept, a blank sheet of paper job. Derek says that we're trying to use existing tooling on the louvers, so that though the louvers may look somewhat different, they are in fact made by ...

R: They are different shaped metal bent in the same way ...

S1: Yes possibly ...

S2: Well, we've a suite of louver tools, we've various suites of louver tools, and we chose one that would fit this particular project.

R: I suppose that would make the design of the louver slightly simpler ...

S2: Well it was simple yes ...

R: If you are starting with something, you are not going to have to work out a new set of optics for instance ...

S2: The thing is, we haven't convinced ourselves yet that we've got the right optics, that's one of the tests we are on at the moment.

R: It might come back to a redesign yet.

S2: It may come back to something slightly different, even if it's a movement of the lamp up or down. So we're not convinced we've got everything right. We've put the louver in, put the lamps in, then we designed a fitting to go round all of that.

R: You looked at the louver, looked at the lamp, and then you thought 'right we've got a box to go in the ceiling' ...

S2: We put a tin box round it, yes ...so that's how we built up the four stages.

R: So your design parameters are the louver ...

S1: The first limiting thing is the ceiling, that is not of out making, and there is a limited number of types on the market, when you are making a product like this that's going to go into a warehouse to be sold on to anybody, you'll never ever know what ceiling it will go in to except that you will attempt to make it go in to as many of the ceilings as possible. We do know from surveying the market that there is a limited amount of common ones, the ones that will come up again and again. There's always going to be the odd ball that it won't fit in. We think we know pretty we the scope within which we need to work. That's we have done. That's the first limitation if you like ...

R: So the ceiling is number one, and you've got the louver and the lamp - source. Then you use those three things to work out the 'box'?

S2: We there's the louver, the lamp and the body - it's called the body.

R: Right so they all go into the body. They all help to design the body. Then because you are only going to sell 20% as plastic attachments, you design the body to take the louver, and then design the plastic attachment to go in the body?

S2: NO. What we did in this case, we designed the package to except the existing plastic attachments, because we didn't want to spend money changing them. It gives continuity of supply.

S1: Some of those have extruded plastic sides, so tooling gets a bit expensive.

R: So for the same reason you are keeping the tooling for the louver, you are keeping the tooling for the plastic ...

S1: Even more so with the plastic because there is less of it, so you don't want to mess about making new tools.

The louvers, there are different optical categories that we are coming to, that's according to how they direct the light, how they control it from people seeing it who are working below it, they are known as categories one, two and three. Category one is very recessed, very difficult to see, if you were using a VDU screen you shouldn't be able to see a lamp, the lamp should be sufficiently hidden inside it. Because of that, that one tends to be the less efficient one. As you come down the categories the lamp effectively come closer, or the mouth of the louver opens, permits more light to come out at shallower angles. Three would be just an ordinary reception area, or a supermarket, or retail type use where you don't worry about that sort of thing.

R: So probably the more restricting louver would take more design ...

S1: It could do I suppose yes ...

S2: Well what we've done on this one is we've aimed for category two, because that's the most common...

S1: I don't think we've manage to get 'one' did we?

S2: Well, I think we will, I can't see we've overcome the problems of 'one' ...

S1: It's more difficult to design for category one, doing it as we're doing it, using existing bits is more difficult, because it does have very specific limits. When you look at it in a complete conic angle, it's brightness mustn't exceed certain levels at certain angles, whichever way you look at it. That is quite difficult to get right.

R: The more restrictions cause you more design problems.

S2: It may be, or we can make it by different methods if we ever get an order ... make it as a special or a semi-special.

S1: It wouldn't be a big seller in any range, it the sort of thing you would use in control rooms, only in very severe conditions. An ordinary VDU office probably would use category two. They would find that adequate.

R: So that might come out as a special with a different manufacturing technique, so you wouldn't be too worried about the existing tooling?

S2: Not too worried no.

R: So those options, you are looking at the biggest seller first in those options.

S1: I think so yes, with anything like this you've got to be careful that the tail doesn't wag the dog too much. There's this business of post anodising, what that means is that ... the most economic way to make this part is to buy the material that has already been anodised, in a great big coil. The down side is that when you chop it, you have no anodising on the cut edges, and when you form it and bend it you can get crazing along the bend. There's always the hope of minimising that, but there's no way to eliminate it completely. Another way i to post anodise, where you make it up first and then anodise it, that is more expensive, and probably works out at one and a half to twice the cost of doing it the other way. There is one specific company from Germany that has their own plant, and for that reason pushes it. It often gets put out of context with architects and consultants, they don't probably understand the advantages and disadvantages. I don't think we intend to go down that one, but it has been asked that it be looked at as a possibility, so it could be switched on if need be. The only time I ever knew of it being absolutely demanded was in Saudi Arabia, because of the very high humidity, so we decided that we didn't want to risk corrosion, the nodic thickness is higher opposed to anodising, so it is a more protective coating. But for normal office use 99.9 times the normal method is more than adequate. That's a sort of side alley if you like.

R: So you wouldn't put too much emphasis on looking at that.

S1: I think that's going to be looked at ... the problem with it actually is that it just happens to be that nobody in the UK can do it. A slight disadvantage ... The next one is panels. It mentions there having a version which is of some vintage now, it's shown to have sold very view, so we've dropped that.

R: That was to link in with air conditioning systems ...

S1: What happens now of course is, if links in they use the louvers which is no problem. For air extraction, sucking into a void, as its pressure reduced, it's quite common in buildings.

R: Then we go on to the ceiling tiles, which is where you said you would start from ...

S2: Well that's where we started from on this particular project. In fact we've two fittings here, we've one for exposed 'T' and one that suits the other two, the concealed fixing and the spring 'T'.

S1: Its impossible to economically, or even sensibly make one body that will do all that lot.

R: So you make one body which will take all your bits ...

S2: No in fact it's a different louver as well ...

S1: But still using the same louver tooling. Optically it would be very similar.

R: So you are using the same tools to bend it but the metal would be a different shape.

S1: Yes that's right, the actual body shape is slightly different as well.

S2: We can show you we've got some examples outside. That make it more clear.

R: You know from having designed for them before that the best way to attack those different types of ceilings, is to group the exposed 'T' together, and do two different bodies.

S2: Exposed 'T' is also the most common one, by exposed 'T' we actually see that runner which is a 'T' shape made from rolled steel. That's made up by a ceiling man, in this grid, and the boards lay in, and the light fitting is design to fit in exactly to those modules, usually 600 wide. That's the bog standard one in this country, so if you make a fitting which will pop into there, which lots of manufacturers do, it's nice and easy to use. That's about 75% of the market. That was one of the short falls before, it didn't totally address that market, so that's one thing to put right because that market has grown recently.

R: Looking at the air handling stuff again, is that the same as in ...

S2: Well the air handling is a continuation from the existing fitting ...

S1: The present one has slots punched in the body, to allow air to run up through from below to the ceiling.

R: So that's not a very complicated thing to have to introduce. The control gear and lamps are all standard stuff, it's not as if you've got to develop new control gear or anything like that ...

S2: No again it's a continuation from the existing fitting ...

S1: You then get the three types again in ascending order of cost roughly. You've got the switch start, which is the basic one which goes 'click, click' when switching on, the other ones are an electronic start, which has a much more reliable built in starter, the other one is the high frequency, which has no flicker because it's running at very high frequency. Again that's all corporate offices and that sort of thing which demand that, whereas a cheep spec. office would go for the other ones. There's quite a difference in cost between those two.

R: So the 'Vivatronic' is more efficient, than the standard lighting, and than there's high frequency ...

S1: More reliable perhaps in that sense. A starter switch is a curse on a big installation if they start giving trouble, because you've got to be climbing up ladders to see to them, whereas with the electronic shouldn't need replacements, it either works or it doesn't, if it's working it's there for years. High frequency has many other benefits, but it's a paid for benefit, it can be shown ... you can make a case for using it spread over five years or so ...

R: I suppose it stops eyestrain and so on ...

S1: Well yes, but it's also more efficient electrically, there's not so many watts used, so there a pay-back period where you start to gain. Yes the fact that there is no flicker either ...

R: So that's all standard equipment, would all these ... all these different options here have got to go into the different bodies, and they have all got to take the different options ...

S1: ... we've got quite a big range. So you see they are looking for about 10% effectively.

R: So that's by ...

S1: Well it's probably achievable in ... the aim here is to, particularly in the exposed 'T' version, to make a slightly simpler body than the present one. That's one way to save some money on ...

R: It says 'removing some of the extra features of the quatro', so it's a sort of simpler ...

S1: Well it's not always as straight forward as you think, sometimes you remove one bit, if you're not careful you can start creating something else. I think what Derek's done has shown a decrease ...

S2: Yes, were on the right side of the price range ...

R: I suppose the dropping of the air handling versions of the panels ...

S1: I don't think that ... This 10% if you like is, in fact, any particular combination that you are likely to mix up. Say 'that one, that costs so and so now, it wants to 10% less in it's new design, for market value. We can forget the air handling frame because it's probably going to be dropped anyway. The fact that there are air slots in the back of the body doesn't make any difference to the cost, it's as it was and as it is really, that's a constant. It's more to do with it's ease of manufacture, how complicated it is.

That's really a list of the possible combinations.

S1: That's the possible combinations, I think some of them will get dropped, there are far too many.

R: Are the ones with two stars the most important ones?

S2: No it's the finishing on the louver ...

S1: Do you know what we mean by specula and semi- specula? Specula means like a mirror, ad semi-specula means like a brillo pad over it. It scatters light. Linear tube only, well that's the conventional fluorescent lamp with a connection at each end, the other type would be the new lamps, which are like a hair-pin shape, with all the contacts at one end.

R: So what sort of ... when you've taken into account all the things you've got to consider while you are producing the design, from looking at that brief, could you say roughly how each thing contributed to the time it would take to design?

S2: It's very difficult to put times on these things ...

S1: You mean in terms of lump ... if it takes ... it took a total time from start to finish, what you're looking to do is to divide that time up ...

R: No not so much that, but say you were going to design a light fitting with one type of louver, a basic light fitting with one type of louver, one type of box to fit in to one type of ceiling, with one type of control gear, and then you add on the extra options, you say 'well, if we're going to put it into four types of ceiling instead of one type of ceiling, that will take say an extra 20% of time' or something, could you do that?

S1: A percentage increase in time?

S2: I don't think I could ...

S1: You could easily be talking of 100% extra really, compared to a very simple one off fitting if you like. Were talking theoretically here, as if we're starting from scratch, just a fitting we've never seen before ... if it was recessed into one particular ceiling, to make it recess into all the other ceilings, it could even be a factor of four in terms of time. It sort of mushrooms out ... I'm thinking of Derek's specials ... often you find that it's just one version is a nuisance which is making all the others have to be slightly different, but you've got to do it to complete a range ...

R: Like 20% of your causes causing 80% of your problems ...

S2: Yes, I wouldn't disagree with that.

R: So how long has this been going on for now?

S2: Well we're ten months into this one, but we haven't worked on it ...

R: No ...

S2: We've had to drop it for other things going on. In fact that suggests we've been on it a lot longer.

S1: We've probably not worked on it full time for more than about five months ...

S2: We started in February '92 ...

R: So it's three and a half months.

S1: That's about what's been on it at the moment I suppose, yes, I guess ...

S2: I say we're ten months into the project actually, this must have been written ...

R: Right so ...

S1: So what you're implying is that there's another two to three months to go ...

R: So you are at the stage where you've got working prototypes at the test house.

S1: We've got this meeting tomorrow, which is partly to look at these prototypes, so we are at a fairly advanced stage now. It's only a question of things that could spoil it are that the photometric tests are not favourable on some of them, or it's decided that changes need to be made because of that.

R: This category one thing might be a problem you were saying ...

S1: Well, yes that could be, but it could be that the louvers we made on existing tooling to do the other jobs don't ... maybe ... let's say for example the one that's been done for that category turns out when we test it not to meet it, where it does at the moment as it's the tooling that it's made from, when we put into this new shape it doesn't do it for some reason, so we've got to start fiddling around, which in turn could cause other things to change.

R: So you might have to go round the cycle again.

S1: Might have to yes, that's possible. Some things have a knock on effect on others.

R: So you ... I suppose you would be more confident with using louvers you know work on one model, rather than designing new louvers, you'll be more confident that it will get through the test ...

S1: Yes, the thing is, what we're trying to do is make them look like new louvers, even though they are made with existing tooling ... so they have got certain requirements which today's market is specifically asking for. Certain aesthetic things, which when that was conceived weren't so important. We want to be able to present them to the trade as a new product, even though it might be made on existing tooling.

S2: Maybe at the end of the day we will have to move away from some existing tooling.

R: And that would add a sizeable chunk on to the development time, and cost.

S1: The problem is that a company the size of Thorn, we can't really get away with things that a little tiny outfit will do. We can't stick two fingers in the air and say that this is what we're going to do. We would be expected to put a product on the market which if we said it would do a so and so job, it really would need to do it, otherwise we can get into all sorts of problems. Especially as how we've got people who sit on all these committees and write half these reports ... It makes a bit of a nonsense if your own products don't even meet those things. I think that we would be duty bound to fall within a certain frame on these things, and that's why in the event that those things won't work we may have to back round the circuit again.

R: So you've got to maintain your reputation for being able to deliver a good product.

S1: Yes.

R: So from this project meeting tomorrow you go on to ... if all the tests turn out to be okay, do you go on to pre-production run, or final design or what?

S1: I guess in an ideal world if everything was okay tomorrow, you go from there to production ...

S2: A this point in time there's still a bit of controversy on the tooling, we've got the existing tooling, it's a matter of releasing it for use on this project. That's got to be resolved too.

R: The tooling is already being used by another product.

S2: It's being used by another product, yes, so that's got to be resolved. The prototypes tat we've made for this meeting have shown problems to ourselves that we've got to address after the meeting.

R: Manufacturing problems, or lighting problems, or ...

S2: Well a visual problem, mechanical problems. They look good on paper, but when you try them they are not working as well.

S1: You see, although this is a thing which recesses into a ceiling, you still see certain elements of it, what tends to happen on jobs, is that when these things are bought, they are often bought by ... they get several manufacturers to lay them out and look at them. If one is particularly better made than others, or worse made than others, it tends to show up, so that side of it is important as well. There isn't a great scope for aesthetics, although there is some in a recess fitting, more perhaps than a lot of people think. That is important, you have to address it as well as the optical performance of it, it's got to look nice as a fitting as well.

S2: I feel tomorrow's meeting is going to discuss the optical side. Assuming it's okay, what we're looking for is the agreement on the mechanical side, it's to do with strengths of materials, on paper it's a bit of guess work. When you make them you realise you need to change shapes, make things thicker, and we're going through that stage now.

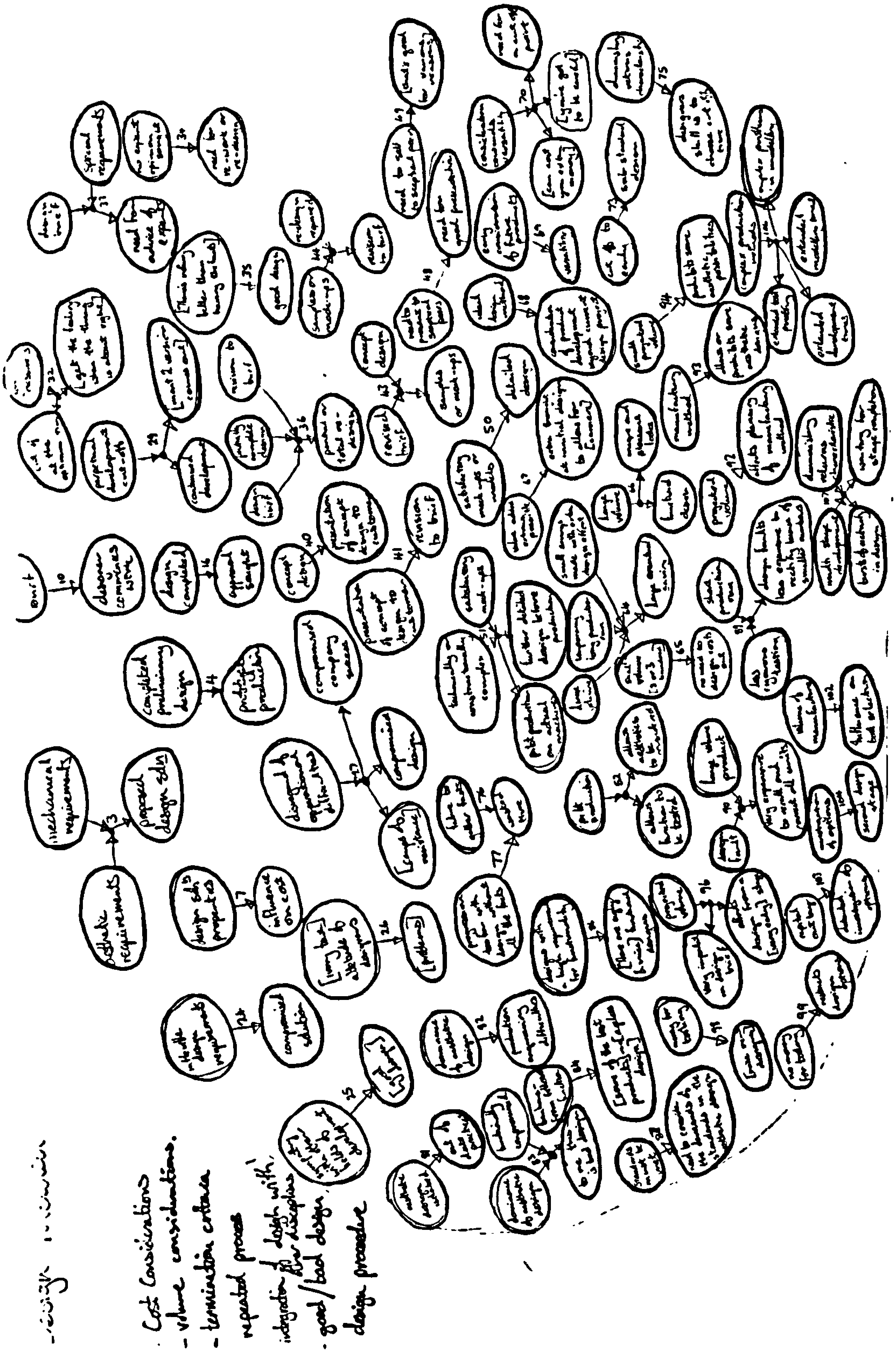
R: Right, I think that's pretty useful ...

S2: What I can give you if it's any help Is I can give you a set of reference drawings on this project.

Transcript ends.

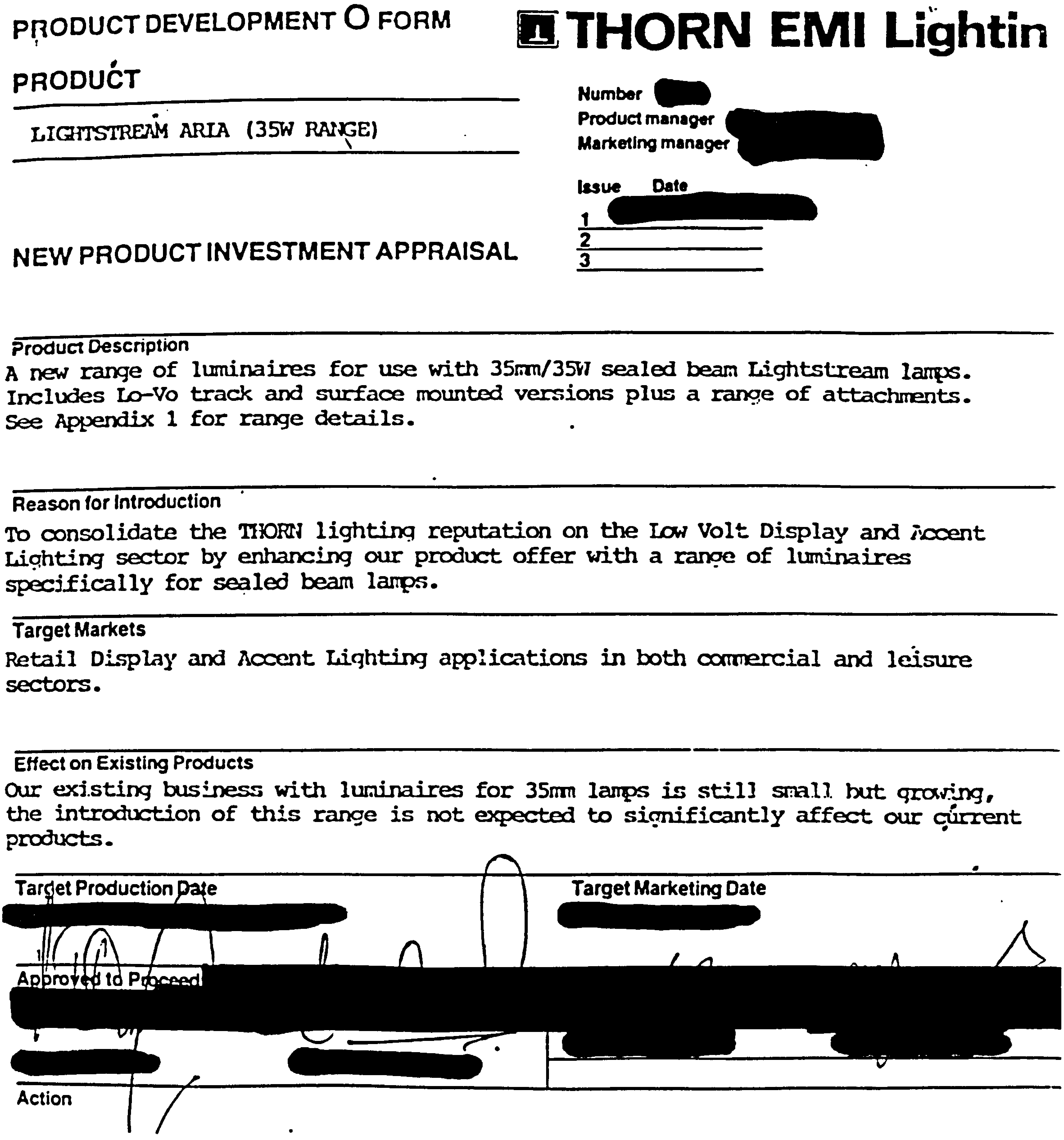
Appendix C

Illustration of a hand drawn bubble diagram.
Developed from and interview with a Design Manager at Thorn Lighting, 8th May 1992.



Appendix D

Example of a document copied during a case study.
Project origination ('O') form from Thorn Lighting.
Details blanked to preserve confidentiality.
Copied March 1991.



PRODUCT DEVELOPMENT O FORM

THORN EMI Lightin

PRODUCT

LIGHTSTREAM ARIA (35W RANGE)

Number [redacted]
Product manager [redacted]
Marketing manager

Issue Date
1 [redacted]
2
3

NEW PRODUCT INVESTMENT APPRAISAL

Product Description

A new range of luminaires for use with 35mm/35W sealed beam Lightstream lamps. Includes Lo-Vo track and surface mounted versions plus a range of attachments. See Appendix 1 for range details.

Reason for Introduction

To consolidate the THORN lighting reputation on the Low Volt Display and Accent Lighting sector by enhancing our product offer with a range of luminaires specifically for sealed beam lamps.

Target Markets

Retail Display and Accent Lighting applications in both commercial and leisure sectors.

Effect on Existing Products

Our existing business with luminaires for 35mm lamps is still small but growing, the introduction of this range is not expected to significantly affect our current products.

Target Production Date [redacted]

Target Marketing Date [redacted]

Approved to Proceed [redacted]

[redacted] [redacted] [redacted] [redacted]

Action

Appendix E(i)

File: I12405SD
Transcript of a model generation interview.
From Michell Bearings.
24th May 1992.

S1: Chief draughtsman for land based projects
S2: Chief draughtsman for marine projects
R: Interviewer

Transcript follows:

S1: We both have the same job, basically. I'm chief draughtsman for bearings for industrial applications, land based. David holds the same position for marine applications, on board vessels.

R: So, most of you work comes in through tenders, it's mostly engineer to order?

S2: Yes, definitely, we don't make to stock.

R: And the repairs side is dealt with in the workshop?

S2: Yes, mostly. The repairs are stuff that we've made already so the drawings normally exist. Sometimes we get awkward bits of alteration work, or modification work, but it's few and far between. It's not really relevant.

R: Obviously, since this is a sales managers office, there are people who go out and try and get orders through a selling process ...

S1: The way the company works is, they go out chasing, or sometimes customers just come to us, and work filters through from the sales office to our office. So customers would come to the sales office with enquiries, if there was any drawing or design work content in that, they would then pass that information to our office, and the same with orders.

R: And for almost all your orders you will have had to put a tender in?

S1: Not always, but on large contracts yes.

R: The tender would include an arrangement drawing ...

S2: It would be computer documents [technical calculations], price, terms and conditions.

R: So you would work through say - what you see as the technical difficulties, oil temperature changes and such like ...

S2: Yes.

R: Right, so who works on the tenders?

S1: In our office?

R: Yes.

S1: The design draughtsmen.

R: And that would be the design draughtsman that job would eventually go on to ...

S2: Ideally, yes, but not always, sometimes it's just that it's a time in the sequence when that just doesn't happen. But ideally the same man who works on a tender would work on it if it became an order.

R: And that comes down to you, who works out the tender, or is it ...

S1: Yes.

R: And I suppose the deadline for the tender is whatever the enquiring company ...

S2: Yes, when he requires his price basically. I mean some times it's unrealistic, and he says he wants a price for a totally new design, and he wants it tomorrow dinner time, we might ask for an extension, but basically it's to suit the customers requirements. Obviously we try and hit his deadline, because we're aware that the competition are trying to hit the deadline as well.

R: When you've won the order ... if and when you win the order, does that go through the sales office and then on to you?

S2: It would still go through the sales office.

R: Then you have a project deadline. How do the various departments work how long their work will take up to the deadline.

S1: We have a system called the 'work-to' system, which is basically a piece of paper, which says the order consists of so many bearings and the customer wants it by so and so date, and each department involved puts down a date on that piece of paper, and hopefully the date at the end of the day after it's been round each department involved, meets the delivery date that the customer wants.

R: Yes ...

S2: It goes through the ... the departments are sequenced in the order in which the work would go through the factory really. So it starts with the drawing office, and then goes on to purchasing, and patterns, and right the way through, so we all put individual times down for what we think it's going to take our department to do the job, and at the end of the day the time should match up with when the customer delivery is.

R: Right, and is there some negotiation goes on in this process?

S1: We don't always ... yes there is. I mean, sometimes we have to juggle ... 'can you cut a couple of days here?' or 'can you get it out any earlier?' We often issue advance information, to order patterns to be made ...

R: Long lead time items ...

S1: The design office in this company gives the authority to order all the different components. We decide on the materials, we decide on what the pattern shapes are going to be. Once we've decided that we can give the information to the purchasing department. We often short cut the ... no we don't short cut it, we have alternative procedures to get information out early - within the bounds of the law [laughter].

R: So you know that you've got to work on the long lead-time items first?

S1: Yes.

R: Say if you've got a casing which has never been made before, that would influence the time you would put down on the work-to document, ...

S1: Yes.

R: What other sorts of things ...

S1: Availability of labour, certain people are more reliable than others, obviously some people have been here a lot longer than others so they can do jobs more quickly, more efficiently. Depending on who I would want to do a particular job ... when a certain kind of bearing came in I would have in mind, who, ideally I would want to put onto that.

R: Right. So you know ...

S1: I know roughly how long it will take when some people can do the job quicker than other people, and it's really that sort of thing.

R: And some of the ...

S1: It's technical content, there's labour considerations, there's material pressures, as you say the casing, all that influences the time and the way we work.

R: You might have some tight tolerances ...

S1: Well, that's not really that important ...

R: Right. Performance calculations, do you produce any documentation in this department?

S1: Yes. Performance calculations, how hot the bearing's going to be, what the power loss is going to be, stress calculations on components that are rolling.

R: Right, and that ...

S1: Some of which is passed to the customer, some of which isn't.

R: Right.

S2: We also produce a list of parts, which make up the order, which is separate from the drawings. A parts list.

R: The, if the customer required some special documentation, would you take that into account in the design time? Do you do things like that?

S2: Yes, I suppose we would if it was something ... then you'd probably take the run-outs into account, which can take several days.

S1: Generally, most of the calculations we have to do take 15 to 20 minutes on a computer, which out of the total time to do the job is not a lot, but if there's hundreds, which some times happens, then yes we would. But that's not really an everyday occurrence.

R: And you get your information on labour ... well, you know the people and you know when they're going to be taking their holidays.

S1: Well there's knowing what any person is doing at any one time. So if you take a two week break or you go away on business and you come back, then you've got to spend a little more time just getting everyone back into your brain.

R: What sort of unknowns are there that crop up when you're looking at the work - too document?

S2: Changes in specification, the customer will often let us know, he'll get on and say 'by the way we've doubled the load,' or, 'it has to run at a different speed for X number of minutes.' Material availability, we've an idea that we'd like to make it out of cast iron, but it's going to take X number of weeks to get a pattern, then we might make it out of steel. Those sorts of things, but hopefully we can take them into consideration early on.

R: How early, in comparison with the rest of the people who produce an estimate for the work-to document, do you have to do it?

S2: The first ...

R: You're the first to do it, and the work-to document would usually take how long to produce?

S2: To actually do our bit?

R: For you to do it, and for everybody to do it?

S1: The time to do this can probably vary for my part from fifteen minutes, to two hours, to do one, depending upon what kind of job it is. That's the complexity of the job. And I suspect it's the same for the other departments. But the actual time that it takes to circulate round could be a week, because I might have it and haven't got time to look at it for a day, that could go on.

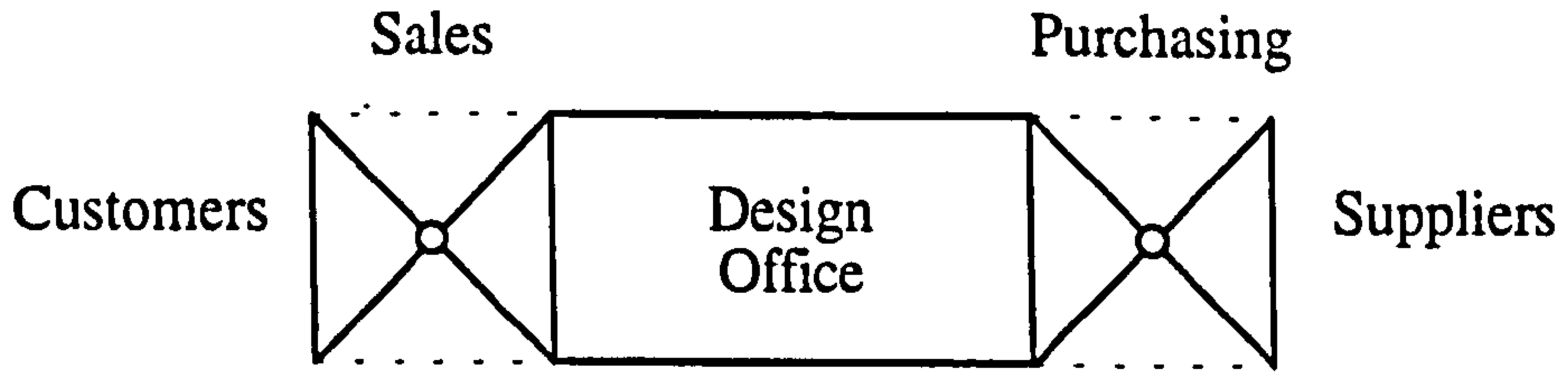
R: Every body could have a busy day, so it only gets passed on every two days or so. What goes wrong, other than changes in specification, with your estimates? I suppose you get sickness with staff and so on.

S2: Different priorities, another job may come in that's far more important, and you've got to take that man off that job and give him some other one to do.

S1: If you're working on tenders ...

S2: You're working at the same time as you're doing all this ...

S1: ... and orders at the same time, so you've got to continue chopping and changing. Sometimes you have to change things because the material you want is scant, or the forgings are made to the wrong size, and you re-draw the various parts rather than re-order the forgings because of the long lead times. The design department have to give the authority for all bought out parts and materials. It's order driven supplying with up to six weeks lead times. Sales and purchasing are a focus for the company (sketches on paper - see below). The purchasing for one project is done through one person to many suppliers and the sales is the same.



R: You said that sometimes you have to go away on business. That gets planned does it?

S2: People can still work when you're not here.

S1: You can find that you might be er ... I would say that the most notice you'd get that you were going away on business is a week. The other week I got about three hours notice! So that kind of thing can happen. But you wouldn't generally get more than a weeks notice. It wouldn't be something that you can plan. At the end of the day, even when you're not there somebody will be running the section or whatever.

R: Yes.

S2: The work will still progress even if we're not here to keep an eye on it.

R: Sorry, you were saying some of the problems you get with the work-to ...

S2: As I said, the more important job coming in on a shorter delivery date and you've got to pull the man off. Also, enquiries, the draughtsmen don't just get one order to do, they're working on enquiries at the same time, so I'll come up and say, 'look I want you to stop what you're doing for a couple of days and do this enquiry.' That happens.

R: So the enquiry can take quite a while to do I imagine ...

S2: Yes. It would depend upon the complexity of the enquiry.

R: Yes. If you had a complex enquiry, I know that quite often if there are two bearings in a job you'll give one to one designer and one to another, would you do that with an enquiry, or not.

S1: I doubt it, depending upon how much time you've got to get it done. More than likely one person would do one enquiry.

R: I suppose if it was a valuable order and the tender had to be out. Would you say that the deadlines to quote by have a higher priority than the deadlines to finish actual drawing work?

S2: For an order you mean?

S1: No. Not necessarily, because often we don't get to know what those deadlines are for tender. We just get to know whether an enquiry is urgent or not. A lot of the time every tender is marked urgent, so how do you decide? What we have to do is go to the sales department, go to the sales manager and get a priority list, 'which one do you want to work on first,' and get a list of one to six which you have to work on first.

S2: The ones that you've got the best chance of getting the orders for, you know ...

R: Right ...

S2: The priority.

S1: It gives the value, whether he thinks we've got a good chance of getting it ...

S2: The previous customer history, have we got a history of doing business with these people, or have we never supplied a bearing to them before ...

R: If you have a history of tendering for them and never getting anywhere.

S2: Never getting an order, exactly. Some people use us for the pricing basis, and that's all they use us for.

S1: At the end of the day when you put a date, and you have to sign something, they've got a date from you and you've got to meet that. The whole work is scheduled through the factory by that, which is reviewed and looked at by the production director. I'm under an obligation to try and meet that much more stringently than if something has 'urgent' across the top.

R: That's still vague isn't it. Looking through the order book, unless there's some thing like 'waiting for customer specification,' things like that, you're quite often almost dead on with completion times. Do you find that the draughtsmen might work up to the deadline?

S1: I don't know. But having said that, it's very unusual for them to be working on that one order full time. I'm quite convinced that if you say 'okay, I'm going to ...' What I try to do is allow as much time as I think I can afford in the drawing office, but still meet the requirements for all the other departments as well. So I'm first on the list.

so once in a while they'll come back and say 'look we're going to have to change that date,' or 'do you think you could manage to cut that time down a little bit?' ...

R: Or 'can you release these parts ...'

S1: But if that doesn't happen then I've got to say he's happy with it. I'm not going to put down ... if I think I can get that job out there and then in a week, but I'm putting myself under a little bit of pressure then I'm not going to do that, I'm going to put down two weeks, then I know I can definitely get it out. But if nobody comes and says 'that time's too long' I say fine, but I'm not going to commit myself to a tight delivery before I've committed myself to a longer delivery. It's like bartering for something you want from a street trader, you're not going to offer the price that you can afford, you're going to offer something much lower first. And maybe you will get it for that price.

R: So you've got your ideal time and your fall back.

S1: Yes, but I'm not going to give them a simple job that I know definitely they can do quite easily in a week, and give them four weeks to do it. I'm not doing it just to give the draughtsman an easy ride, it's a happy medium.

R: But I suppose that if you allow some ...

S1: If there's time in there, most of the time they're working.

R: Also they could be working on tender jobs and such ...

S1: Yes. I know when I put a time down I think 'oh yes, that's it, that's quite easy for that one.'

R: So you carry around with you in your head what jobs which draughtsmen are doing, and also how many tenders they are looking at. Almost the total workload for the various draughtsmen.

S1: Yes.

R: Thank you.

Transcript ends.

Appendix E(ii)

File: I10805BT

Transcript of a model generation interview.

From Thorn Lighting.

8th May 1992.

S: Chief Designer

R: Interviewer

Transcript follows:

S: Some work I have done has been direct catalogue products, which maybe have some similarities to some of the stuff we've done with project work, again because often we're feeling the market for these things, making sense of what is needed. Our marketing department find that quite useful as well.

R: There's no better way of finding out what the customer want's as when they're telling you what they want is there?

S: That's right yes.

R: So, you do sort of industrial design for the projects, so you're working on the shape and the where it's going, the specifications of it.

S: Yes, if it's for a particular job then usually it would be, sort of, co-ordinated work if you like, possibly with an architect. Some times architects have more input than us, sometimes they will have zero input, in which case we do all the design work. Other cases they say 'it must look like so and so because it has to fit in to this type of building'. So one would have to take that sort of requirement on board, then you start off with early meetings where effectively form a brief. It's a practical brief in a sense, and then we would then come up with a design which we think is technically correct and suits there aesthetic requirements, and any other mechanical requirements. Then it would go to prototypes, then hopefully orders. Again there's no set pattern to this, there may be three companies involved, deliberately they will have three companies all doing the same thing, and pick a winner from the results.

R: Like a tendering situation.

S: Well it is then, it is a tendering situation, then the design aspect can be also linked to cost as well, so although you might have the most beautiful looking thing, you won't necessarily get the order if it's too expensive. It looks nice but it's difficult to use, and one of the others has a feature that appeals to them. I that sense it's perhaps more practically orientated. If it's standard products then of course we generate a marketing brief, the Marketing department generate a brief, usually following meetings with various people, including people such as myself, then the brief would be given to the initial designer, and it would be started then.

R: Are the marketing department involved with the custom made stuff?

S: No.

R: That goes straight to you.

S: They have no function in that at all, it would be unnecessary. It's a much faster track, working on projects in that sense, because you've usually got a building going up, and there's a time scale, and you've got to hit these times, and there's no slack on it. Whereas if it's a standard product and something goes wrong, well okay it goes back, and you just loose you're market for that time. You've got away with it.

R: So do you lay down a strict schedule, because I know marketing lay down schedules for the development of the standard product lines. Do you lay down a schedule for the custom stuff?

S: Yes, there has to be a date. What would happen, following the meeting, which I suppose in a way is not unlike a marketing brief meeting, but following the meeting with an architect or whatever they may be, it will be agreed that you will go back to them within possibly three weeks, four weeks, maybe even shorter, with initial designs to look at, and then fine tune the things until you get it to what's wanted. But yes there will always be a time scale. There has to be. Similarly, once the design is agreed, then there will be a time scale set for the prototypes to be looked at, analysed, changed, and maybe there will be a second bite because the thing needs changing, take it away and do it again. Hopefully in the custom product you have a product they say 'yes we like it, okay, go', and similarly with a standard product you would have a situation where they say 'right that's it, stop it there, now we'll engineer it and put it into production.'

R: So often you've got a certain amount of time of design, you work up to a certain point with the design and you could go on a do more but you've met your deadline.

S: No, that's quite important. That's a similar scenario to our laboratories, if you ask them to, say, develop you a reflector to do a particular job. If you just leave them, they will carry on for ever developing it, perfecting and perfecting it. There's got to be a point when you say 'right that's it, enough, adequate, we'll take it there', so in the same way, when - and this would all of course be part of the design process, because in the English language design is a funny word, it means different things to different people, perhaps you and I consider it to be more to do with the aesthetic function, but there are people here who consider design to be purely developing the contours of a reflector, irrespective of what it's going to fit in to. As part of a development programme of a product, for example, the optical side of it will be developed in the laboratory, there will need to be technicians working on it to establish a particular shape, and that could be that you have to stand back for a while and wait for that to happen before you can finalise the shape of it, or the exact shape, because you might - this is often the failure of some designers, if it's too aesthetically dominated. They say 'it must fit in there' and you finish up, you can finish up with a compromise. I think a really good designer is one that can have a sympathy with all these other fields, and be prepared to modify the aesthetics to accommodate the practical needs.

R: The aesthetic designers have got to have a feel for the practicalities of the object, so if this light is going to produce this much heat, therefore we need this much space.

S: I know that we have had problems in the past with chaps who have an ivory tower attitude and they just regard people in the laboratory like scum -

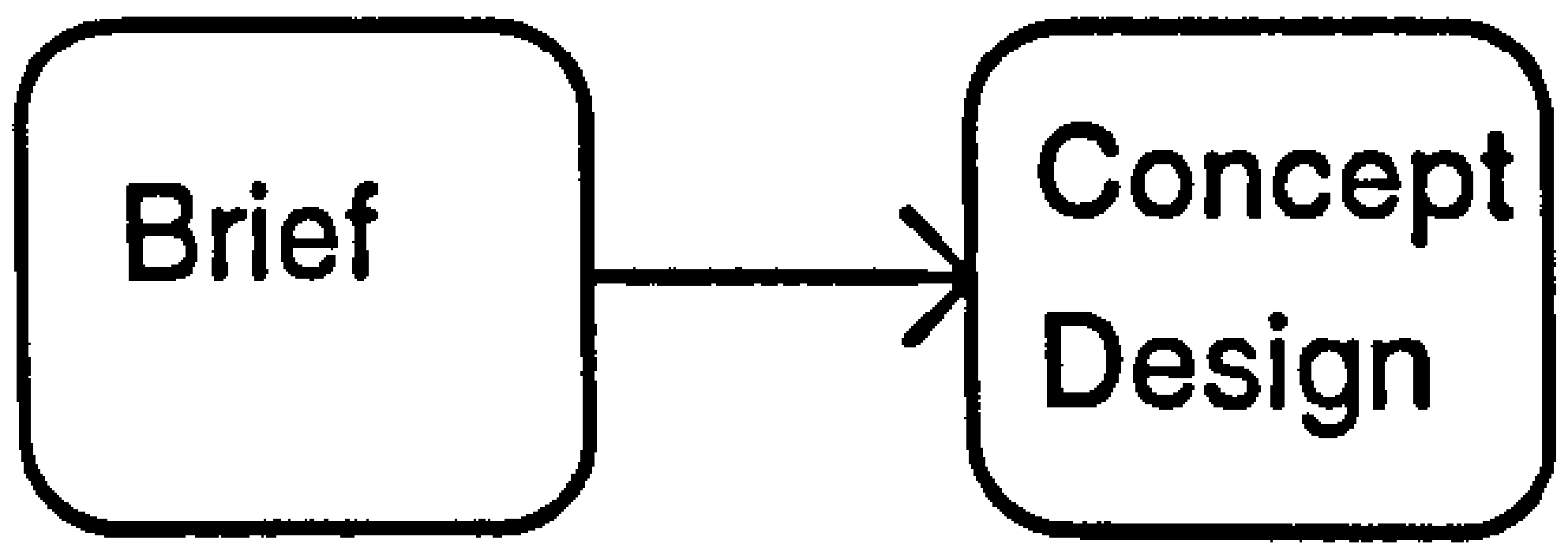
R: 'Make it work ...'

S: Don't bother with why it won't work. What happens there is you get little battles developing, camps of resistance. That's not good because in the end the company suffers, in that sense if the product suffers, refuse to compromise in some way or another. So I think that's quite important.

R: Do you find a problem with designers wanting to design on and on with the same project.

S: Yes, you can keep on improving something, and often in reality what happens is that you stop it at one point and go to production. This happens with everything doesn't it, cars and so on, then development goes on afterwards and a mark 2 version comes out. Perhaps it's quite important when that decision is taken, as when to stop and let the further work go to the mark 2 version, because if you stop it too soon you can bring a product out that is not fully thought out, and that gets you a bad name in the market. If you leave it too long your competitors can move in with something and loose the market. Again the designer has a good role to play there, if he understands what the thing is going to be used for, he'll get the feeling of when the thing is about right and then say to stop it, any further work you can leave for a bit later, add-on goodies or further variations.

R: You mentioned that you sometimes end up waiting for another department, say to do some testing, or the labs to put a reflector together. Is the design process that you run for the custom job a sequence or different aspects go on at different times. So if I were to draw it



R: You get you're design brief. Would it be straight in to concept design?

S: Yes you could have a little intermediate stage there, if there was some funny requirements that need some input from say laboratories, even in the sense of talking to an optical expert or something like that. It would worth knowing that information before you jump to the concept design, because if you're not careful you can forget about it and you find that you've then got to do it again. It gives you two bites of that.

R: So that would be sort of expert data or standards,

S: There's nothing better than having the facts, I think that's very important, because I've done it, and no doubt you've done it, you've gone in to something and suddenly realised that there's another factor to it that you didn't know about. It again happens on the custom design stuff. You can look at it as a sort of microcosm of what happens in the real big developments, often you get a requirement for something, you work away and you come to an idea. You think 'Ah we've decided to change the ceiling or change the furniture' then of course it's pulled the rug from under you and you've got to start again, or start large lumps of it all over again. That's another element is designing light fixtures that go on to furniture, I mean office furniture. If you beaver away on a particular design for one make of furniture and the client decides to change it then you've got to rethink it again. In that case it's not your fault that you haven't got all the information.

R: In that situation you would probably overrun.

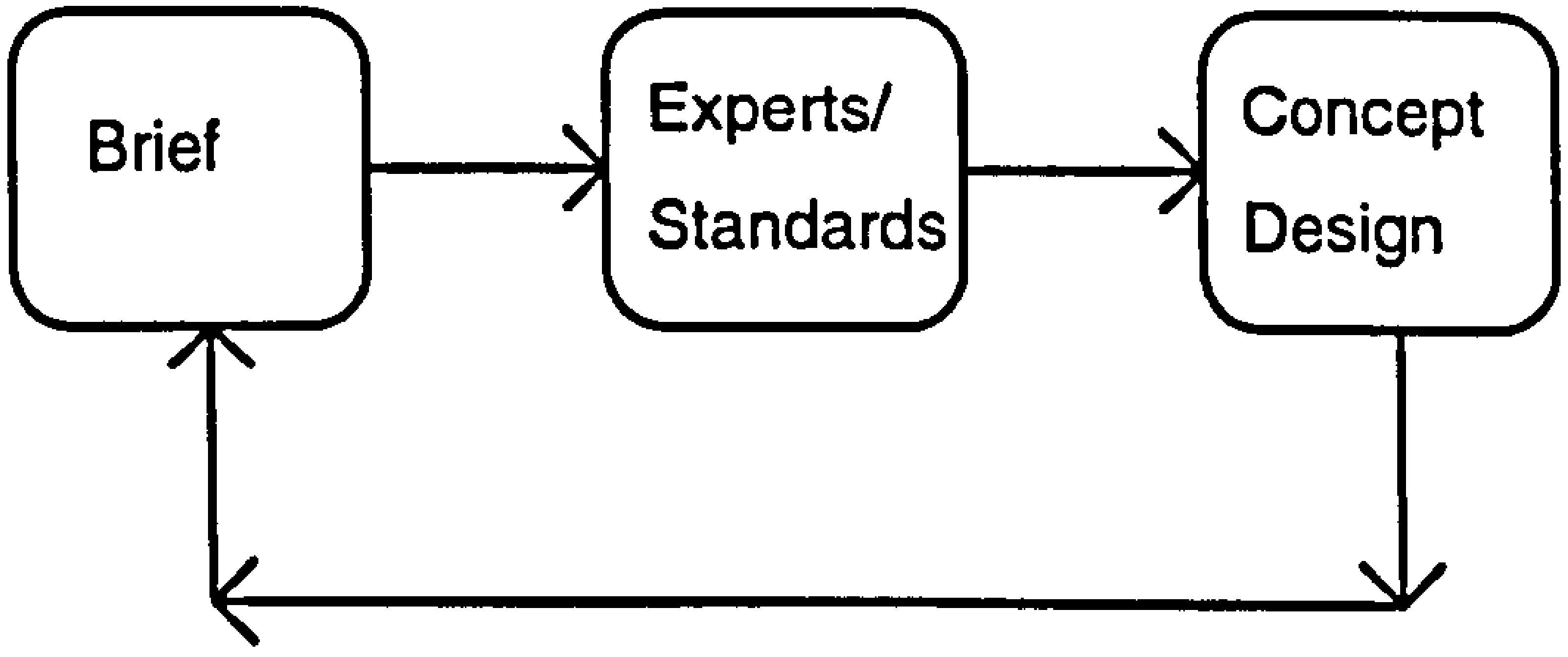
S: You could overrun, because you've wasted time, things could happen again on the standard product in as much as we had it ourselves about eight years ago we developed a new line of light fittings, and they decided at the factory to invest in new machinery. These things had all been designed to be made on the old brake presses and that sort of thing, and they bought this new machine, the Salvagnini, it meant that some of the things couldn't be the way they were, or if they were it would be uneconomical. Whilst most of that wasn't aesthetic design it did involve certain mechanical elements being changed. If you like, time was wasted there. Those that worked on it didn't know that the Salvagnini was coming, the decision hadn't been taken at board level, so they had no idea, you just have to grin and bear that. So you will get hiccups along the way, and that's the real world. It is important to get all the facts if you can.

R: At this first stage.

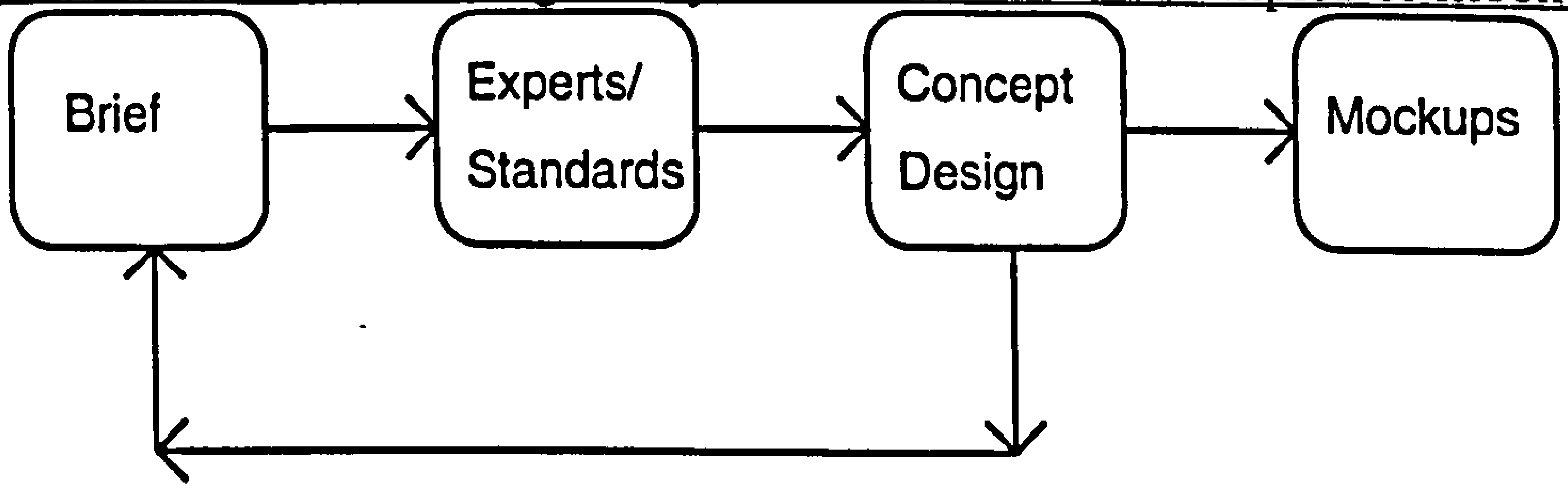
S: Then you would move on to a design concept, then often that concept is then presented. You then probably effectively go back to that panel there.

R: Back to the customer.

S: If you like customer or Marketing, however you like to think of it, it's effectively the same.



Following that there's either changes or you then move on to samples or mock-ups.



You can go back again to the beginning. Sometimes if the designer's got a brilliant idea that he thinks is something new, he could produce that in the mock-up, because of the need to present things to panels, usually however good your drawings are, whether they be paper, or on CAD or whatever, they never have the impact of a model, especially a working model. Even a timber model, or a model made of cardboard has much more impact. Often the sort of people you're looking at, be they marketing people or consultants or whatever, they often haven't got that feel that you can have as a designer. They don't appreciate things, but if they can pick it up and see it they can understand. They can understand drawings, but a sketch is something that is easy to change, you see 'oh I don't like that, we won't have it like that, do it differently.' you can argue then and it's difficult to put your point over, but sometimes if you do have a finished model you can say 'well if you look at it like that, that part is that shape because when look at it in this direction that's what you see' so the power a model is very important. I think also the power ... well the necessity of good presentation when people are sceptical, that can make a difference. You've effectively got to sell the design to your peers, who take a lot to be persuaded, that this is good for various reasons, be they customers or architects, or your own Marketing department, the directors of the company. That is quite important.

R: So from the mock-ups you do on to detailed design?

S: Yes, you probably would then, again depending on the type of product. Some products, if you were making it just in card or timber, a visual, if it was something a bit more detailed, say it was a light fixture that had a louver in it that had been worked out by the lab, almost certainly the drawing office here would run it through, and the model shop facility for it to be made as we would like to make it, say on the Salvagnini. It's pointless putting things in that you can't make or can only make at great expense. That would mean then that your sample could to see if the louver performed as you hoped it would do. It could be a louver in the ceiling where you have a particular light distribution that you want to achieve. At the same time you would consider the aesthetics.

R: You've said that the consequences for running on in standard product design aren't as severe as running over in custom design, what sort of things would you see as being the consequences as running over in custom design.

S: Well you can become very unpopular, it depends at what stage you ran over it, if you ran over it early on you would loose the job, if you had to design a fitting for three weeks time, the meeting was called, if you didn't present your proposals you would just get excluded. If it were further down the track after you had an order, then there is no hard and fast rule, but it could get legal if you were holding a building up. It could be something for transport use, we're doing lighting for trains and that sort of thing. If a manufacturer is building trains, working to a programme, he's got to have his lights to be able to go in at a certain time, if they're not there then we've held them up. You start to get these things called penalty clauses.

R: Right so you do include penalty clauses.

S: There can be yes, they are not automatically included.

R: Would you put a premium on the tendered price?

S: No.

R: You're confident of working to the dates.

S: If you did that you'd never get any work at all, it's very competitive, especially at the moment. You have got to hope that it doesn't happen. I don't remember it happening in the last ten years, we've managed it one way or another.

R: So do you finish in advance of the dates that you are given sometimes?

S: Yes we do sometimes, that is not part of the design programme. It doesn't necessarily benefit you to have the products earlier than you need then, because things get stored and damaged. Often they like to work to a programme, you may have read about the way they did the Canary Wharf, when they did that barges came in containing the stuff that they need for that day, and that's all that came on that barge, it saved having stuff lying about. That applied to things like modules, the whole wash rooms and offices were complete modules which came in and were craned up into position, as they wanted them - just in time stuff. They use JIT here on the factory for materials.

R: Right, I know about this time last year they were organising a lot of supplier conferences and things.

S: It doesn't always work for some things, but I guess the bigger the sausage machine you are the better it's going to work. What mucks it up is if you have to stop certain lines to run other things for some reason or another. I guess here it's just about worth it. It depends what lines they are doing, the things where a couple of million are produced a year, that's worth it. Again for how much design effort that goes into it, say for a batten fitting, a few fractions of a penny saved on something can make quite a difference over a long period, whereas if it was only two or three hundred you wouldn't bother to design things out.

R: You're putting more effort in than you are getting benefit out.

S: Yes, again that is a difficult thing. Styling is very limited on that obviously. So that will tend to have more a functional look, although it is important that it looks unique, pleasant. The styling features that are there are again add-ons, and it ceases to look like a batten, and starts to look like something else. You would bear that in mind when you did the initial design, to be able to incorporate carriers for things like that.

R: So you're almost thinking about your mark two's whilst you're doing your mark one's.

S: In an ideal world yes you would. You're trying to build in versatility, that's always a nice feature, but sometimes it can cost you extra money, you've got to be careful. To make everything all things to every man is sometimes very expensive. Again, there's a kind of a cut off point, you've got to decide what range of versatility do you in fact make the thing with.

R: You were saying that the labs will test and test on, or perhaps a designer would be able to sit and play with a design, work it out, keep getting better and better, almost indefinitely.

S: The graph usually is sort of a diminishing returns thing. What you've got to do is decide where to hit it. We'd probably hit it about there somewhere. If you use it too early then your product is not so good, too late and you've wasted time.

R: So part of your skill is to note or be able to pick out where that point is.

S: I think so yes. When you turned up this morning we were looking at a new design for a recessed fitting, what ceilings to use it in. They've done some initial looks here at it, but they haven't considered all the ceilings. That's what I was showing them, these extra ceilings, and they've perhaps not totally understood it. In effect they've not complied with that [the second stage of the design process], we're not talking of aesthetics, this is more mechanical design, but the law still applies in the same way. They haven't armed them selves with the facts, they've wasted time.

R: So they've gone on the concept design without thinking about the ...

S: They went too far. Okay we're fairly early down the track on this one, and what this is all about is going to the meeting which is coming up shortly. Never the less, now you've gone down that track - and they're having some samples made to take to the meeting - those samples haven't taken account of all the factors.

R: They're already out of date.

S: They could have been more up to date, so again we've wasted time. That's the pity.

R: When you get a brief in, would you say that you could predict the time to the optimum point [to cease design work].

S: I think you probably could, you wouldn't be thinking of it as a graph, because you just think of it as what you've got to do. In the standard product you would be talking quite heavily to Marketing, because you're looking at a launch date down the track somewhere.

R: But you've got a lot to divide up into your time. Perhaps Marketing developing the brief, then the aesthetic design, then model building, detailed design, production planning, pilot runs ...

S: I think aesthetic design should not be looked at as an island. That's an out of date concept. The stylist. You've read about the way the American auto industry worked, what happened for a while in Detroit, the stylist became ultra powerful, design these fantastic thinks with wings and chrome, then it was slung at the factory and they said get on and make it. They had all sorts of problems making all these wings and points, but usually it was only the skin, what went inside it was left to the engineers to work out, and was usually the same. Quite often the end user suffered by this. When you got out of the door you cracked you're brains out on the run back of the screen because that's how the stylist wanted it. To me that is bad design and those things should be looked at, keeping the appearance of it in mind all the time. You can make it be practical.

R: Almost Bauhaus really.

S: Yes, I think some of the best products that are around tend to have had that applied to them. The ageless designs that come up now and them.

R: So what sort of things would you be looking at in a design brief to give you a clue as to that time.

S: Well you would be looking at the extent of the products - I'll assume we're doing a range, a family. You would want to look at the extent of that family, how many items you're talking about. You would need to do a bit of checking up there, what could affect that time is what extent you need to involve others, such as laboratories, test houses. Now again it isn't laboratories looking at the light output things, we have to, suppose its a street lighting fitting. Now aesthetics and function are very closely linked on that, although there ugly and nice looking ones, it's function is very important. Someone has got to get up on a gantry on a windy day and service the thing. It's got to be electrically safe, and it mustn't fall apart. It has to be weather proof. When you do the design you will get to some stage where there will be samples made that are tested to see it the seals are correct, there are certain standards called IP ratings for things like jets, rain, dust. So your design has to be such that this can be easily incorporated. It's possible that if you were too heavily into the styling of it could become a nightmare to seal. Thinking of more simplistic shapes there. You could perhaps take some account of that.

R: So the level of functionality of the job ...

S: That could be applied to all sorts of things. If there was some other testing needed to make it electrically safe and so on. Obviously if it was a one only product, this is not so important, what you need to do is check that the control gear doesn't get beyond the heat that is supposed to operate at. If it does it will fail. If you're making half a dozen it doesn't matter so much. If you have a product of which you make thousands, and two years into it's life you have a problem come up, like on cars again, it gets expensive then. The level of test house input to these things would be dependent on the overall volume. Volume is another problem. Volume can lead you down all sorts of alleys. If the volume is high you can look at different ways of making it.

R: A sort of value analysis thing?

S: Pressure casting or injection mouldings become viable, because you're looking to spend lots of money on tooling, but not much time fiddling about with things to put it together. Castings and mouldings also lead you into certain aesthetic possibilities which would be difficult to achieve otherwise. I the volume is low, then you cant think down those sorts of lines, you have to think of things like extrusions with ends on and pressings, although even pressings can be expensive.

R: So you would be using the automatic tools like the Armada.

S: Yes the Armada would be used a lot on the shorter runs because of its ability to chop and change. Actually that business of volume comes in very early on, that's one of the leading features of a design brief. It's no good saying I want you to design a new Vauxhall Cavalier if there's only going to be ten of them! If it's 'X' hundred thousand a week then you know where you are.

R: I saw a few 'O' forms while I was here last year. The sort of things they've got in are value, expected market, expected unit cost.

S: With the design of products, and I guess that this is going to come up with all industrial products now, with the Europeanisation. You no longer think of what's good for just the UK, if you're going to be successful, and Britain is supposed to be an industrial nation, to survive you've got to export, therefore you're products have got to be good for the market. That as you know is where we fail and design has an input to that. Similarly we have no reputation for high aesthetic design. It's partly true, if you look at Italian cars they're really no different to anybody else's, apart from the exotica. The family car is no more heavily styled than it is from anywhere else. I've just come back from Hannover, and you can sense the pulse of the German economy there. There industry spans a very broad spectrum. There are some quite nice new designs there, somebody has spent some money on tooling to get castings matching to extrusions, linear and non linear, suspended ceilings. That's something that we have to address in this country is this reluctance to spend money on tooling. Trying to make do and mend.

R: The financiers in Britain tend to work on a three year investment cycle, whereas in Germany it's longer.

S: And Japan as well, that's one of the killers of a lot of our industry. We find it here in the same way. We had the Salvagnini in here, but I'm sure our foreign competitors had them before us. So again as a designer if you come up with a standard product design that needs a bit of money, there are two ways of doing it. You can make do and mend, and get something that might get you by, or you can spend some money on tooling and get something that has unique features in it.

S: And that will go back again to the volume.

R: Yes volume, and your ability to persuade you're peers that you need to spend this money on tooling. They will always try and dissuade you from doing it, is there no cheaper way of doing it.

R: Marketing, might say 'well we didn't really mean those sales figures!'

S: That's right. The classic is this thing here. This was done for the British embassy in Bangladesh. I think we made two hundred of them. That shell is just hand laid up GRP. Because it looked a successful product we decided to put it in the range. It checked out thermally no problem. It was always on the Marketing file, should they spend money to tool that shell. If you make 200 or 200,000 it's always going to cost the same because it's so labour intensive. To this day they haven't made the decision to spend money on tooling that shell, and really they should have done. If it was fully tooled it would be a lot better. We may be doing it actually because Finland want to take a lot of them, we're a pan European company now. The tendency is that the Marketing departments stuff their catalogues with each others products if they can because it makes them look nice and big and impressive. It means that half the stuff is not stocked in this country, its got to come in from France or wherever. I guess everybody does that. It's this presentation thing. Yes tooling is quite important, that is linked to volume, that again is linked to the second design stage, because you might want to do more investigation. If you're going to spend lots of money on expensive tools you want to get it right. I can remember us making mistakes and tooling things too soon.

R: It also extends the development cycle, say if you're doing injection moulding you may want to do mould flow analysis, which could take a while. You will want to test the components and certify the tool so it increases the whole development cycle.

S: Yes it does. That is important. I guess that with mouldings the prototyping takes longer as well. It has to be more carefully modelled, more skilfully done. If it was a sheet metal component. It would be much easier to make a fully working model. With louvers, if you have things like spinnings they can be modelled, but it takes time. The diagram could have steps in it, because you might hold back until you have seen the model.

Transcript ends.

Appendix E(iii)

File: I10610IW
Transcript of a model generation interview.
From Labman Automation.
6th October 1993.

S: Design Manager
R: Interviewer

Transcript follows:

R: We're going to talk about time estimation.

S: Right.

R: First of all, is all the work you do made to order stuff? Is it all out to tender and things like that. Do you have to compete on tender, or do you go out chasing work, and then if you get the order, you don't actually have to tender, is it more sort of you've got a budget to work with to produce a robot?

S: Basically, yes. That's the way round. Rather than competing with any other companies particularly, the situation is usually that we're the only people who will do it, and provided our client is compatible with the budget, it's a go ahead.

R: Right, and you do a feasibility study?

S: That's right yes.

R: How is that costed?

S: It varies on the size, we're doing a £5,000 one for a water authority, and a £2,000 one for an Australian job. But those are quite unusual, it's usually about £1,000 - £1,200.

R: So it's a figure that would be within a departmental managers budget?

S: That's the idea yes.

R: Do you get all the information, when you've got the design to do while you're doing the feasibility study? Do you get it all at once or do you get it in trickles?

S: It tends to start off with a wad of information that the customer thinks we need. Then that is augmented by the information that we actually need. But that tends to be, as you say, in dribs and drabs.

R: So you go back to them with ...

S: Basically yes. There is quite a lot of to-ing and fro-ing during the feasibility phase, to ensure that the end result is compatible with what they actually need, rather than being some form of academic exercise.

R: Once you've got all your information from the feasibility study that would be enough for you to produce the final robot?

S: In theory yes, but inevitably there are little bits of pieces, that, although look great on the design study side, transpire, aren't that great when it comes down to the nuts and bolts end of the business. It can lead to quite marked problems, but usually at that point there is yet more discussion to try and deal with those problems. It's not fool proof, the design study, no where near. It just can not give the depth, not without doing the project before you start!

R: That's it! It's a chicken and egg situation. Once the design study is complete you can get changes in specification coming through as well.

S: That does happen yes. What a feasibility study tends to suggest is a set of potential different ways of doing areas, and gives a ball park cost figure for alternatives. What tends to happen is that the customer totally, beyond any reasonable way of our thinking, will come up with a whole new way of looking at it. What happens more often than not is that they come back with a completely re written spec., which some times is all for the best, but quite often there's a lot more avenues appear that were not instigated in the first place.

R: Do you find that once you've completed the design study, and come up with an approximate price, that they'll come back with a simpler problem, in order to try and cut the price, or they'll come back trying to solve more problems than they were originally because they've been pleasantly supprised?

S: It can go either way. Quite often what happens is, the complexity from the design study through to the physical machine tends to diminish. We tend to find that what they had thought was a major benefit that they wanted, was actually completely unnecessary, and it ends up being scrapped. It dropping out of the frame makes the whole job a lot easier. That happens a lot. On the other hand, there are those projects which you launch into that you originally think are quite straight forward, and as you dig deeper into the subject the customer starts to change the goal posts. That can be quite an irritation. As they seek more and more flexibility perhaps, they have weird and wonderful ideas over the weekend and say 'we want this, we want that', when we've already committed to some system that just can't handle that. You get a bit of both. The former is the more frequent case. The latter we try to avoid. But unfortunately we have them.

R: I suppose, in order to cost the design report, you have to do some estimation of how long you're looking at for development times and production times in order to give a budget.

S: Yes.

R: So that is all based on the information you get all at once, and in a trickle.

S: Yes.

R: In the written brief what sort of things do you take into account when you're looking at that?

S: We break down the system in to handle-able components, and each of these components we look at from the point of view of uniqueness and complexity, which some times go hand in hand, and sometimes don't. From that we give it a weighting, and much more time and effort is allocated to those areas with higher rating. For instance, if we've done a de-capper, and a similar system comes up which needs a de-capper, but a few of the parts are changed than we'll keep roughly to the proven time and cost details from the original de-capper, with a very very small element of re-design and, if you like, risk, because it's a repeated feature. Other things that are completely unique then we've got to really cover ourselves, and no matter how much we sit there and say 'we can do that in two weeks, we can do this in three weeks', it always ends up with four, five, six weeks. That's our approach.

R: So you break things down into what you've done before, how close it's going to be to something you've done before, and then also you look at the units that you've never had to tackle before, and put your finger in the air and allow quite a large margin.

S: That's right. We try as far as feasibly possible, without doing too much work up front, because obviously this part of it is relatively lowly paid so we don't want to put massive effort into it, we try if feasibly possible, to come up with different scenarios for the complicated ones, three different potential ways of doing it, and choose the most expensive one of those which is feasible to go forward as the first choice, just to cover ourselves. It can actually turn out to be the best way of doing it! [laughter].

S: The units that you haven't done before, would you quite often find that your budget was out. Those do suffer from the highest degree of fluctuation. I would say that it's luck and a prayer that they actually come in on budget. Some are lovely and grossly under budget, where you look at a problem and think 'how could we possibly have considered this to be that unique and difficult when it actually isn't', and it's solved in a relatively cheep way. Unfortunately in the real world that doesn't happen to often. The majority of the time it turns into a bit of a beast. A lot more work and effort is pushed into that than has even been budgeted for in our system of inflating the figures.

R: So you would hope that the ones that turn out to be a dream can compensate for the ones that turn out to be a pig ...

S: That's the plan. Off the top off my head I would say that it will take a long time to work that way.

R: Yes you've got to do 200 projects before it starts to pay off ...[laughter]

S: Yes ...[laughter]

R: The ones that you've not tackled before, do they involve new technology, or technology that's new to you, or functional systems you haven't had to work with?

S: It tends to be technology that is new to us that really creates the headache. There's a kind of learning curve that you have to go through.

R: I suppose that would also create the difficulties with trying to estimate. If the technology's new to you then you've got no handle to get an estimate on how long it's going to take to prepare.

S: Quite. You can only go by the parameters of your existing knowledge. When it's beyond that you can only really stick your finger in the air I suppose [laughter].

R: Yes. Once you've done the design study, and there's been a budget agreed by the customer, do you prepare a strict time plan for the various parts of the design stage and manufacture stage?

S: Yes we do. We try as feasibly possible to timetable everything into it, i.e. major purchases, the work effort involved, and from that when it's a large project the customers like to come in and see it at relevant points. What we'll do is we'll build up a timetable whereby the customer can actually confirm that we've reached each stage.

R: Right.

S: Yes, we give them quite controls which we're going to work in.

R: Yes.

S: Unfortunately what happens is that these time frames are all well and good for the individual things involved, but what tends to happen is that when we've got no other work on, and this can make a bit of a mockery of the figures we produce, is that people who are not associated with the project, because they've got no work, can be brought in on the project to do little side beneficial jobs to it, which can complicate things quite a lot. But that's the way of it, and if they weren't doing that they would be unproductive. It's a bit of a problem, but there you go.

R: So, the relevant people in your firm all know the time plan, and the customer as well knows the time plan.

S: That's right. Each project is run by a project manager, and it's really up to him to keep everybody buzzing on it.

R: And there's what, two project managers? You and Peter?

S: That's right yes.

R: And the time planning is done during the design study phase, or the detailed time plan, is that done after the budget has been approved?

S: The detailed time plan tends to be after the budget has been approved. Again it comes down to not really wanting to put work effort in if the thing is not going to come into fruition. For a start, the individuals involved don't really have the time to start doing things that might not come off.

R: But you'll find that in the design study phase that you're actually find that you're doing a small amount of design work. Arrangement drawings, and breaking the things down into units and so on.

S: That's right yes.

R: But none of the trying to fix dimensions and so on?

S: No. Overall dimensions certainly, but nothing detailed.

R: Yes. The influences on the time plan, would things like long lead time bought out parts, and labour and things and complexity?

S: Well, the start point really is organising the lead times for the major parts. They really dictate how we fitted the rest of the frame in. In the last project we did we had a six week wait for guide rails for the mechanics. That really lead to how much we could do physically in term of design and manufacture, without needing those rails. That was a major basis for when the project started in terms of manufacture, and where my job stopped, being pure design and turned into more of a feed to manufacture and the workshop.

R: I suppose you get problems with bought out parts, with them not tuning up and so on?

S: Yes, those things happen. You can guarantee on any one project that you're going to have at least one major purchasing catastrophe, and several minor ones. It's part and parcel of it.

R: You allow for that. I suppose you know which suppliers you might have trouble with?

S: Yes, over the years we've kept quite good records of our suppliers, and they're categorised under past performance, how well they have complied to the details of the purchase order. Some are very up and down. Like RS for example. They had a perfect score for about three years now, which is quite something, considering that they are delivering to us nearly every day. People like SMP have had a spiral down through the grades, and only now are beginning to rise again. They've got their act together. On this project, the linear guide rails that we used that had the long lead time were the actual part that cocked up, and turned up two weeks late and not to spec. which was a fundamental thing that was not foreseen. Although we'd made allowances for slight fluctuation, we did not envisage two weeks.

R: So in that situation, would you re-order, with it being a long lead time item, of would you adjust the design.

S: Well, as it turned out there, as they didn't turn up, we had to stop progress in one particular area. In fact we had to re-organise the plan completely, and go off and start the plan from another section, and work on some parts which weren't due to come on line for another month or so, and then come back once we'd got the guide rails and try to pick up the thread, which I can't say was a very good way of getting around the problem, but it certainly caused the least hiccups. I'd rather not do it, but there you go.

R: You've got to work round these problems. With it being a small firm, I suppose you've got quite a few people in the firm who can actually do a variety of the jobs that need to be done, a lot of multi-skilling, but do you find that if you've got perhaps two or three projects in the factory, that whenever you're producing the feasibility study, your time is very much influenced by how much free resource you're going to have, in terms of designers, and people who can manufacture, and electrical people who can wire the control up for this of whatever?

S: Ah, yes. What tends to happen is that although there is a lot of multi skilling goes on, what you tend to have are your A1 squad of staff, who everybody wants on their project, and they have to organise themselves in such a way as to at least have some time on each project. It does have an effect on the scheduling. When you sit there and you've got a couple of projects in front of you, and I know for a fact that Simon, the electronics chap is going to be hard at work on another project. You're got to really time table other things to be going on while he's on that other project, up to the point where you can get hold of his skills. It can be difficult, even though there is a large degree of people being multi skilled here, even with that in mind you still try and get that A1 team in place as soon as feasibly possible.

R: I suppose with there being quite a large variety of different sorts of input needed to complete these projects you can actually rearrange these schedules reasonably well.

S: That's right yes.

R: Work on different areas of the project.

S: Yes, I mean nine times out of ten it works very well. I wouldn't say perfectly [laughter] but lots of things aren't.

R: But I can see that remaining flexible would be very beneficial.

S: Yes.

R: You mention your A1 people who have the input, do you find that once the design is ostensibly complete, that somebody who is manufacturing something will come back and say 'there's a loads better way of doing this'?

S: Yes [laughter]

R: They look at the manufacturing problems for instance, and then that would be integrated into the design.

S: Yes well, you always hope that somebody is going to spot a better way of doing things. All we can really do, without going through a complete redesign is to put it at the back of our minds, and to try to incorporate ideas the next time. Really, it can be very annoying ...[laughter]

R: Hindsight's marvellous isn't it!

S: Lovely, yes!

R: I know you do wind up costings, and how much design time has gone into the project, and work out exactly where you've made the money, and where you've lost the money on a project.

S: That's right yes.

R: Do you try and keep a more formal record of these lessons you've learnt about design, or does it go into your expert knowledge?

S: Well, in a way it's a bit of both. It certainly goes into the expert knowledge, but for each project we have a project file, and that's getting even more detailed now, and within that file now, there are appropriate sections for adding things like 'if we'd known this we'd have done it this way' in the hope that in the future, should we approach a similar project that we'll actually say, well here are the comments on this, and that should be taken up right the way through the project. I have yet to see it work, but I'm very hopeful.

R: How many projects have you had running through the new regime so far?

S: So far we're on to our third. It's relatively new. It's a pain but systems have been tweaked and prodded here and there, and I still wait to see any concrete results After three projects you can't tell, but my instinct is that it's going to get better.

Transcript ends.

Appendix F(i)

File: I21412SD

Transcript of a model corroboration interview.

From Michell Bearings.

14th December 1993.

S: Chief draughtsman for land based projects

R: Interviewer

Transcript follows:

R: There are four sheets. The first describes the overall method that you might use for estimating how long a design will take. Stage two, stage three and stage four break down into more detail. It is not supposed to run in sequence. I don't know whether you would take a new design problem and do all of the first box, then do all of the second box, and then all for the third, or whether you would look at the design problem, understand one aspect of it see it will break down into small units and then go on with each unit as far as you can through the sequence, and when you get stuck go back. Maybe we will be able to discover whether you do that or not after we've gone through the model. It's not supposed to imply that it's really rigid and you have to do every stage for every design or every part of every design.

So steps one and two imply that you've got some idea of what form the design solution will take when you've seen the design problem. Would that be reasonable?

S: Yes, because when we start estimating time it means that we've got at least a drawing or a basis that you've got to have to produce detailed drawings.

R: Right. So not only have you got the arrangement drawing you did for the enquiry, but you've also got some idea when you get the job in.

S: Generally you've done similar things before so you can relate to those.

R: Yes. If you say it was a fairly new problem, and you had to think of a new way of solving the particular problem. Do come across that sort of problem?

S: Yes, and it's fairly difficult to put a time on them.

R: Yes. Very difficult to put a time on. Would you think about more than one solution at the estimation stage?

S: Erm. Not generally speaking, because I think if it has been a new design it'll have been done in a tender, so more problems will have been ironed out during the tender stage. So it's just a case of trying to get a handle on the nitty gritty.

R: So you're down to detail work after the tender stage?

S: Generally speaking yes.

R: Right.

S: So the new design problem would have a tender stage when you have a deadline to meet, but that's certainly not as strict as trying to get work out of the door in sixteen weeks or twelve weeks or whatever.

R: I see. So you've actually got the line you're going to take with the solution worked out once you've completed the tender. Okay onto step two. This breaks down into more detail. The first stage. Assuming you break the design down into manageable units, say perhaps you've got the casing design, the oil ways ... would you break the design down into manageable sections in order to estimate?

S: Yes. At the enquiry stage we would have an assessment of how many new patterns we would have to make, you would know whether something was already drawn, or whether the pattern existed or not. The unit you would divide it into would be how much you knew, complicated drawings which have to be done from scratch, how many are quite similar to what we've done before, we may only have to alter part of an existing drawing to satisfy it, and probably an overall assessment of how many drawings have to be made in total. So the units would be what's brand new, what can we crib from somewhere else, what do I not have to do anything at all with.

R: Yes, so the units would almost be the parts that go towards the finished bearing, and you'd go through those parts to see which ones you're familiar with, and obviously if you're familiar with those the design time will be smaller or maybe zero. Then if you get something you're not familiar with do you break it down into further units to see where the problems might lie with it?

S: Not generally speaking, I would say that we would probably stop there.

R: The new units, you would have been considering them through the tender?

S: Yes, you would know the overall shape and size and what sections they had to be to satisfy stress requirements, but you wouldn't know the nitty gritty, what tolerances they are going to take and what machine finishes you are going to have, whether you would have to do three drawings to relay the information to the shop floor. So that's the kind of thing you would look at, how long you would think you need to convey the information you need to form each particular component.

R: So for this overall stage you would be looking at a parts list of what the tender requires, and deciding what's familiar and what's not, and then what's familiar you would be able to estimate pretty quickly what time is required, and what's not familiar would be more tricky.

Okay, stage three again breaks down. 'Identify what factors influence the design time for each of the parts'. So whether you've done it before influences the design time. If you've seen it before and have got the drawings for it you know you won't have to do much design work. If you've seen the drawings before but you need to alter something that's going to affect how long its going to take, so you would look how different it is from the previous work. Are there any other things that would influence the design processes take the time for these familiar parts?

S: Generally speaking not many. Most of that we probably know already, so if something is as simple as that then the greatest time that it spends in our office is the time that it's in the queue waiting for someone to do the work. It may be three weeks waiting, and then only three days on the board.

R: So its actual drawing time, putting the lines on the paper, and checking that nothing interferes with it?

S: Yes.

R: With something that's unfamiliar, a new part you've got to draw from scratch, what drives the design time with that?

S: Delivery time.

R: So it's a matter of working to the deadline?

S: It's a major influence. You might be unsure of something, sometimes you're forced into trying give yourself as much time as you can without compromising some other departments position. We do things like release advance information, so people can make fabrications or patterns or put them out to tender without having released the whole job.

R: So do you have some idea of the amount of work a new part is going to take?

S: Yes.

R: So you would help that to jump the queue or make sure that was going to the bloke in the office who could do it the most quickly?

S: That's right yes.

R: You try and allow yourself as much time as possible, you perhaps find that whoever you went to in the drawing office with it didn't have such a problem with it and you were left with quite a comfortable margin?

S: Not often.

R: If you were running late that person would work longer hours?

S: Yes.

R: So it's a matter of altering the amount of resources to solve the problem in time, rather than estimating accurately.

S: That's right yes. I can put two men on one job if I need to, which I've done just recently. Generally speaking we're not too bad at the moment.

R: Right. Like you say, you can issue some drawings early, I suppose you have to see what parts of the design interfere with other parts before you can issue drawings early. For instance if you'd got to put perhaps temperature gauges in a casing, I suppose they're not too critical, but if there is something that is critical and you want to issue that part drawing early, you would have to identify what things are critical on that part drawing and get them done first?

S: Yes.

R: So you identify where the interference comes between the two parts?

S: Generally speaking long lead items are forgings, castings because you might have to make the pattern, but even if you have got the pattern it still takes four weeks to get them from the foundry, and fabrications. I would consult the other department to see what he wanted first. That's the way we would work in the office, if its going to take them weeks to get a forging then make sure that's the thing that gets done first.

R: If you had to do some other design work before you could complete the forging, that would have to be done as well?

S: Yes.

R: So you identify what you're going to have to do before you can get the drawings for the forging out?

S: Yes.

R: Step four. When you've decided what parts you need to look at first, and how soon you've got to get them out, to match that to the resources you've got available, for instance, the designers you are able to put on that job. That would influence how long you put in the estimate?

S: Yes, that's right.

R: From knowledge of previous projects part drawing times, long lead time items, resources available and required, you produce an estimate for the part drawing times?

S: Yes.

R: Now the rest of the steps try to develop the estimates for the individual parts into a coherent estimate for the whole job. So you've looked at where critical parts are dependent upon the completion of some of the other parts, so you have to get the drawings for the forging out and you have a few parts of the design which affect the drawing of the forging and you work out what the total time for designing the forging and the parts it is dependent upon?

S: Yes, it would have take into consideration everything that affected that component before you could release the information.

R: So you would be able to produce an estimate for how long its going to take to produce a drawing for the forging, so you can produce a rough time for each new part you've got to design?

S: Yes.

R: So from those estimates you know which parts are critical to design and you know which parts to drawings can be brought out and amended once the critical parts have been released. You wouldn't be working on different parts concurrently?

S: No, generally speaking we have one person working on one particular project. The time that you are talking about is anything from two to eight weeks project time. He would work through it sort of 'what information do I need to complete first?' 'how do I get that information out as quickly as possible?' 'what things affect it?' 'do I have to draw those before I can release that information' and then when he's done that he follows on from the major components, things that make up the casing, the main working components, down progressively until he's down to probably nuts and bolts, what he needs to hold the things together.

R: Right. I suppose for the major parts you would know the time to design it, and if the part is already drawn that time is very small, but for the nuts and bolts and nitty gritty stuff, you would know for a big bearing that's going to be two days, maybe for a small bearing its ...

S: Wouldn't even think about it in that much detail.

R: Right.

S: We think in terms of weeks. When I think it's in terms of 'does it take two weeks, or does it take five weeks or does it take six weeks'. Not down to hours or days.

R: If there you're perhaps a couple of days short, the designer would be working a couple of extra hours.

S: Yes, we quantify delivery times in terms of days here. They used to be acknowledged as twelve weeks or ten weeks or something, but now we do it in days. So I've got a specific day down that I'll complete the work by. Generally speaking over the last ten weeks since we've been looking at it very closely we've been on time, never been more than two or three days late. That might be because I put very safe times down, but if I can allow as much time in my office then I'll do that.

R: Design is the sort of work where the more time you spend on it the better it's going to get though ...

S: It's not just that, we have to deal with tender work as well. You never know, there could be ten tenders we have to complete, there could be none. There's usually a few that you've got to fit in and you never know when they're going to come. People will be working on tenders as well as working on orders. How do you allow for that?

R: Particularly when you don't know when they're going to come in or how urgent they will be.

S: No. They can take two days or two weeks. Customers are notorious for not giving all the information, or coming back and changing things. We sometimes can't get what we want from suppliers so we have to modify and change drawings. 'We can't get it in the time', 'we don't have it in stock'. All of that goes on but you can put any time down. If you wanted to say purely say, 'right it's going to take him three hours to do that drawing, two to that one, and one for that one, that means the total design time in my office is going to be half a day and I can't give it to him for another three days so that means it's going to take four days' if I put four days down I'd be out of my mind! If I had the delivery time, roughly speaking I know how long I can allow people on the shop floor to manufacture it, I try to not take too big a proportion of the total delivery time up. If I do take too long then the guy from the shop floor comes back to me and says 'can you not get that out urgently?' or 'can we have something in advance?'.

R: You might be able to estimate down to the day, but there's not point because you can't rely on suppliers or the customer.

S: That's right, no point at all. Yes.

Transcript ends.

Appendix F(ii)

File: I22408BT

Transcript of a model corroboration interview.

From Thorn Lighting.

24th August 1994.

S: Chief Designer

R: Interviewer

Transcript follows:

R: This session for me is to get your opinion of the various steps I've laid out, it's laid out in a sequence of steps but it's not supposed to imply that this is the strict order of carrying out the steps it is meant as a guide line so that it can be adapted to each company's own needs. Therefore you may find that you do the first few steps but then find yourself having to go back a few steps until that particular stage in your work is satisfactory.

I have a different model that you can look at which is for one off design as there is not the same number of manufacturing methods to consider but it is more or less the same thing.

S: So you are saying that this is the typical thought process that designer's go through when they are planning something but in maybe not in such a discipline way that your diagram shows, but these are the aspects that they consider.

R: You might not do it exhaustively for the design you might just break it down to certain areas of the job .i.e. you might just consider what effect the volumes going to have, or what affect the target market is going to have.

The first step I would expect the planner to do is to find out what is the design problem that he has got to solve. Therefore he has got to identify what the requirements are, identify what the market is that he is aiming at, see what sort of a volume that market is going to be and what will be the influence of that on the way that the product is designed. Also to see what the affects of the various requirements on the way that the product is designed, and see what the market can withstand in terms of completion date. From all of this to try to come out with a rough idea of what the design is going to be by either doing a sketch or arrangement drawing, and from this you would see what sort of units you can break it down to.

S: Could these units be parts of the products?

R: Yes, if you have to design them or if you have to just specify them, you would ask how long it would take to design or to specify them and perhaps you would need to break it down into a few more bits before you could work it out. If it looked familiar you would just leave it or if it didn't you would continue to split it up until it did look familiar.

Onto the next step.

Now that you have identified the constituent parts which you think that you can estimate for you see what things are going to influence how long those constituent parts are going to take to design. For instance if it was a very high temperature bulb you were using, you would consider the affect that the temperature and the space is going to have quite an affect on how long it is going to design. So it's mainly identifying which aspects greatly affect the design time.

Next step.

Now that you know what things affect the time, e.g. weather-proof seals, temperature, space. You now have to estimate how much these things are going to affect the design time.

Next stage.

This is to compare your market window, how long you have got to design the product in and the amount of work you have gauged that you have got to do on each piece with the amount of resources you have available to try and solve the problem. So in planning the design you're not just setting your target time and amount of work you have to do, you are also estimating how much resource you are going to need. It is a marketing decision as well as technical.

Then once you have got your various units and the areas that are going to affect the time that those units are going to take you look to see if there is going to be any interference between the units. This may cause you to have to design something internal before you can finally fix the shape of the aesthetics of the product. From the amount of interference that you anticipate between units and the factors that are going to affect the completion dates for the units you try to give an overall idea at what the actual times for completion for the various units.

S: So if you constructed a chart to illustrate the processes that you are going through, so that you have some sort of aid or check list so that you can work out how long you are going to need for a particular product, whether it's a three component product or a multi or complex design with thousands of parts where a team of designers are involved. How exactly are you going to get this logical sketch of events down so that it can be used in a large industry.

R: A problem that I come across is with the diversity with the projects that I have been looking at. I've looked at a large bearing, robot stations, lighting systems, ship stabilisers, and various other things, so trying to cover all these thing with one model is difficult.

S: Do you think that it's possible to have one?

R: I've found that there is quite a big difference in the company's that have to design for an open market and haven't got there development costs covered by a customer before they actually start to develop their product, and the bespoke design where costs are already covered. So for the bespoke design you have to cover your design costs on one contract, you have to be very strict in the way that you control the time that you spend on something as you know that you need to be able to cover the costs from that one sale. With designs for the open market you have a more delicate balancing act because you have got to work out how much the design is worth doing and see if you can do another bit of value engineering on it to see if it's worth spending that extra one-hundred thousand pounds in order to get the unit costs down. So the two problems are that you have to be very accurate with your bespoke work and you have to be able to balance things in the open market work.

I could put together a model for you or an illustration if you like for applying this scheme to one of the Thorn custom products.

S: Is the ultimate intention to give us this and in the format that we can give to a design student?

R: There are two ways that it can go, either given to an experienced designer or estimator to go through and if not improve the way that the estimate is done to at least help document it so that you can present the problems or points that you want to show a lot more clearly and therefore in a more definite and conclusive way. It also may make the thought processes clearer to the estimator therefore enabling them to produce a better estimate than they normally would. Another application of documenting the processes would in helping to train novice estimators as you could easily point out the things that have to be considered when trying to produce an estimate.

S: There needs to be some judgement applied to it though, you will need an experienced designer going through the process. I don't see how you can train someone who is not involved in the design process to evaluate time scales because even experience designers find it extremely difficult. One of the problems that we have here is getting a long term view of a project we can see maybe two weeks maybe up to a month ahead but after that it becomes very unclear, so if you give the job to an analyst to break down the product. For example to say that this product will typically consist of ten particular parts, which some of standard design therefor no design time is required for those parts but two parts are new technology of which we have no previous experience so these cause there to be a big question mark over the design time. There will need to be some input from the people who are going to be dealing with these parts how long it is going to take them.

R: In these stages, almost every one, you will find that they draw back on previous experience of management projects and actually being a participant in those projects. So it can be used as a guide to as what to consider, rather than for example saying that if have read this and understood this you will be able to estimate it.

S: It's not very user friendly.

R: No. It would need to be altered for each particular firm.

S: Is the intention that this can be used by both the designer and the estimator?

R: It can be used by whoever has an input on the deciding what resource and how long you are going to have to complete the design. It's a tool for the designers in that they will be able to say that 'I looked at these stages and I know that it is going to take this long, and if it goes to the marketing people they'll say that they need it by this time'. They may ask if there is any reason why you can't do it in this time? You will then be able to clearly represent your reasons why.

S: Why can't you do that on a simple gant chart? On the left hand side list all the activities and some estimate of the time scale. Because the advantage with that is if it gets too complex and too analytical at the end of the day you are going to end up spending a week doing it come within a degree of accuracy of 10% or you could spend an hour doing it and come to about 15% accuracy. This would probably be all that is actually required, so on the more complex projects that you are going on about that are worth millions of pounds and teams of designers being involved I can guess that it is probably important to plan the thing. But for a simple product generation such a our requirements, usually one designer as part of a team initially but his first estimate would have to be updated at a minimum monthly but maybe as much as weekly possibly so if you have a laborious task that he has to go through the purpose of the task becomes all forgotten, and the process becomes all empowered. Then you can here yourself saying that you couldn't do the job because I spent the time estimating how long it would take me to do the job! So if you don't come up with something that is simple to use and that will take less than an hour it won't get used. Because I won't authorise them to spend more than an hour a week to plan what they are going to do over the next five days. In detail you have your long term projections and dead-lines and your launch dates and you work back from that and decide what you are going to do today or tomorrow and as far forward as you can accurately plan. The reality of this is that you can very rarely plan for more than two weeks ahead at the most. So it needs to be updated every week and for it to be a job that will take matter of minutes.

R: This is actually taken from talking to people who do spend up to two hours on complex jobs, maybe not as complex as a new product, perhaps on a varying design.

S: Are those two hours for a weeks work?

R: The man who was actually doing this was a design manager so he was perhaps getting two or three projects on his desk a week so he was perhaps spending two hours on each project.

S: Yes, but he was not getting paid to design it he is paid to co-ordinate the plan.

R: Yes so this would be gone through by the person who is doing the planning.

S: Yes, that is typically my role, but I do not estimate how long it is going to take an individual to do it. I want there estimate and then we can negotiate, that's how we compile our work capacity. But I am a firm believer in getting the people to make the commitment themselves by stating when they are going to do each activity and how long it's going to take them.

R: So when you are working out how long something is going to take you look at when it has got to be done by.

S: We work back from the long target as we have a production deadline and we work back from those.

R: And you hit these deadlines?

S: No, not always. We try to control the process and break it down and focus on the various activities, particular design as it has been a notorious area as you are talking about a creative process which is difficult to estimate. Because someone who has forty years of experience may come out with a very different estimate than someone who has only got five years of experience. So it depends on the complexity of the problem and the experience of the individual.

S: This scheme does not relate to working backwards, does it?

R: It is not laid out in the format of being able to work backwards, it assumes that you are going to work forwards. The same points for give and take are still there, so you can work backwards all you do is change the emphasis from estimating the time to working out what the resources are you are going to need.

S: I don't see anything wrong with the logic of these questions because it is a fairly logical, common sense type of questioning. I am quite happy about the actual processes of breaking down the units of work and to identify the areas where there are question marks and focusing on these. It's putting it a form which is easy to use because I don't think this is.

R: No it's not. One of the major criticisms I've had from other estimators is that it is laid out in sequence when it is not actually done as a strict sequence. It's a lot more flexible than the lay out of the scheme suggests.

S: That's why it is done incorrectly mostly as it is not done as a logical sequence.

S: Really you need it laid out in a continuous format. What you are really describing is the ability for looping back and making yes/no decisions at certain points.

S: An activity flow diagram is all you need. Because then you can skip the irrelevant sections or follow the whole process but that is not to say that it will lengthen the process, it's just going to make sure that every aspect is going to be covered. This is where we fall down as we usually under estimate the problem, it's not until we are two or three weeks into the work that we realise that we haven't got a solution to the fundamental part of the product. Until the designer can do that he can't release any drawings for product because he does not know which parts he wants to change or modify. So I think that you need to emphasis "to identify the problem" and to do these first.

So two things that we need doing with this is would be to make it simpler to understand the ideas that it is trying to get people to recognise and to look at it with the point of view with it having a start and finishing date and working out what you have to do in between rather than having a start date and a problem and working out the finishing date.

The problem we have is purely with the design aspect as we are confident about the actual mechanical side of actually producing the product, and in some cases if we estimate that it is going to take for example three weeks to produce a drawing and it actually takes three weeks to do it, customers or the sales people are not impressed and wonder why one drawing is going to take so long to do. Only when we have looked back at that job we find out that for that project we had to produce thirty drawings, because of all the dependencies, do we understand why.

R: This model should allow you to identify that perhaps after your first drawing you are going to find that another thirty drawings depend on this one drawing, since you will have identified that there are some interconnects between things. This is not so much as providing a better way of doing things at this moment, what will come out of this eventually will be a simple flow scheme of what will need to be gone through in various levels of detail and accuracy depending on it's application.

S: Let's go through it and look at the details as we have been talking about it in general terms. In step one you need to "identify the requirements" what to do mean by this?

R: If it's for a volume manufacturing problem it would be getting the marketing specification.

S: We've got that later as 'identify projecting volumes influence on design method', or is that something different?

R: That is something different. So what this is 'identify the volume the target market' i.e. what sort of standard of product is it going to be. This volume than has an effect on the way the thing is designed, for instance it may or may not be economic to use extrusions in the design, depending upon the projected volume.

S: Right. 'Identify requirements influence on the design method', what's this?

R: Things such as if it is going to high powered product, will there be thermal constraints etc.

S: That would be classed as technical issues. 'Identify the markets restrictions on time and specification' ...

R: That would come from marketing in your case.

S: For instance, the products got to be available for a particular time. So that would be time constraints, project time constraints. 'Form pre-design concept', that would be a sketch design.

R: That's OK so we can now go on to step two.

S: Is there any difference between dividing into interconnected units and a list of parts?

R: It is very closely linked and in some cases that all that the units would be a list of parts. But often the units are also functions of parts as well as the parts themselves as it depends on how far breaking down the design is useful.

S: Then do you have to recognise the broken down units as fundamental work or of a fundamental level of detail?

R: If you think that you cannot can not break this down and further than this and this is a new problem that's fine, or you may find that you have seen this before it then becomes a familiar unit. If you have not seen it before and you think that perhaps there is a bit more detail you can try to get to another level of detail.

S: So I can write next to this step for my personal understanding 'list parts'. If the units are unrecognised and are not yet of sufficient detail, loop back. What exactly would I have to loop back to?

R: You would loop back to the previous stage and try to think about that specific unit you are thinking about in more detail.

S: So step two finishes with a list of parts when you have identified what is standard and what is new.

R: Yes.

S: Step three. 'See what design processes are needed to design each unit'.

R: For example if you were designing a reflector, you could say that you could design a profile but you would not know what sort of light output that would give. So you would have to look at the optical design and then pass that on to the test house and see what sort of a profile the would give me. That could then be a very strong time influencing process because you do not know how busy the test house is and perhaps you may have to do that process two or three times. If you do not have to go through any optical design you know that a large amount of time may be saved from not having to do this one process.

R: From our point of view these areas are going to be either optical, mechanical, or thermal. Should we not say that you have to refer back to specialist area and then maybe break this down to smaller steps?

S: Yes. That would be referring back to the second stage in step two, for it to be in a recognisable level of detail.

R: Yes. A problem we have is not demanding enough in terms of specific details of design requirements.

The next stage 'identifying the factors that control the processes that strongly influence design time', this is basically looking at the process and determining if the area that is holding up the time is of high requirement, or of standard or low requirement. This would determine how difficult it would be to perform the time consuming design processes.

S: So you need some specification. So that would be specification of new parts from our point of view.

R: For step four if you find that you have three different processes all from different areas and each process is going to take a different amount of time to overcome. If you are presented with the problem that you are not going to have sufficient resource to do the amount of work you have estimated you will need to do, that is the one that you are going to have to look at the most.

S: Okay. So that would be to highlight the process with the longest lead time.

R: The end of step four is trying to capture the knack that some experts have in identifying when a selection of problems which aren't in themselves demanding, when put together prove some sort of problem.

S: So its risk assessment really.

R: I feel that this stage is the one that comes down to the expertise and experience of the estimator.

S: So you do a risk assessment and allow some time for iteration. Contingency allowance on high risk parts.

R: See what units interfere with each other, so one part determines the way another is designed. Its basically working out the dependencies.

S: Right.

R: Step six would be considering the problems with each unit to come up with the design times for each unit.

S: Yes.

R: The it all goes together, perhaps like a gant chart to come up with the time for the whole project.

S: Okay.

So looking back over my comments, you give that to a designer and he'll say,' oh we do that anyway' but they don't. As it is it's extremely unfriendly.

R: Would you find it of some use?

S: I think so, it was produced in a more comprehensible form. And its got to be something that can be done in a matter of minutes, and a logical sequence that they can understand, with all the options, without having to think about. Like any check list its so you don't forget things. It makes you think.

Transcript ends.

Appendix F(iii)

File: I21012IW

Transcript of a model corroboration interview.

From Labman Automation.

10th December 1993.

S: Design Manager

R: Interviewer

Transcript follows:

R: I'll give you a rough description of what the thing is intended to do so it can make the most sense. The main scheme is supposed to describe the overall processes that the planner has to undertake in order to estimate the time taken for a new design. The arrows joining the boxes up aren't intended to imply that it is a rigid process, and that for each one you have to go through for the whole design before you can go on to the next box. It's the stages between the beginning and the end, rather than you have to do for the whole design and then you move on to the second box and you do that for the whole design, then you move on the third box ... its a more 'well we've got one part of the problem here so we can decompose that into manageable units, then we'll identify what factors ...' and so on. You do it in dribs and drabs. I'll just try and describe each box to you.

The first two boxes imply that you have some idea of the form of the design solution before you can go on and estimate how long it will take to design. Is that reasonable?

S: That's absolutely true. The prerequisite to starting any planning is to understand the parameters, you can't really do anything until you have that. That's absolutely central, so that's fine.

R: So would you perhaps go through the estimation process, taking on board a couple of design variations? So for instance, you think 'I might be able to solve this problem in this method, and I'll estimate how long it will take to produce an solution in this way, but if that doesn't come off or it turns out that this design might be nicer I'll just work out how long it takes to do it a different way.'

S: I think when it comes down to problem solving, what we tend do is we'll do the synthesis of getting a design that is optimum in terms of whether it will work, or whether its compatible with what the customer wants, etc. before we embark on going down to numbers. When it comes to the point of estimating, it's already quite likely that the system is already 99% there. Now it has happened in the past that we've gone down a route and found that actually the costs of creating it are prohibitive, and we've had to go back and make a compromise solution, but I think that happens a little bit later than the planning you require when you come to do the estimating.

R: Right. That makes sense. Looking at step two in more detail, you've got another sheet there. That's just trying to describe in more detail what might go on in step two. What step two says is that you break down the design or project brief that you're given, and you say for instance you've got a de-capper, and you've got a sample rack, and the body of the robot with the controls in. You would break it down into units.

S: That's right yes.

R: Then if you had got a unit that you perhaps are not so familiar with, would you break that down further into more units until you were either coming to a level where the sub-units were familiar, or you were in fact designing from first principles.

S: The answer to that is yes and no. If a design solution has apparent routes through it, in other words it can be broken down, then we do it the way. More often that not though it requires a more fundamental head on research process before a solution can be brought out of it. Once the solution is there it's reasonably easy to go through the routine of designing it. Trying to estimate from an early point a novel solution or an innovative solution to a problem, is incredibly difficult.

R: So perhaps the more levels of detail you have to go down to before it becomes familiar, the less accurate you're estimate will be.

S: That's true yes.

R: Right, we can go on to step three now. Again it breaks down into three sub steps. 'See what processes need to be undertaken to design each unit'. So say for instance you've got to design the base on which to build all the units, the pick and place, and the de-capper or whatever, but you've also got to put all the electrical gubbins in there as well, so you've got a routing problem, the positioning the units problem. You've got various problems you need to address with that unit, and you see which of those problems are going to be the most difficult, and the ones which will affect the design time. Say you've only got one person who can do the electrical design work, so if they're busy that's going to be a critical part of the design process.

S: There is a certain amount of critical pathing goes on through the process, and it is largely dependent on what is the major resource requirement at the time. For the electronics we've only got one chap so if his element of time has got to be compromised then we can work around that. In terms on physically designing something, the place where you start is the place where it has the greatest effect, so you leave the peripherals. For instance if you're designing a de-capper you design its footprint first, and then go to the peripherals of holes in place and bits and pieces which are just kind of ancillary to getting the major part of the project going.

R: Yes. So you do have critical parts of the design, which will affect other parts of the design, and you will work on those before you'll work on everything else. They have the priority.

S: That's right. There may be parts from each segment, if you've broken it into areas, there may be a part from each of those which has to be almost simultaneously organised. So you'll pull those out.

R: What sort of indicators do you find in the project brief that say 'ah we're going to have a critical stage there'?

S: Ah ...

R: I suppose it comes down to your pre-concept design.

S: That's right. It's the experience of past projects. Certainly every area, every sub-division of the project you can pick out the most important factors which will relate to the system as a whole. It's experience that helps that I'm afraid.

R: Yes. Well you're remembering your previous solutions, and saying 'oh we had a similar problem here and this is how we solved it and I remember that part of the design was critical in that'.

S: It is all part of the process, yes. So that's what we do.

R: With this estimation problem, we're always going to come up against this problem of experience.

S: This also relates to manufacturing, because quite often the tight schedule that we run to manufacturing has got to start long before design has finished.

R: So the critical point won't just be dependent on the parts of the design that every other part is dependent upon, its also the parts of the design that every other part of the design and the manufacturing people are dependent upon.

S: That's absolutely right yes. It gets more and more complex.

R: Step four, up to now we've been breaking the problem into more and more detail and now this stage starts to draw things back together into an estimate. At this stage you're looking at the people you're going to need to solve the problems of the units, and once you've got a rough estimate of what sort of design work is involved with the unit you can look at the way the units interact, and your knowledge of the projects you've done before, and anticipate any problems you're going to have with integrating those, and any resource you're going to have to throw at that to solve the problems of integrating the units together.

S: Yes. The designs can be held up by one part of the problem, but we just have to work around that, by working on something else. We could be waiting for specifications for one part and so on. Having said that the scheduling for the project is done quite tightly, and if everything goes right we do it in the time of our best estimate. Unfortunately nine out of ten times something of some sort will go wrong, maybe just a small thing, and we have to allow a contingency. You compare the resources you need for the critical things with the resources you've got.

R: Step five describes the way the estimator tries to cope with the problem of units of design which interact with each other. Say for instance you can't position the sample rack until you've finished with the de-capper footprint, or whatever. You have to know when one unit is going to affect another?

S: Yes.

R: How do you cope with the problem with interdependency, do you work on both things at the same time or do you work on one as far as you can go and then move on the next one and so on?

S: I try to avoid switching from one to the other too much, the problem is you can loose the thread and it's not a good idea. What I try to do is work on the elements which have to most links. It can be difficult from the outset to resolve the interrelations, and quite often as the manufacture goes through, you can see other relationships that weren't apparent in the design synthesis, so what may happen at that point is that you have to re-shuffle the end of the design process to take into account that new relationship. You've got to have flexibility at the end of the day.

R: So when you're planning a design, you're aware that you've got to have flexibility to cope with these things?

S: That's right yes.

R: Right, step six. Do you generate a rough time for the various units of design?

S: Yes.

R: So this step implies that you look at those times you've got and you consider them against any interference, at the level of the factor of the design for each unit for instance the footprint which are going to be critical ...

S: Interference as you call it, we call it integration, and that has to be accounted for.

R: Yes.

S: What we tend to do is to look at these number of linkages which leads directly to the amount of integration time that we need. So that's a way of accounting for interference.

R: Right, and then you come up with a time for each unit?

S: That's right.

R: Do you do this for more than one unit at the same time if they're interdependent, or do you try and concentrate on single units?

S: We try to keep it down to single units. We try to keep it a simple as possible.

R: Okay, last step. This is where you get all the unit times together to produce the final estimate. It's not simple addition, obviously because you can get things running concurrently, and you might be able to start one only after you've completed a more critical one. You might have conditions which have to be met before you can start designing in a particular area.

S: Yes.

R: What sorts of things do you find that cause these sorts of problems?

S: It can be physical dependencies, for instance the design of the bed, wiring routes and so on.

R: Do you tend to design the control element after the mechanical system or the other way around.

S: What tends to happen is the electronics are worked out from getting the hardware together. With the mechanics we would start from the physical entities, and then going into the mechanisms. Wiring routes can be problematic. The more space you have, generally the easier this is. That tends to be approached later. So the simple answer is you try to make an allowance for it. I don't place that great an importance on it.

R: When you're doing the estimation would you see yourself as doing each of the stages drawn here stage completely for each part of the estimate and then moving on to the next, or would you identify a unit of the concept design and then take that through either as far as it will go or as far as it is manageable, through the estimation route, an once that becomes unmanageable because there are too many unknowns then you go back and start with another unit and sort out some of the unknowns and simplify things? Would you do it all at once or all in sections?

S: It feels like we do it all at once, but no you're quite right, I start off going down the route and then perhaps I have to double back or start another bit off, or scrap it and try something completely different. It's very dependent on how it falls together, and each project is different unfortunately.

R: Yes. When you're integrating these estimates for the unit times together, do you do it systematically and have a list of numbers that you've worked out, or do you do it by feel. For instance 'I thought that would take a long time so that equate to four weeks, and I thought that would take a very short time so that would be two days'?

S: You try to be a systematic as possible, and then you look at it to see if it makes sense.

R: Right.

S: I'm afraid that instinct and feel for these things does play a large part in it. You use it perhaps to be clear in your own mind and give credibility to what you've calculated, or equally to check what you've calculated and say 'well there's obviously an error here'.

R: Yes. That's the thing, it's like any maths problem where you're typing numbers into a calculator, you always look at it and think 'that would mean that the wall thickness has to be 4m where it should really be 4mm' or something like that.

S: Yes, obvious factors! [laughter]. The closer the relationship is the harder sort of decision. We use various other quick back of the fag packet estimates, and when things begin to look about the right sort of area then you can be happy with it.

R: Yes. What sort of notes do you make when you're doing an estimation? Do you make notes of interdependencies, critical stages, rough times?

S: Well you start off any process by picking out those elements that it is important to get over first. Every interdependency that you can see you make a note of and from that you can get a layout that will reflect what is actually manufactured. You have the chance then once you've got a layout you can see in front of you further interdependencies, and from that you write down the elements in the order that you want to do them to suit that project.

R: Right. And would you make notes of times for the different times?

S: Yes. These are always useful when you have to go to the board of directors [laughter].

R: Yes, you've got to sell your work. Do you think the overall scheme describe what goes on?

S: It does yes, its pretty good. As you say though, those arrows do imply its a step by step approach, and there are elements of each that coalesce into each other.

R: Yes. I was wondering how to get that into the diagram. Do you think if it was followed systematically that it would improve the quality of the estimation?

S: I think it would improve the documentation. I'm doubtful about improving the overall quality of the result.

Transcript ends.

Appendix F(iv)

File: I22308WB

Transcript of a model corroboration interview.

From Brown Brothers.

23rd August 1994.

S: Design Manager

R: Interviewer

Transcript follows:

R: We went into an engineer to order firm which was Michell Bearings, who I've found to be quite good at planning design times because they do it so often. We also went to another company, Thorn Lighting which were not so good at planning their design times as they only have to do it every six to eight weeks.

S: With us it depends on the product .Our standard product is a folding fin stabiliser which is about half a million pounds worth in total and we may do half a dozen of those a year. Therefore the detailed drawing work in each contract is relatively small, about six hundred hours or so. We have also got a very good idea about the processes that we need to do for each contract. The design process is such that we may get a proposal for a completely new product. For example, three years ago we decided to redesign the folding fin because it was un-economic in it's old form, and technologies had advanced to make different designs possible. Our competitors were catching up. Now that has taken a lot longer than we expected, and is only just now beginning to pay off, but without that development we'd have lost our competitive edge. Another area we're looking at the long term development is the off shore industry. The offshore business is now looking for multi-path swivels so we can get several lines for fluids with fairly high pressures, up to five thousand psi and also up to one hundred and twenty degrees C. The seal design is a critical item when using particularly large diameters in which case we do proposal engineering. It is very often a rough guess at what the engineering content will be once we take the order. There are often variants to the theme and the themes are sketched in the early stages

R: So for most of your work you would put a tender in for either the complete work or for some of the design development part of the work?

S: Yes, and depending on how similar it is in work load to a recent product will judge how accurate our estimate for design times will be. Invariably there will be a number of hours allocated to the technical department which in nearly all cases is less than we actually take. This seems to be a fact of life and this will appear on the costs overshoot.

R: Is the product manufactured on this site ?

S: Yes it is. If you are interested I will show you round the site later.

So as far as estimating the design times is concerned we have an estimating department but they concentrate largely on the production side , i.e. material costs and labour cost in cutting the metal and to put it all together.

R: So would the individual departments themselves estimate how long they would need for a particular job and do they then pass that on to the estimating department?

S: Yes. There are basically two major technical departments, the mechanical and the electrical or controls department. There are sometimes also contributions from the ILS which is the integrated logistics support (manual writing section). So there can be three contributions and each department will work out how much time it will take them on a particular project. Often it is a standard amount of time . For example if the job is a fin stabiliser the estimating department will just give us five-hundred hours. This is because there is a known amount of work to be done in it but that's detail, design and drawing. There is also a few more things to do such as a few more specifications and a couple of liaisons with the customer, and there is a set series of things that we know that the technical department will have to do.

R: Yes, so is the technical department responsible for getting all the detail specifications and so on?

S: Yes.

R: So it's not technical sales as in the sales department are responsible for that side of things?

S: No. The sales department do all the customer liaison before the contract is taken. It is not discussed in any great technical detail with them usually, sometimes it is and they can get out of their depth. Sometimes a technical person will go out to our customer, with our customers being world wide there is often extensive travel involved at the final negotiations. This is usually because of technical requirements and details of the product (what they want the product to do). The estimating of design times tends to be peripheral or subsidiary to this. The design times will have already been done prior to this as the prices will have already gone in.

R: For the tender work for development and so the tender for the jobs that aren't particularly variant in design i.e. fluid swivels what would the estimating be down to?

S: Very often for development work it is company funded, it's not funded by a customer. In this case it is a question of us and the technical department filling out a capital expenditure form for so many hours to develop this product. We do have a couple of project management software planning packages but these are not very much used. I use them to produce a gant chart picture of the start and finish and the stages that are gone through in between, I'm sure if I had more time I would use it in a lot more detail for planning and putting man hours to tasks.

R: That is what they are trying to do at AT&T which is a current project I'm working on.

So the in house development work would be almost like you were working in a situation where you are selling to an open market rather than the bespoke market?

S: Yes. It's not selling to a particular customer, although invariably in our business it's a bespoke market, there maybe half a dozen people world wide that are interested in this swivel and there might be two maybe three companies that are prepared to offer the product. We first plan what the product is going to do and set a brief specification (all that maybe involved), then we say what resources and number of hours that will be needed to develop the product.

R: But your not actually trying to cover all your development costs from one customer.

S: No. It's done on the basis of an overhead on expenditure and hopefully that will be recouped after we've sold two or three, but having said that the swivel product has been in some sort of development phase since 1988. We had built a prototype by 1990 , but we knew we'd have a big problem with the seals so we had two seal manufactures which were offering us designs. We ran both of them in parallel and eventually one looked like it was going to be a more successful than the other and we've had half a dozen configurations of seals in that time so each year we've re-opened another development phase to carry on or to carry on with what we'd done before.

R: So it's done in stages.

S: Yes very much so. I'm sure if someone in 1988 when they said yes in the first place knew that we'd still be developing it in 1994 would have had second thoughts about it. We have actually sold one this year but there is no way that one is going to recoup all the development costs. The potential is still there as we have had people in Singapore looking at the next two and these are very big projects worth millions of pounds.

R: It's fortunate that you weren't quite aware how long it was actually going to take to develop such a class product because then you wouldn't have such a technical lead that you do.

S: Yes.

R: So it's a matter of managing the resource you apply to the product development and matching the perceived need for this product.

S: Yes, it's a case of the sales department saying that they need something now and eventually something happens in the technical department and we gear up to actually try and meet it. For the swivel product they have been saying that for three or four years but there has still been no final decision to say that the development will be finished in a set number of years so the technical department does not allocate as many hours to it as it maybe should.

R: If you look at this sheet the top seven things are the major part of the estimating process as we've managed to find from three firms in the south of the country. They are not supposed to lead on from one to the other, what the arrows are meant to imply is that you cannot do certain processes before you've done the one above for specific parts of a project but you can go backwards if necessary. The arrows are there to try and keep it as simple a process as possible but there is also a lot of flexibility incorporated. I will go through the steps with you. First step: Identify problem, what constraints there are and have a rough idea of the end product.

S: We call this proposal engineering and do a few calculations to see if it's actually feasible and then perhaps an arrangement drawing.

R: So then you would divide this into separate units that you can work on, as many at one time that can be handled.

S: This is done not so much for the stages of assembly but for the different phases of the project that can be estimated.

R: So in more detail you examine your proposed design or arrangement drawing and see what the interconnected areas of work there are. If you recognise these as been approached before that's fine but if you don't then perhaps brake it down a little more. Would this be reasonable?

S: Yes.

R: So largely from this point it would be looking for parts of the jobs or the assemblies that are familiar or for processes that would be familiar.

S: Yes. The first thing that we would certainly do is set the start and end points whether it's starting now or starting in a months time and maybe finishing maybe in the middle of next year.

R: Yes. So you are working out how much work you are going to put in to it, not so much when you are going to finish.

S: Invariably the time scale is set at the out set and then once you've built up a picture of the man hours involved you can then see just how many resources you can allocate. In most cases there will not be sufficient resources to match those required. It's generally obvious that the job will run past it's finishing date because the company as a rule never allocates sufficient resources until at the end of a project where we are starved of resources.

R: So it's not so much estimating the time it takes you to do things but a case of estimating exactly how much work is involved in each stage to achieve it in the original time scale set. Next stage: Identify how long a particular sub-unit or an assembly or process is going to take to do. This breaks down to looking at the design processes for the various parts, then seeing which processes strongly affect the estimated time and determine what exactly about those processes affects the original proposed design times.

S: I don't know whether we actually do all those processes as they seem a bit implicit but it does looks like a good methodology.

R: You're saying that you do not do all of this but it could be a way of doing it. I've found with other company's that some have said that they do this, others have said that they don't do this but it would be a good idea to do it, if not in your head, at least on paper so that they can at least document what they are doing properly. Also by doing this you can learn lessons from it for the next time.

S: Yes but something that doesn't seem to come out very much is which of the processes influence other processes, i.e. predecessors and successors.

R: That is what I was hoping to bring in at the fifth stage. We are going to go up to the unit level of detail from the process level of detail. So you've worked out the processes which strongly affect the design times and compare these with the resources that you have available. Perhaps in your case because you are trying to work out how much resource your going to have to apply to get it done in the time, you'd be almost doing a reverse of that process. So you wouldn't be comparing the work you've got to do with the resources that you have and coming up with a time, you would be comparing the work that you have got to do with the time that you have to do it in and coming up with the resources needed.

S: I'm sure that must be common isn't it? As whether it's a customer or a board of directors that is setting what you have to do, someone always wants things done by a certain date.

R: It all depends in what sort of market you are in. As at Michell they do it both ways. On to the next stage. This interference of what's a predecessor and what's a successor, the time affecting processes and how they interfere with other time influencing processes and how they also affect the units, these would be your predecessors and successors. So perhaps say that you can't design certain parts of the job until you've worked out tolerances for something or the pressure for something else so you would have to do those first. You would have to perhaps go around in a loop and iterate.

S: Yes.

R: From this interference and the time influencing processes you come up with a time for each of these interconnecting units and you can use these estimates to come up with a time for the overall job. If you were perhaps producing a gant chart, putting all that information for your sub-units onto the chart you can say which areas will overlap, then you can get a start and finish date. But in your case you would get a result telling you what resources you need for each stage.

S: As you have said it works both ways as by the time you have you've gone through this process you realise that the time scale is a year not six months as you first thought when you started, and even by putting extra resources on it you can reduce the time to perhaps eight months because of maybe some of the factor things that you've actually got to go through.

R: So you would consider the influences of costing out work and also perhaps doing a bit of research in your own company.

S: We have done research but it has become less over the year. Probably the best bit of research that was done was for the steam catapults. Now we found that it cheaper to buy in parts so we effectively act as an assembly line.

R: Therefore the design work is concentrated on the actual final product that you are selling and the specification of the constituent parts.

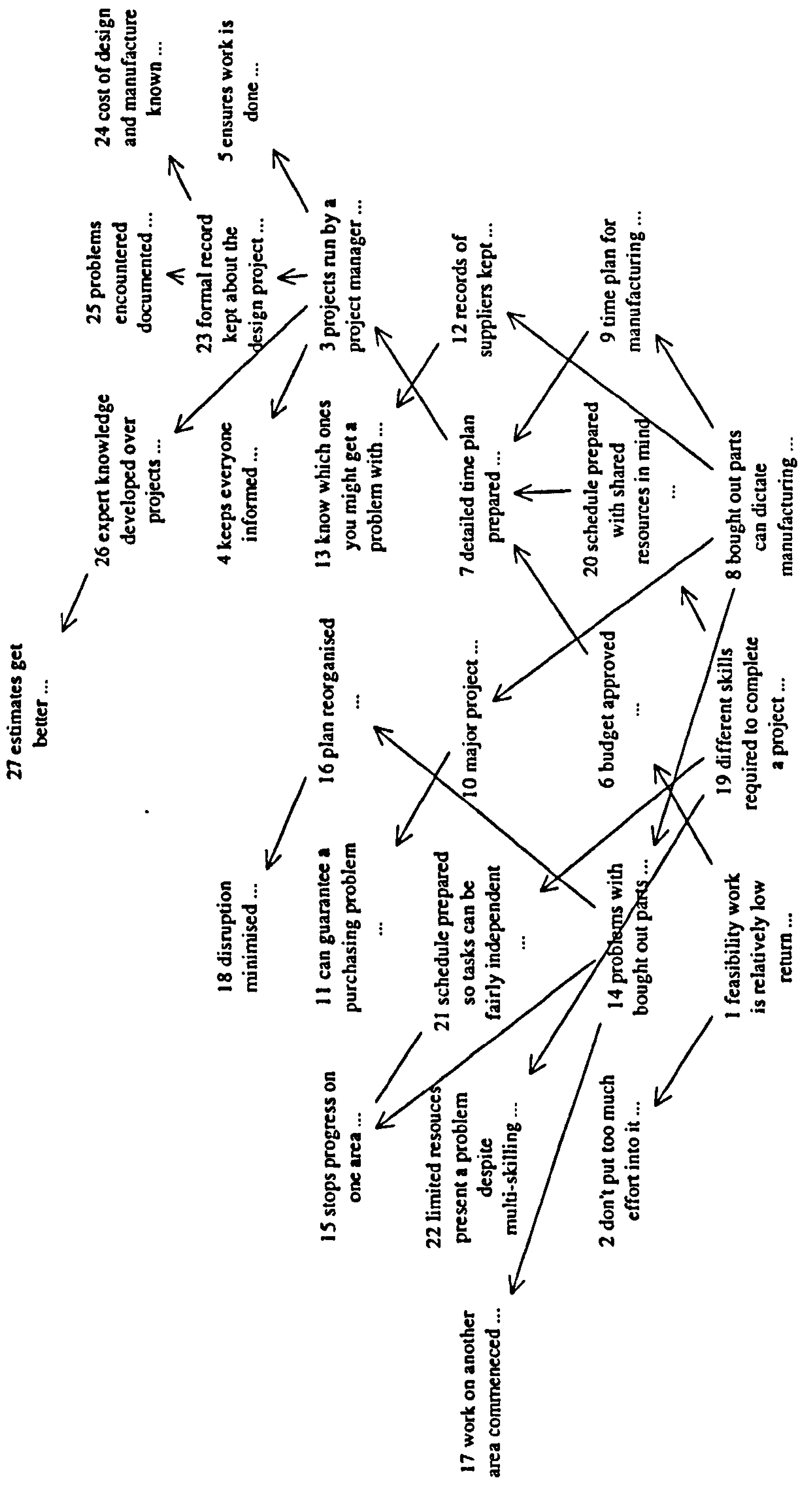
S: Yes.

Transcript ends.

Appendix G

Complete maps of the universal groups drawn from Labman Automation

Co-ordinating tasks:



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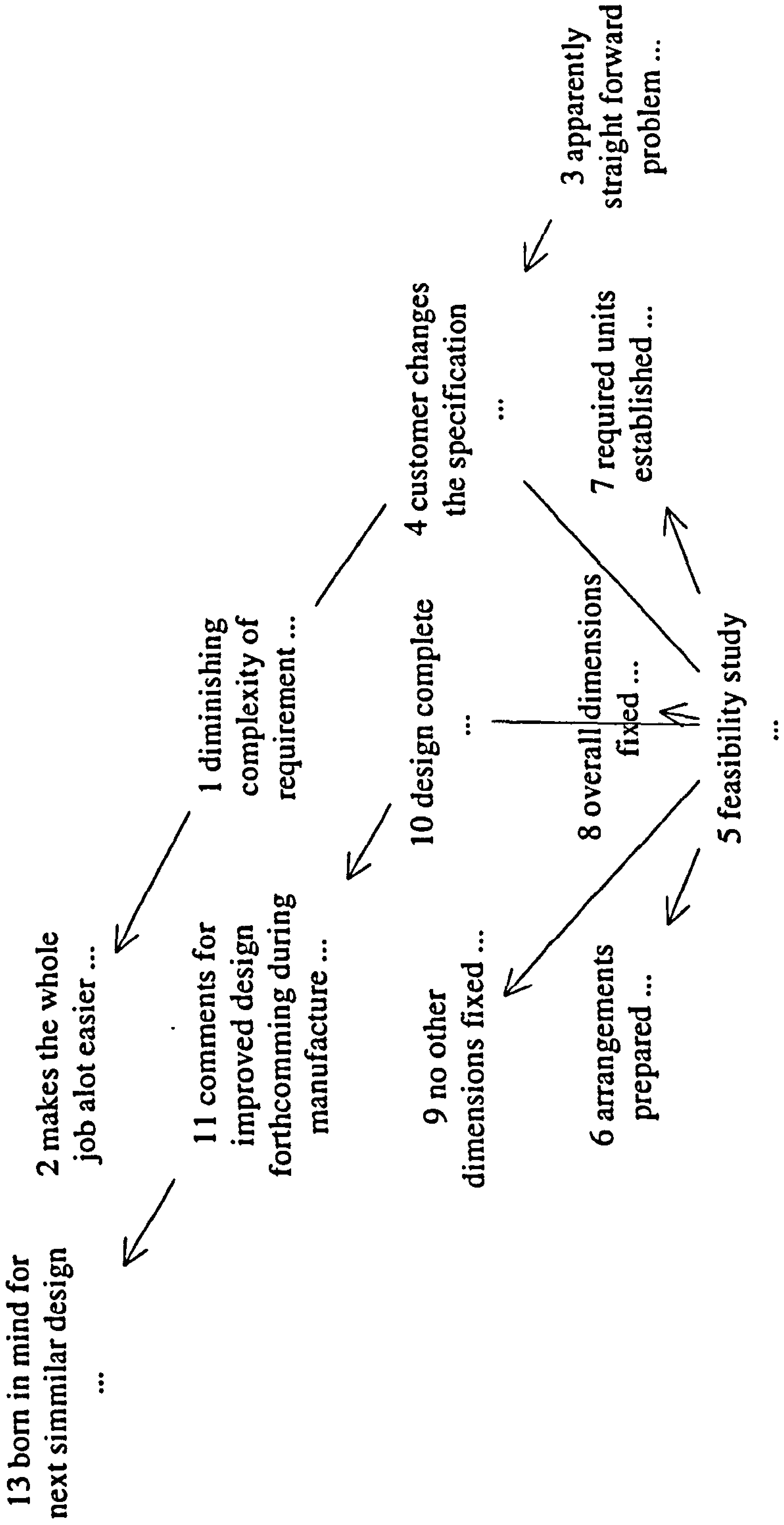

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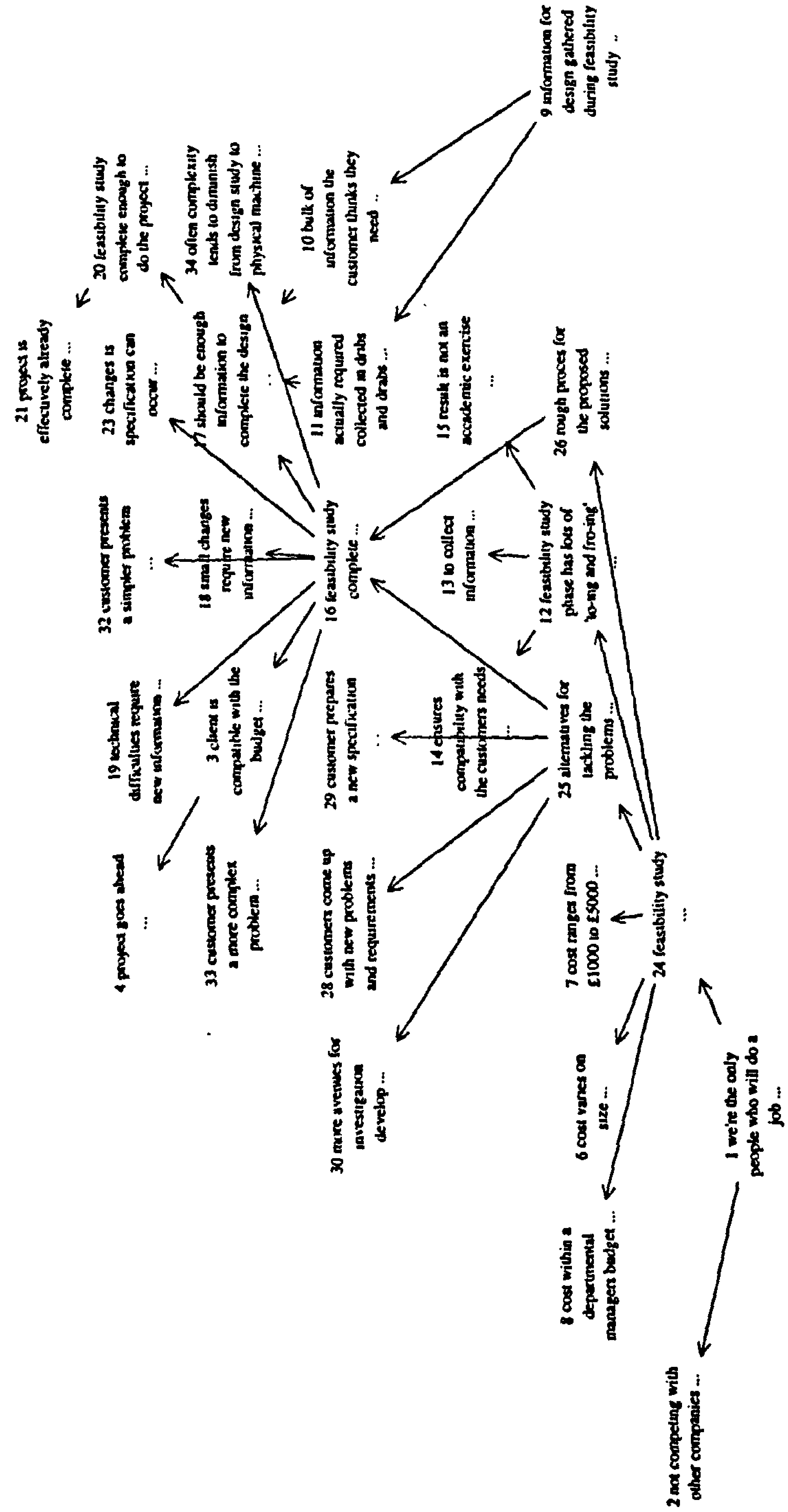
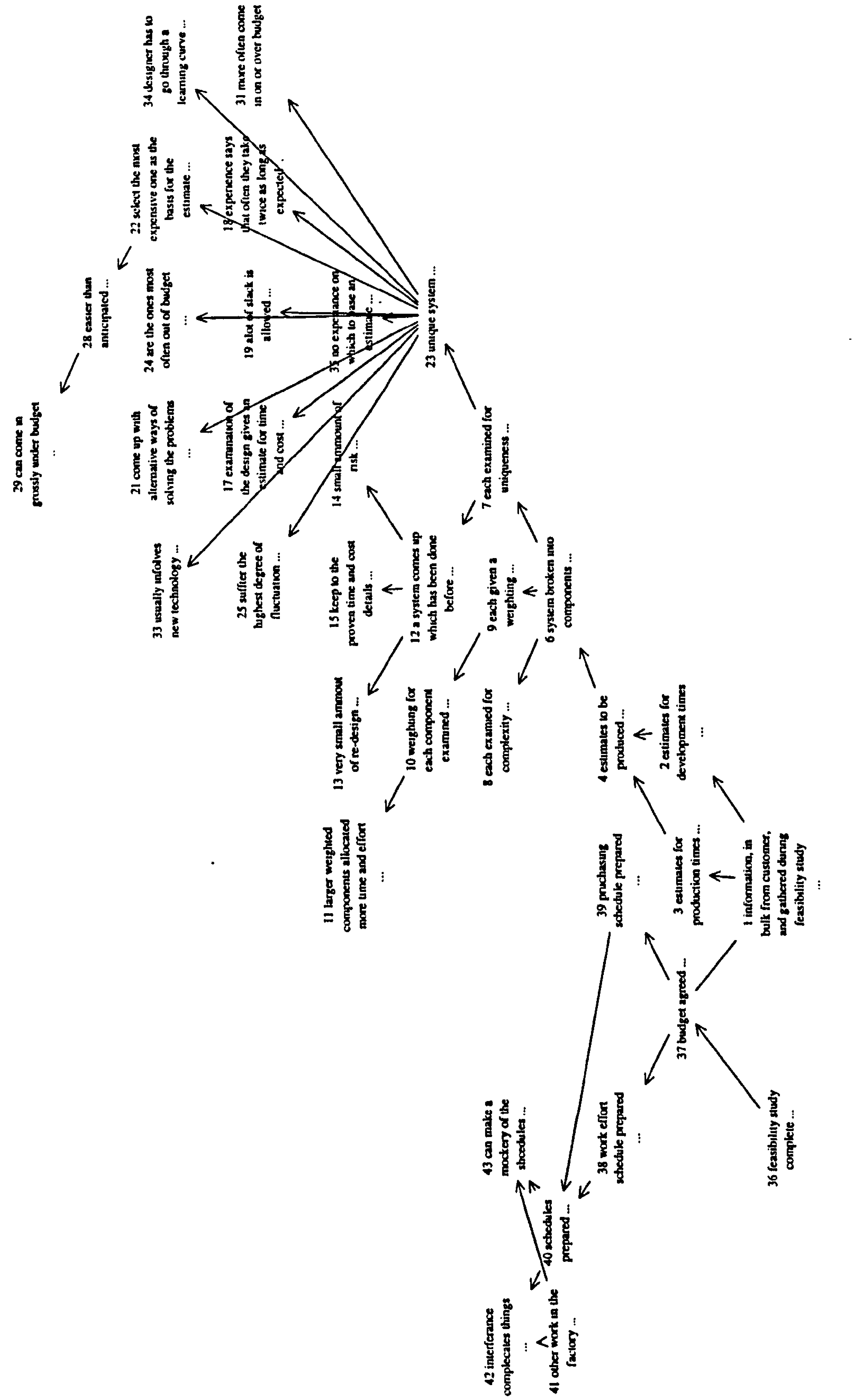
Forming requirement:



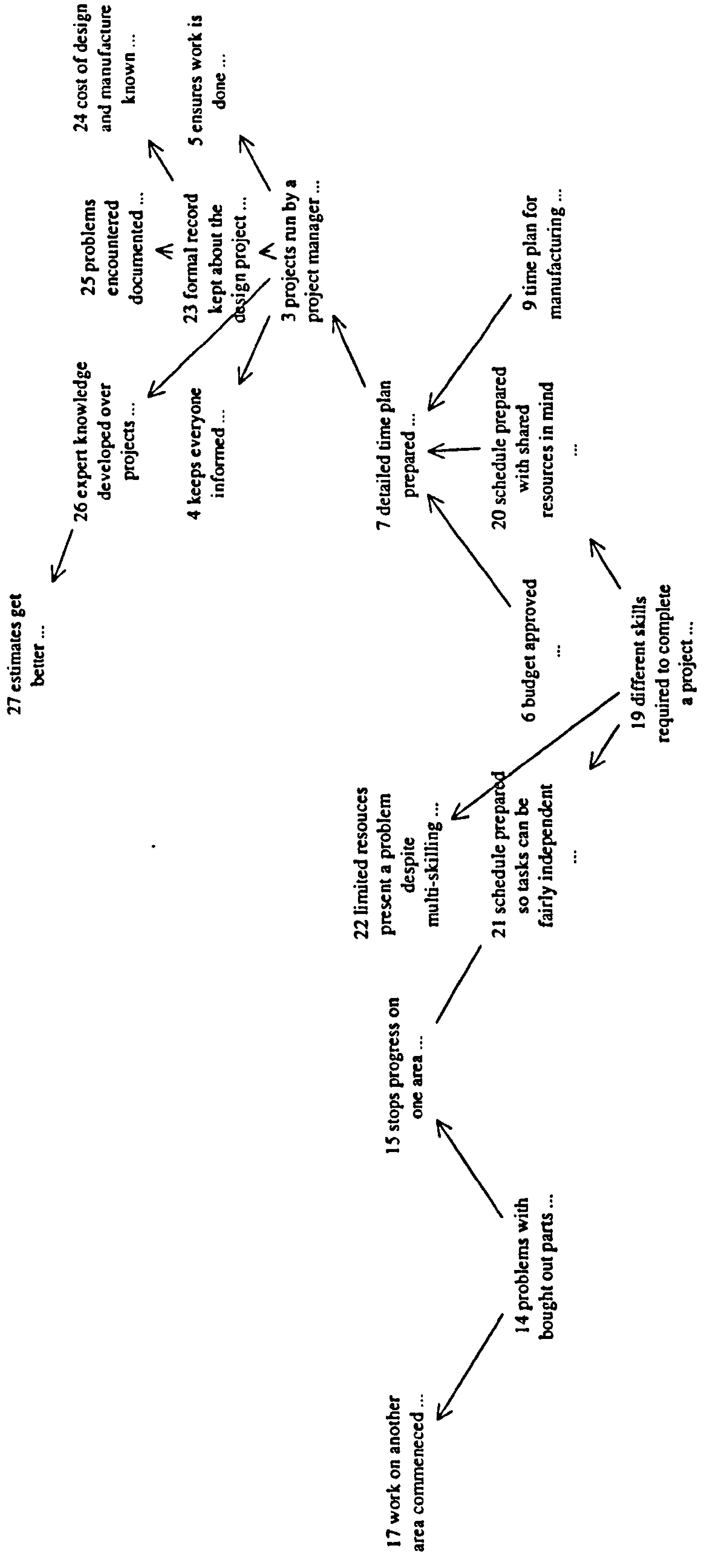
Time management:



Appendix H

Rationalised maps of the universal groups drawn from Labman Automation

Co-ordinating tasks:



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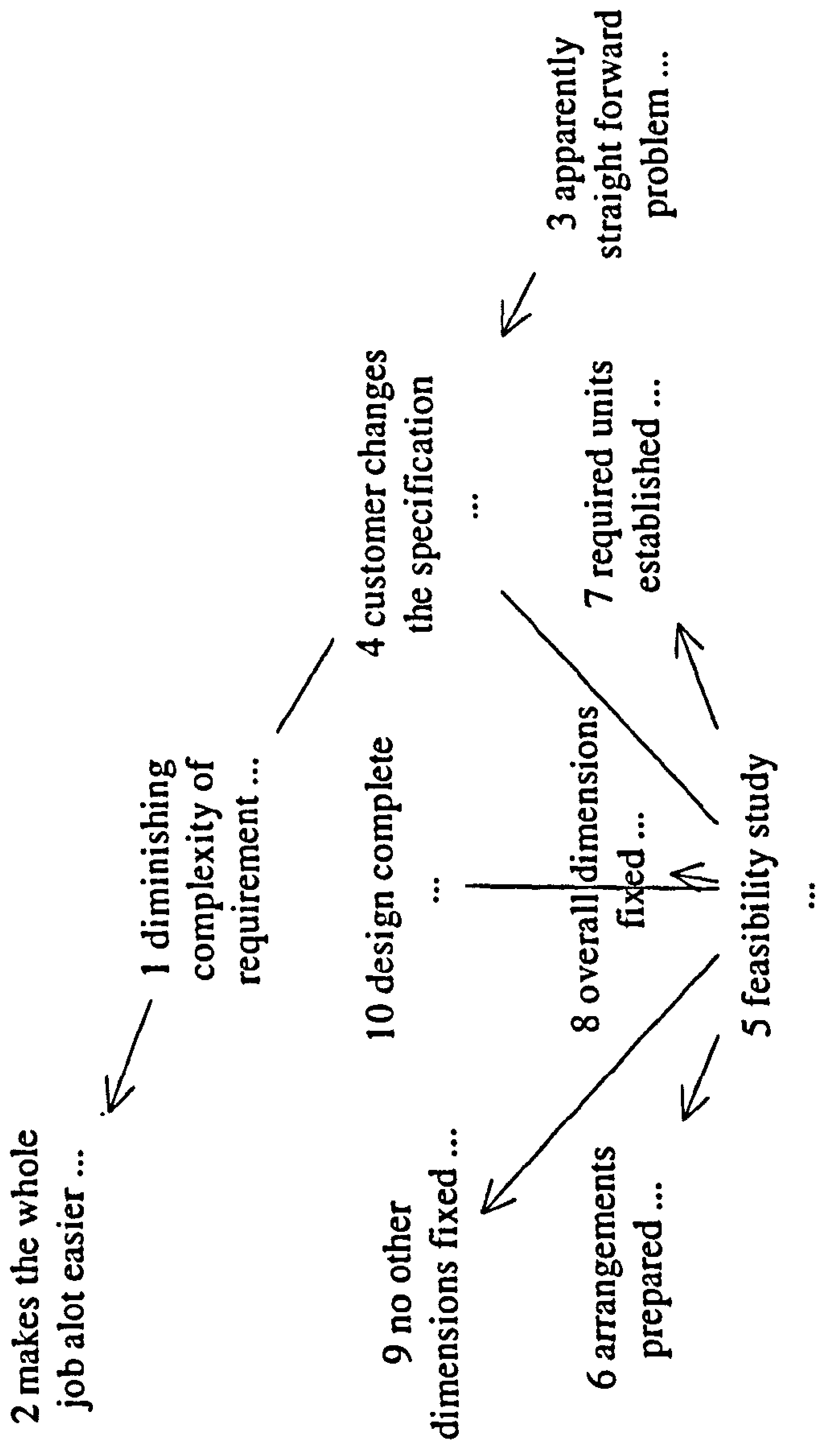

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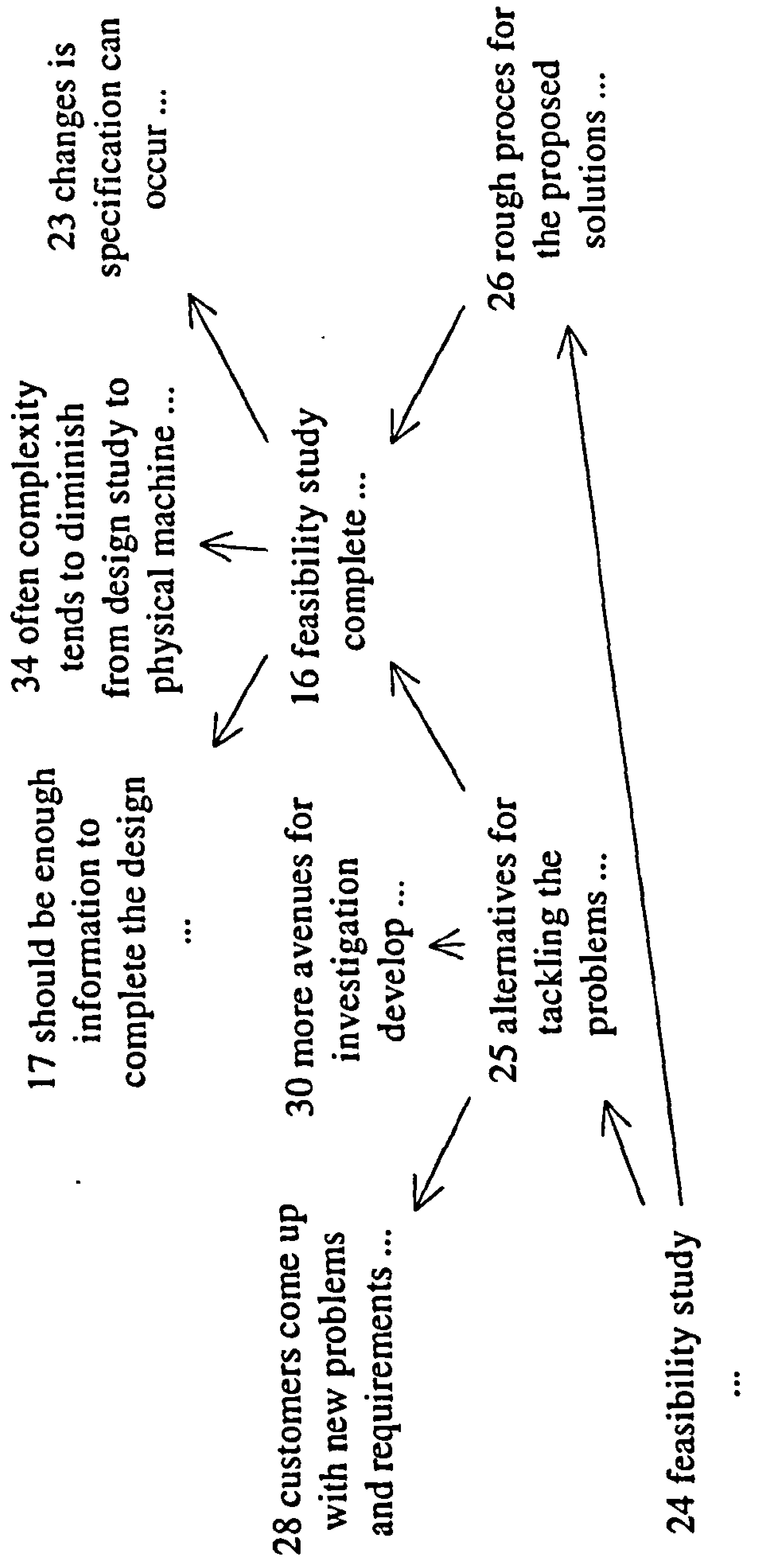
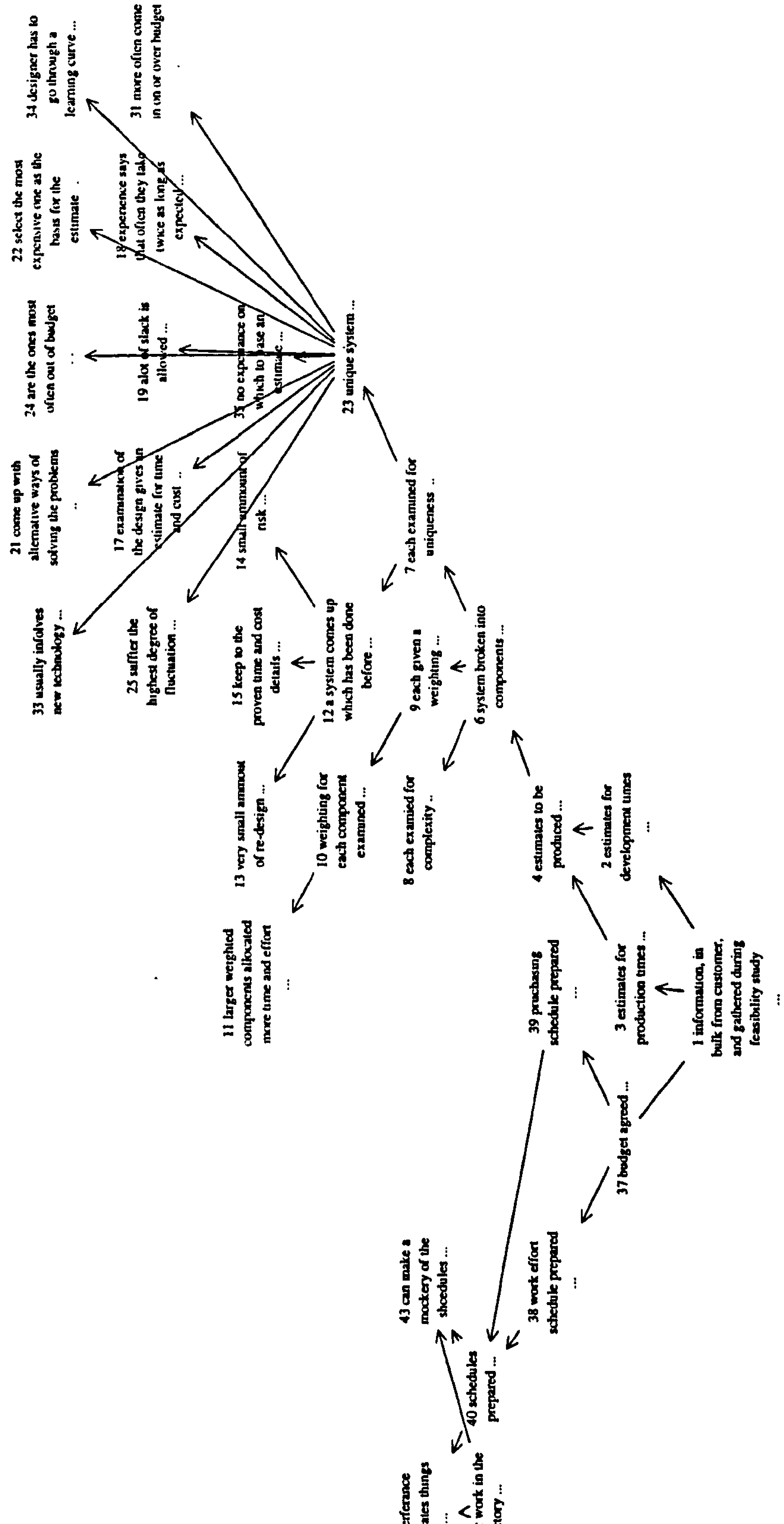


Time management:



Appendix I

Estimation check-list from Thorn Lighting

Develop design specification:

Where will the product be sold?
What manufacturing processes are anticipated?
How do technical issues influence the design method?
What are the time constraints on the project?

Sketch possible designs.

Break design down:

List anticipated parts
Which are standard?
Which are new?

Consider each part:

What optical design is needed?
What mechanical design is needed?
What thermal design is needed?

Estimate lead times for these processes.
Develop specifications for new parts.

Consider development times:

Which processes have the longest lead time?
Which parts have the highest risk in terms of design time?
What effect will further design iterations have on design time for these parts?

Allow a contingency for completion of the highest risk parts.

Use lead times, contingencies and design process information to estimate a completion time for each part.

Use part completion time and integration time estimates to estimate duration of whole development.

Appendix J

INTERNATIONAL CONFERENCE ON ENGINEERING DESIGN

ICED '93

THE HAGUE, AUGUST 17-19, 1993

MANAGING THE USE OF TIME IN MECHANICAL ENGINEERING DESIGN

N.J. Weston and J.E.L. Simmons

ABSTRACT

The research introduced in this paper investigates temporal problems faced by design organisations for both volume and one off products. Through prolonged and repeated visits to companies of different sizes and types a picture of tasks, operations and problems of time management in design offices has been formed. The paper discusses the need for time management, factors which influence it, and metrics for monitoring its success in engineer to order (ETO) and volume manufacturing firms. The existence of companies between the extremes of ETO and volume manufacturing is noted and their implications for research methodologies and the application of results argued. A framework for systematic research and improvement is developed from discussion of the nature of the domain and the requirements of a solution.

INHALTSANGBE

Die in diesem Artikel vorgestellte Forschung untersucht zeitliche Probleme, denen sich im Design tätige Organisationen bei der Bearbeitung von Massen-und Einmalprodukten gegenübergestellt sehen. Durch lange und wiederholt Besuche von Unternehmen verschiedener Größe und unterschiedlicher Typen entwickelte sich ein Bild der Aufgaben, der Arbeit und der Probleme des Zeitmanagements in Design-Büros. Der Artikel diskutiert die Notwendigkelt des Zeitmanagements, die darauf einwirkenden Faktoren und Meßeinheiten zur Überwachung des Erfolgs von Firmen, die im Bereich der spezifischen Einzelaufträge arbeiten (engineer to order, ETO), und von Unternehmen, die in der Massenproduktion tätig sind. Die Existenz von Unternehmen zwischen den beiden Extremen ETO und Massenproduktion wird festgestellt und deren Implikationen für die Forschungsmethodologie und die Anwendung von Resultaten diskutiert. Aus der Diskussion der Natur dieses Bereichs und der Notwendigkeit einer Lösung wird ein Rahmen für systematische Forschungsaufgaben und Verbesserungen abgesteckt.

1. INTRODUCTION

It is now widely accepted that deadlines are best met at minimum cost by ensuring that parts, resources, machines and people get to the right place at the right time with the minimum of slack. To this end, techniques such as Manufacturing Resources Planning (MRPII), Just-in-Time (JIT) and Optimised Production Technology (OPT) are used to reduce work in progress, increase stock turns, reduce rework and scrap and improve delivery due date performance. Whilst the relative merits of the different techniques in various situations are still debated [1], and research in these areas continues, there has been little work or discussion on extending these techniques for improving efficiency to the costly and intractable problem of design scheduling. It would seem logical that when the cost of capital is increasing, improving the total utilisation of resources throughout a company is essential.

In recent years research in engineering design has advanced on two fronts. Investigations have been made on the impact and use of technology for improving design office performance [2,3]. Simultaneously, there has developed a body of research on the organisation of the design process for improving performance [4,5,6]. This work is very often based on the experience of acknowledged experts in the field, and on the findings of extended case studies. Whilst increasing throughput for a specific level of resourcing is a component of improved efficiency, it does not solve the whole problem of improved total utilisation of resources. Indeed, the problem is not completely understood. The research introduced in this paper aims to investigate the problems faced in design organisation for both volume and one off product companies, and set out a framework for systematic improvement.

Detailed observations have been made of design office work in a number of manufacturing companies in the North East of England. The companies were chosen to provide contrasting environments, from the extreme of very large volume manufacture of durable goods on the one hand, to the design and manufacture of individual items of equipment characteristic of Engineer to Order (ETO) businesses on the other. Extended and repeated visits to the companies in question were made and a picture has been formed of the tasks, operations and problems of time management in the respective design departments. The purpose of this paper is to present a synthesis of the information obtained and describe the necessity for, and form of, continued work.

2. VOLUME MANUFACTURING DESIGN

Why Control Time for Design?

There are four major reasons for the control of design time in volume manufacturing. The rank these fall into depends upon the market philosophy and position of the specific firm.

The four reasons are:

- To ensure the market window is achieved.
- The location of the optimum cost/benefit point.
- Control of budget.
- Measurement of departmental efficiently and improvement.

The market window exists between the time that the market recognises its need and the time at which that market need is satisfied. An innovating company which is late to market can find itself having to develop a market share in a mature market rather than creating or satisfying a new market. In competitive markets, being just a few weeks late can turn a product which, if first to the market would be dominant and competitive, into a loss making product with no hope of recovering development costs.

The relationship between cost and benefit of design in volume manufacturing is highly dependent upon the unit turnover. For two alternative design options the choice may be different if the volume is 200 000 or 1 000 000 units. If manufacturing costs can be reduced by 5% by spending an extra £2 500 000 on designing a £100 product, profit margins can be increased by 2.5% in the case of the larger volume, but reduced by 7.5% for the smaller. Since a large part of design cost is made up from designer time, it is essential that this is controlled in order to allow the best compromise between design cost and manufacture cost for a given volume.

As the cost of capital is increasing, tight budgetary control is becoming more of a priority, as is the effective use of the capital available. The cost of design work is very closely related to the time it takes, so in order to control costs, time must be controlled. Similarly, the performance of the design department may be measured in a relative sense by the time design work takes. A common complaint by design office and engineering managers is that design takes too long. Unfortunately, because engineering design is a creative process, work rate can be affected by the 'difficulty' of the problems faced, experience, environment, temperament and mood [5], it is an impossible task to strictly define the shortest time in which it is possible to achieve the 'best' solution - not least because there probably won't be a 'best' solution. Therefore measurements of design office efficiency can only be relative, and involve more than just throughput and cost per design. Design quality and appropriateness must be accounted for when quantifying any improvement or degradation in office performance.

Factors Which Influence Design Time.

In volume manufacturing there are a vast number of influences on design time. The major influences on product development time are:

- Target market.
- The degree of innovation.
- Predicted volume.

The target market influences design time in many ways. Designing for a market niche of perceived quality or styling often takes considerably longer than for simply functional objects. If a product must reach certain official standards, whether because of legislation or as a market hygiene issue, the design will take extra time, as will the testing of prototypes, and any re-design required.

The degree of innovation is dependent upon the company's strategy. If the firm aims to project a high technology or fashion image, being first to the market with new innovations in style or technology, it must ensure that project turnover is rapid - possibly at the expense of detailed value engineering in the design stage. If the product is late to market despite this sacrifice, the market may well be lost due to higher unit costs (in part due to the reduced value engineering) and missing the window of opportunity. The degree of innovation has a profound effect on the difficulty of the problems which must be solved in the design process. Highly innovative projects cause more serious problems which in turn take longer to solve. Further time may be taken up by the need for more iterations of the design cycle when a project must be started almost from first principles. When working within areas of familiar technology the time taken is more predictable. Within less familiar areas, not only is the completion time longer and less straightforward to predict, it also varies over a greater range.

Predicted volume influences design time through its effect on value engineering requirements and the cost benefit curve. High volume implies rigid value engineering analysis, large investment in development and careful selection of materials and manufacturing processes to allow minimal material, machining and assembly costs. Value engineering and investment in development slow design turnover. Reducing the cost of manufacturing processes can add time through the need to design, test and commission special tooling, for example injection moulds. Manufacturing time and costs are also reduced by designing for ease of assembly using, for example symmetrical parts and minimum fastenings [7].

In addition to these individual problems, when the design process is taken as a whole these problems interact, conflict and interfere. This makes design a complex and time consuming act of compromise.

3. ENGINEER TO ORDER DESIGN

Why Control Time for Design?

The reasons for controlling Engineer to Order (ETO) design schedules, and the consequences of poor control are quite different from volume manufacturing. Whilst it is the market which is at risk in volume manufacturing if a project runs late, in the ETO situation the customer is already committed to buying the product. If an ETO project runs late it is the profitability which suffers for many reasons. Firstly, if a project overruns either on time or on resources, the estimated cost will have been inaccurate. If the contract is not on a cost-plus, basis the cost over-run will cut into profit margins, or even cause it to be a loss making project. If deadlines are achieved only at the expense of introducing expensive overtime - depending upon the wages policy of the firm - this will increase the cost of designers' time and that of support personnel. It is not unusual for ETO customers to include penalty clauses in contracts to cover any loss they may incur because of late delivery. In these cases the cost of over-runs is high and easily quantifiable. It is usually impossible for the contractor to include a premium on the price in these situations because of the intensely competitive nature of most markets. One cost of over-run which is less quantifiable is the impact a late project has on subsequent work, through tying up resources. Late completion of one project can cause late commencement of others and subsequent late completion. One seriously late project could in a worst case trigger penalty clauses in subsequent projects. A further possible source of cost in disastrously late projects is litigation. At a minimum this includes the cost of representation, and can include a settlement and court costs. Because of the risk and expense involved, customers use this only as a last resort.

Factors Which Influence Design Time.

There are many things common to the problem of time management in volume manufacturing and ETO design. The discipline retains its creative nature and is therefore susceptible to the same intangibles such as experience, environment and mood. One area that is quite often different is the degree of innovation. Whilst it is possible for ETO solution to be of a higher technology than volume manufacture designs, ETO designers tend to have a quicker turnover of projects, and so have a steeper learning curve, and are more likely to have experienced problems which come up before. ETO tends to involve more of what Pugh would call 'conceptually static' design, which may sometimes be high technology, but is a repeated solution from a previous design [8].

4. MEASURING DESIGN TIME

The measurement of design time per project is often a simpler matter in an ETO firm than in a volume manufacturing firm. ETO designers often work either singly, or in small groups, as opposed to the large and diverse teams of volume manufacturing. Consequently it is easier to record and compile accurate task duration data. The start and finish times are simpler to pinpoint with ETO, from the time when the order is placed to the time when the drawings are signed off and released by the drawing office. Volume manufacturing design may involve some preliminary study before a budget can be approved, which may or may not be included in the design time. The release process is also more complex, tooling may have to be made, tested and modified, parts may need modification or fasteners respecifying for ease of assembly, all of which may extend the roll of the design office and blur the point of project completion. It is therefore more common for ETO firms to take trouble over recording and analysing the use of time in design. This is only to be expected since profit margins are clearly dependent upon design time in ETO. However, it is becoming apparent that the same needs to be done in volume manufacturing for the reasons outlined in the preceding sections, and that systems for time management in ETO are far from perfected.

5. BETWEEN THE EXTREMES OF ETO AND VOLUME MANUFACTURING

Much of the survey work was undertaken in firms at the two extremes of ETO and volume manufacture, but it is clear that there exist companies with working practices which lie somewhere between these, on a continuum. See figure 1.

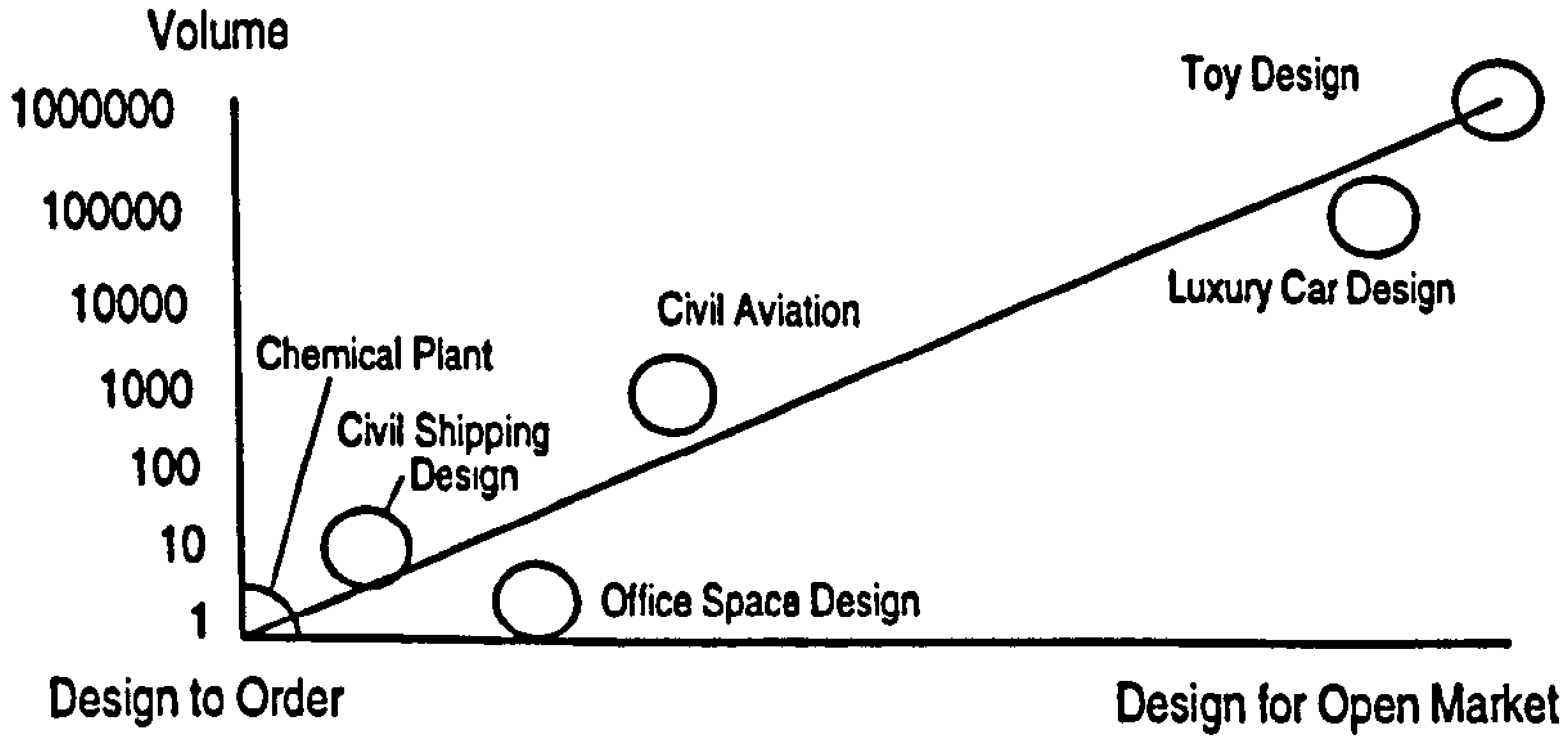


Fig. 1. The continuum between ETO and volume manufacture

One example would be weapons design. Whilst costs must be covered with a relatively small production run of say 1000, placing the situation some way towards ETO, the diversity of the skills required to produce a new missile require a large design team - a characteristic of design for volume manufacture.

Any research which aims to tackle problems in the design management area must have a methodology robust enough to cope with the inconsistencies and discontinuities along this continuum. For this reason much of the work presented in this area has been either in the form of a case study, or guide lines and work books produced by acknowledged experts [8,9,10]. One problem with this is the difficulty these methods manifest when generating truly generic models. A generic model is needed for both a genuine understanding of the problem, and for the generation and application of improved methods for design-time management in a diversity of specific situations. An advantage of the diversity in company working practices in design is that the richness of the domain when gathering data and testing models ensures a sample large enough to give statistically significant results.

Whilst there would be no benefit from imposing a standard methodology across the whole continuum for the prediction and management of time in design, there are lessons which may be learned from the extremes which are relevant to the whole problem to some degree. For instance, it may be that ETO firms have more experience in ensuring that delivery due date is met, and in the prediction of completion times. Similarly, it may be that volume manufacture firms have more experience in managing uncertainty. If this is so then all firms will benefit from the sharing of this expertise. It is the gleaning of this expertise in design management which is both the key, and one of the most difficult tasks of this research.

6. DISCUSSION AND CONCLUSIONS

Implications for Further Work.

The descriptions above indicate the level of complexity of the problem further research needs to tackle. Because of the existence of the continuum between ETO and volume manufacturing design it would be limiting to attempt to solve one problem to the exclusion of the other. Other reasons for examining the task holistically are the richness of the problem space, and the lessons one area can draw from the others. Wishing to examine the whole area multiplies the complexity of the research.

Because of the unworkablity and elaborate nature of systems for measuring the difficulty of a design problem, and uncertainty of identifying the 'best' design solution, any measure of design performance must be relative. This implies that, where the problems faced are not exactly identical, no meaningful comparison between two design firms can be drawn. A company's performance can only be measured against itself over time.

There are inconsistencies and discontinuities within the field of design management which require any methodology for research into this field to be robust. Heuristic methods may fall short in terms of rigour, and an 'investigate - model - test' method break down because of the diversity present. Any research methodology must make as complete an investigation as is possible, but be both pragmatic and valid in its analysis and conclusions [11].

Most importantly, the investigation has shown that methods for the management of design time do exist, but are scattered and locked away in the form of company experts; they may be successful design office managers, engineering managers or even marketing managers. Further research must attempt to learn from this knowledge, and integrate it into a whole.

This last requirement points towards methodologies from artificial intelligence and cognitive science. Techniques such as participant observation, cognitive mapping and protocol analysis have proved both practicable and reliable, given a thorough understanding of their shortcomings [12,13,14,15].

Targets for Further Work.

Further research is progressing with the aim of producing a coherent and workable system for the progressive improvement of design estimation through a more thorough understanding of the specific factors which affect design times in companies. The three methods mentioned above will be used in unison to produce a model of the design estimation procedure, the triangulation compensating for any methodological weaknesses and cross validating results. This generic model will be used to work out improvements for estimation procedures and the best ways of implementing them. Once implemented, the change in design office performance will be measured and the value of the results assessed for fine tuning any new system. The ultimate target is to generate a general framework for the model - optimise - implement - test cycle which may be used by any firm unhappy with their due date performance or new project turnover.

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Mr N.J. Weston
School of Engineering and Computer Science,
University of Durham Science Laboratories,
Durham,
DH1 3LE
United Kingdom

Professor J.E.L. Simmons,
Department of Mechanical Engineering,
Heriot-Watt University,
Riccarton Campus,
Edinburgh,
EH14 4AS
United Kingdom

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