# "AN INVESTIGATION OF THE SUITABILITY OF COST MODELS FOR USE IN BUILDING DESIGN"

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# An Investigation of the Suitability of Cost Models for use in Building Design

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## ABSTRACT

It is proposed that cost models of various types are becoming more widely used in building design, but that their limitations in this application have not always been recognised. This research is an attempt to identify and quantify these limitations. After an initial examination of the building design process the literature of cost modelling in building design is reviewed.

The features of models in this context are considered theoretically and a set of performance criterion are identified. Three suitably defined models are presented, a superficial area model, a model for the evaluation of a subset of building regulations and a cost model for air-conditioning system design.

The work then proceeds to evaluate the quantitative effects of the criteria upon these models. Each model is examined in detail. Conclusions are drawn with respect to the relevance of the criteria upon these models. Each model is examined in detail. Conclusions are drawn with respect to the relevance of the criteria themselves and the implications of the results gained here for the wider use of cost models in building design, are assessed.

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# CHAPTER 1

# BACKGROUND, OBJECTIVES AND METHOD OF RESEARCH

1.1 Introduction

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# CHAPTER 1

# BACKGROUND, OBJECTIVES AND METHOD OF RESEARCH

## 1.1 Introduction

This introductory chapter describes the context of the research problem addressed later, the objectives of the work and the method of research employed. Thus it is not merely a summary of the thesis but provides relevant additional material. The wider issues of construction economics and computer aided design are discussed initially. There follows a treatment of the specific area of design economics, the techniques of which are the concern of this thesis. From this, some problems pertaining to the application of models in design economics are identified and the objectives of this research are outlined. Finally, the method of research used in this work is described.

## 1.2 Economic Theory and the Construction Industry

The subject matter covered by the term "construction economics" is indeed widely based. Economics is concerned with the allocation of resources, in these terms construction economics clusters into four major areas of importance. These areas are macro-economics, planning economics, design economics and site or production economics.[1]

Macro-economics, in this context, is concerned with the relationship between the construction industry and the economy. The industry itself is a relatively large one, the value of the final product of the industry makes up about 12% of the gross domestic product.[1] Hence, any changes in the activity or efficiency of the industry are likely to have significant effects on the national economy. The central issues of macro economics in this application are firstly, the measurement of demand for the various types of building, for example, housing, social and welfare type buildings, industrial projects, etc. Secondly, the supply side of the industry involves a consideration of the nature of construction firms and materials' manufacturers and suppliers. This is necessary in order to evaluate the capacity of the industry, knowledge of which is a vital input to economic and social planning.

Planning economics is the regional level of construction economics. Urban and rural planning teams need to undertake demographic and cost-benefit analyses to assist them in deciding on the locations for the various buildings and developments under their control and also as inputs to the regional and local plans.

At the level of the individual project we may distinguish between the economics of the design and of the production process. Design economics seeks to assist the building designer by providing him or her with the information necessary to complete a design within the economic constraints of the client. This will involve economic comparisons of design alternatives, and also some prediction of the likely tender cost of the building. Recently a longer term view is being taken and the life-cycle implications of design decisions are beginning to be considered. In the United Kingdom the techniques of cost analysis and cost planning have, in the past 25 years, been developed from the established traditional tendering procedures and the documents which are produced as a consequence.

The economics of the production process is addresed to the allocation of resources in assembling the physical building. Construction managers seek to optimise the use of the resources needed to constuct the building. These resources will include labour, plant and equipment, supervisory staff, financial charges on working capital. The objective may be to maximise profit, or turnover, or to avoid loss while keeping the workforce occupied. Clearly the choice of objectives will depend, among other things, on the manager's perception of the state of the market.

Many of the difficulties of 'cost modelling' in building design, which are raised later in this chapter, arise from the nature of the construction industry in economic terms. Buildings are unique, tailor made products. In marketing jargon, each one is 'individually designed' and 'custom built'. This leads to a number of features of the industry which have implications for the application of any form of economic model.

Each 'product' (or building) is produced only once. Hence there are no prototypes and no long production run which may be used to refine the design and sort out any difficulties. Clearly this places an increased reliance on models. Each building is unique. If no two buildings are the same, models of building cost which rely on comparisons have an inherent weakness. Buildings are designed and built by teams of people who are temporarily brought together, usually for one project. The nature of the tendering process in the U.K. ensures that after a project has been completed, the team breaks up and individual firms and members go on to new projects. This random gathering of personnel increases the dissimilarities between projects. This characterisation of the fluid nature of project teams is not universal, but is certainly the case in the majority of building work in the U.K. at least. Finally, the method of price determination is in most cases a discrete process for each project.

Thus theories of economics which deal inadequately enough with the production of toothpaste or motor cars or wireless sets, do not sit at all easily upon the design and production of buildings. The above are, in economic terms, some of the dominant features of the construction industry and of the design of buildings in particular. Before proceeding to consider in detail the techniques of building design economics, there is one other major feature of the construction industry which warrants attention, it is computer aided design.

## 1.3 Computer Aided Design

It is well known that models of various types have been used in architectural and engineering design for thousands of years. However, the nature of these models has changed immeasurably in the last fifteen years, since the introduction of computer aided design (CAD) in education and in practice.[2] The number of appraisals which may be carried out on alternative design proposals has increased greatly as has the amount of detail which may be incorporated in each.

Consider as an example "FACET", a computer based design aid which appraises and simulates lighting design.[3] This model enables the designer to position luminars anywhere in a room or building, they may be suspended, flush or recessed.

The designer inputs the orientation of the space and the size and nature of the fenestration. The model may then superimpose the daylight level on the artificial lighting levels for any time of the year and day, producing as output contour lines of consistent lighting levels. The model may then be used to explore the energy likely to be saved by incorporating automatic dimming or switching. The example has no particular significance other than to show the level of detail of appraisal which may be carried out, any one of a dozen or more CAD models on the market could have been chosen. Before the advent of CAD such a detailed appraisal would have been so time consuming as to have been undertaken only in very special cases.

However, there are a great many unknowns. One of the most important is that the field of CAD (at least in terms of its general application to building design) is too young for anyone to hazard a guess at the nature of its real effects on the design process. Clearly it increases productivity but does it have an effect on the type of solution reached by the designer? Some experimental results, which indicate that the solution derived for a design problem is related to the method used to represent the problem are discussed in chapter 2. Computer aided methods were not amongst those tested however.

The software required for CAD models of any import is highly complex. The writing of such complex software is, it is suggested, becoming less and less difficult. There are at least three reasons for this. Firstly the proliferation of increasingly structured and powerful high-level programming languages. Secondly the increasing availability of more powerful hardware. It is now possible to obtain 32-bit hardware in desk-top configurations. Plotters for example, now have much software built-in to the hardware, this gives immediate access to functions such as scaling and rotating which ten years ago would have required additional software on the part of the programmer. Thirdly, the ubiquity of the computer itself has important consequences for the future generations of analysts and programmers, who are becomming familiar with the techniques and philosophy of computer science from a much earlier age.

If indeed CAD software is becoming less difficult to write, one could assume that there will be an increasing number of CAD systems on the market. This has a number of implications. Many people will be in the position of using CAD models where they do not have the skills to perform the appraisal calculations manually themselves. There are both beneficial and detremental consequences. One such positive consequence is the increasing ability to incorporate building users in a much more active role in the design process. On the other hand, some designers, technicians or operators may not be aware of the complexity of the modelling and appraisal computations and the assumptions on which they are based. Computer scientists have long been familiar with misinterpretation of results and the attribution of a greater degree of accuracy than is really warranted. Unfortunately there are no concrete answers to many of these questions. CAD systems purveyors usually emphasise that the designer him or herself should be the one to use a CAD system or model, and not an operator or technician. The field is too young to establish with any certainty the longer term effects of CAD.

## 1.4 The Techniques of Building Design Economics

This research is concerned with just one aspect of the wide spectrum outlined above, namely the economic models which are used to appraise building projects during the design process. An underlying principle of the work is that economic performance should be incorporated as one of the active criteria to be considered in the appraisal of any building design. It is not held that economic performance is the most important criterion, economic models should service the designer with clear, accurate economic information which he may consider together with the other constraints of the brief, the site and any aesthetic matters. The task of optimising these decisions is usually carried out informally by the designer or design team, although some CAD models attempt to do this by using mathematical optimisation techniques. However, the techniques used in the economics of building design were not specifically designed as systematic computer based solutions to the problems facing the designer, rather they have evolved from the documentation and procedures used to award building contracts.

In the U.K. this procedure has usually been some form of competitive tender based on drawings, specifications and bills of quantities. The accepted tender is usually analysed in a summary form using up to thirty headings, this is known as a cost analysis. This analysis has become the most enduring model of building cost, the superficial floor area model.

Cost analyses are indexed for the time of the tender and are then used as comparisons to prepare a 'cost plan' for buildings currently on the drawing board. The techniques are discussed in detail in chapter 5, but a number of points may be made from the outset. Firstly the term 'cost analysis' is a misnomer, any accepted tender contains a very volatile tactical element which reflects the contractor's desire for the project and the state of the market. Secondly, the basis of the technique of cost planning is comparison. It was shown earlier that certain characteristics peculiar to the construction industry render methods of planning based on comparisons less effective than in other spheres of economic activity.

The advent of computer aids to the techniques of the economics of building design has been signalled by the emergence of two dominant model types, regression models and computerised versions of the old manual methods. The use of models based on econometric techniques is relatively new in the industry and has historically been very rare indeed in practice. Computerised versions of the manual techniques also bring their own problems. These issues will be discussed below.

## 1.5 Objectives of the Research

### 1.5.1 Problems Identified.

The climate of excitement and anticipation prevalent in the late sixties was reflected, and perhaps even generated in part, by the writings of Negroponte and the CAD research group at MIT. There is no doubt that the fervour lead to vastly over-optimistic goals being identified. The future has turned out to be far less spectacular than was anticipated. This has been a reflection of the experience of systems science generally. Churchman, one of the leading figures in early operations research, articulated this inadequacy and suggested reasons for it and a direction out of it in his "Towards Theory of Application in Systems Science" in 1975.[4] It is worth considering briefly some of the points raised.

Grouping together the fields of organisational development, economic models, ecological models, biological models, operations research models, planning models and decision theory under the general title "social systems engineering", it was proposed that "most of the important decisions made in today's society do not seem to be influenced by any of the items on the preceding list".[4] This has been recently echoed in economics by the view of Thurow that economic models and theory bear little relevance to the 'real world'.[5]

Churchman proposed that the modeller himself is a system and that for the systems scientist to function, at least three major assumptions have to be made, namely:

1. The systems scientist has the ability to identify the 'felt need' of the client, and can translate it into a set of realisable specifications.
2. By creating a system of measurements and models, the best route to realisation may be identified.
3. The systems scientist can communicate prescriptions to the decision makers which will cause them to adopt the route to the goals.

This gives rise to the paradox of the model builder who is so curious about the alternative decisions of his client, but shows little curiosity about his own decision making. Thus we have a situation of having rational decision aids which are not applied in practice. However, there are approaches which are not 'rational' but which are 'applied'. These include the 'political', based on the assumption that all those who are able and who so wish, may exert influence so that society makes changes, the resultant of all these influences is the appropriate policy for society. Similarly, there are aesthetic, moral and religious approaches. The systems approach by itself is inadequate, other approaches manage to capture reality in ways that systems analysis can never do. The solution lies in a world where the conflict between approaches is beneficial and not detremental as it is now.

A plausible counter-argument would be to suggest that we have only considered the negative aspects of the development of systems analysis. This is true and there have been major achievements due to the process of modelling, but the fact that inadequacies have been identified should lead us to take a critical look at the tools and techniques of modelling. Models are themselves complex entities which need to be carefully designed to suit their purpose.[6,7]

### 1.5.2 Objectives of the Research.

It has been shown above that as more experience has been gained in the use of models of various forms as problem solving aids, so too has there been, in research circles at least, an increasing awareness of the inadequacies of systems models. This is not altogether surprising, there is an old saying "the more you know, the more you know you don't know!" T. S. Elliot put it more elegantly in his Choruses from "The Rock", "All our knowledge brings us nearer to our ignorance ....."[8]

The optimistic solution to all this is to learn from experience and to rigorously examine the tools and techniques of modelling in order to improve them. It is therefore worth noticing that most of the models reviewed in Chapter 3 have been produced independently as particular solutions to particular problems. Each published study gives an account of the model and its features and area of application. Some of the more thorough presentations describe weaknesses and limitations of the model. Noticeable by its absence, however, has been any attempt to stand back and take a critical look at the techniques of model building in this field in order to avoid repeating the same mistakes or producing models with similar weaknesses. Further, the increasing number of commercial applications of CAD means that many models are not presented for discussion and criticism in academic journals, rather they enter the market place as the children of systems purveyors who have no immediate interest in exposing weaknesses in their models. On the other hand of course, it may be said that their long term interest will be well served by investigation of this nature.

Therefore, it is proposed that although the use of models in building economics has increased, little attention has been given to the evaluation of the strengths and weaknesses of the modelling techniques currently being developed and used by researchers in this area. This research attempts to obtain some quantitative results of these strengths and weaknesses based on criteria derived from a critical study of current work.

To this end, the objectives of the research may be summarised as follows:

1. Make a critical review of existing cost models applied to building design.
2. Study the relationship between the design process and cost models.
3. Identify a set of criteria by which the performance of cost models may be measured.
4. Produce quantitative results, testing the influence of the named criteria on the performance of specific models.
5. Review the criteria on the basis of the results and reformulate if necessary.
6. Evaluate the significance of the results gained and indicate areas where further work is necessary.

## 1.6 The Research Method Employed

This work is predicated on the assumption that models are best discussed in the concrete rather than the abstract. This being so, an overview of the method adopted is that of an experimental investigation, insofar as that is possible in this field. This thesis does not consist of the description and justification of a model or models. In fact three such models are presented, their major role is that of being part of the apparatus used to test the influence of certain criteria on the performance of models. Their secondary role is that of representing very good examples of their genre. The method of research may be summarised.

1. Examine the nature of the design process.
2. Review the literature of 'cost models' in building economics.
3. Make a critical study of the models reviewed. Identify recurring problems in the models.
4. Identify a set of criteria by which the performance of models may be evaluated.
5. Build and validate a set of suitably chosen models.
6. Test the quantitative effect of the above criteria on the models.
7. Evalute the significance of the results. Check whether the results from specific models have any validity when applied to models in the field generally.

Research of this nature necessarily crosses the boundaries of many disciplines, which in this case have included economics, construction technology, computer science, the philosophy of science, design studies, system modelling, building regulation, air-conditioning design. Throughout the thesis a serious attempt is made to avoid presenting information which is easily available in the text books of these areas, where relevent the reader has been referred to the original sources.

The research for this thesis was funded by a Local Authority assistantship and a donation of a microcomputer to the Polytechnic. This gave rise to two minor constraints on the research. Any models built were to be applicable to multi storey office buildings and any software was to be capable of being supported on a microcomputer, although clearly the full mainframe facilities of the Polytechnic were available for the purpose of analysis. Finally, due to the public funding of the research, the computer code for the software developed during the research is presented in the appendices. This code is not an integral part of the thesis, it is presented merely to give access to software to any interested researchers.

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# CHAPTER 2

# THE NATURE OF BUILDING DESIGN

2.1 Introduction

2.2 Design

2.3 Design Methods

2.4 Empirical Work

2.5 Synthesis: The process of building design

## 2.1 INTRODUCTION

This chapter considers the nature of the building design process. The economic models, which are later described, criticised, built, tested and which generally form the core of this research, do not exist as entities in isolation. They exist in a context, and that context is the design of buildings. Any critical examination of models which neglects to give detailed consideration to the context in which the models exist, is incomplete to say the least.

On the other hand this is not presented as an authoritative, comprehensive review of the 'state of the art' in design and the study of design, that is perhaps best undertaken by a designer or a specialist in design studies. The building economist can only hope to consider the most important of the historical approaches coupled with a survey of current thought on the subject, and from this to draw conclusions regarding those features of the design process, as it is presently understood, which have an impact on the derivation and use of economic models in building design. The building economist, if he is to build models which provide useful information for the designer, needs to be aware of the nature of the problem which faces the designer and also of how the designer sets about his task. A thorough and comprehensive review of the economic models themselves which are central to this thesis is given in the following chapter.

It is worth reiterating that the economic models considered later, exist to service the building designer with information to assist him/her in making good decisions which hopefully lead to improved design. How is it possible to recognise a building which has an improved design? Why do we regard some buildings as being well-designed and others not? A first attempt to understand the characteristics of the problem would be to listen to working designers descriptions of how they have designed certain of their buildings. A book published in 1980 did just that, ten internationally acclaimed architects, each with major buildings to his credit, discussed their own processes of design and construction.[1] This produced ten different descriptions of the design process which primarily outlined the most important of the personal concerns felt by each designer but added little to our knowledge of the general case. On the other hand, it is possible to read articulate descriptions of design methods and descriptive models of the design process by people who do not have acclaimed buildings to their credit. The suggestion would seem to be that good designs may be produced when the books have been thrown away, but as in so many other areas you cannot throw the books away until first you have read them. This maxim provides some justification for the solution-oriented teaching of design which takes place in schools of architecture.

The process of design is notoriously difficult to study (whether indeed the term "process" is applicable is itself a matter of some debate and is discussed below.) The difficulty is increased by the fact that the only evidence it is possible to physically observe is the end product, the building. It is important also to have some knowledge of the mental activities which take place during the period before the design problem is solved. To this end the strategy of this chapter will be as follows: firstly the activity of design will be considered in terms of definitions and aims and conceptual views; secondly some design methods will be considered as these often throw light on the process itself. Finally the relevance of the above to building design and to economic models in building design will be discussed.

## 2.2 DESIGN

Until relatively recently the act of designing buildings or artefacts had not been very well documented. Literature began to appear in abundance in the early 1960s. The concern was with 'Design' in the global sense, encompassing, inter alia, painting, crafts and all branches of engineering.[2]

While it is impossible (or at least extremely difficult) to ascertain the mental processes which take place when a designer is at work in the traditional sense, i.e. without the aid of design methods, there are however three points about which many writers agree. These have been outlined by Jones[3] and may be summarised as follows:

1. There are very often long periods when the person who is about to make an original work seems to do nothing except take in information and labour fruitlessly at seemingly trivial aspects of the problem. This is known as 'incubation'.

2. The solution to a particular problem or the occurrence of an original idea often happens when at some particular point in time everything seems to fall into place. This is known as the 'leap of insight' or 'change of set'. Basically the problem is perceived in a new light and very often an apparently complex problem turns into a very much simpler one.

3. The main enemies of originality are mental rigidity and wishful thinking.

This view of design owes much to the Gestalt school of psychology, prominent in the first half of this century.[4] This school aimed to articulate some of the processes and representational structures which underlie behaviour and consciousness. However current thinking and recent experimental results (in the past 12 years) have greatly reduced the importance of the school,[5,6] and indeed of schools in general[7] in this context. As the phenomena of incubation and change of set must be familiar to most people who have ever had to deal with a seemingly difficult problem (building design certainly qualifies) they are worth pursuing a little.

Incubation as a concept came into currency in psychological circles in 1929 with Poincare, whose work was anecdotal and essentially derived from the introspective accounts of eminent scientists and artists.[8] He saw the conditions for creativity as:

1. A period of conscious work, data assembled, problem defined etc. and some trials made at solutions.

2. The unconscious works at useful and fertile combinations during this time and useless areas are inhibited.

3. Hypothesis is derived which gives a fruitful direction. In his own words 'a period of preliminary conscious work always precedes all fruitful unconscious work'.

The implication of Poincare's work and of the first two points proposed by Jones[3] was that following a period of intense work, the solution to a problem was likely to pop into the mind spontaneously after the problem had been set aside for a while.

This of course assumes that design is a 'problem-solving' activity. For the sake of argument we will assume further that in building design the particular design which is eventually produced is the 'solution' to the 'problem' as perceived by that particular designer. We should not assume that it is the only solution or that its accuracy is in any way objectively measurable, but merely that it is a solution to the problem as perceived by the designer. The further implication of both Jones and Poincare was that the solution was produced by an unconscious thought process. This mystical approach is remarkably similar to the concept of 'satori' or enlightenment in Zen Buddhist thought.[32]

Empirical evidence which apparently supports this was presented by Silveira in 1971[5] who found that an interruption after a period of effort lead to an increase in the probability of solving a problem for both long and short interruptions, with respect to a control group. A further finding was that subjects did not return from the interruption with complete solutions in hand. It is important to know why this is the case, but this is not so clear.

Some possible explanations are:

(a) Incubation is a matter of rest. Rest gives a break and reduces fatigue.

(b) During incubation the subjects forget inappropriate sets and directions formed during the original strategy searching.

(c) The rest provides an occasion for additional practice on the problem.

(d) Incubation offers scope for a chance occurence of an external event which completes the problem.

(e) Unconscious processes result in a random fusion of memory structures. This is blind and undirected but selected by the tendency to retain the more appropriate attributes and fusions which contribute to the solution.

One reason why this approach does not enjoy much currency today in cognitive psychology is that, although providing a useful conceptual framework for the discussion of problem solving and the carrying out of creative or original works, it does little to tell us how these are done. Current thinking on human cognition tends to view thought processes in terms of information processing theory,[6] which will in outline form be familiar to anyone who has a rudimentary knowledge of computer science.

The whole field of "design studies" which is even now a keenly contested field of debate has, like any relatively young discipline, been characterised by large numbers of 'theories' and 'conceptual frameworks' and relatively little empirical evidence. This of course increases the difficulty for an observer in identifying the main characteristics. A consideration of differing definitions is often helpful. The literature surveyed produced almost as many definitions of design as there were writers on the subject. A diverse selection follows:

> "To initiate change in man-made things"
>
> (Jones)[3]
>
> "Finding the right physical components of a physical structure"
>
> *(Alexander)[9]
>
> "The optimum solution to the true need of a particular set of circumstances"
>
> (Matchett)[10]

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* A very early (1963) definition from Alexander and one he may not hold now, it is presented merely to indicate the range of the definitions in the literature, and not as his current view.

> "The architecture of Beaubourg becomes an expression of the process of building: the optimisation of every single element, its system of manufacture, storage, transportation, erection and maintenance all within a clearly defined and rational framework"
>
> (Richard Rogers)[11]

It is accepted that the quotation from Richard Rogers is not strictly a definition of design but it is relevant all the same. The differences among these definitions are indicative of the complexity of the issues involved. The words of Jones and of Matchett are clearly intended to refer to design in the general sense, they are presented here though for the light they can shed upon building design, the form of design which is the concern of this chapter. The definition of Jones is difficult to argue with but it seems to be based on the doctrine of reducibility carried to its logical conclusion and tells us little. By the same token, a biochemist could define design in terms of the chemical changes taking place in the neurones, its verity, although admirable would not be of assistance in this context. The definitions of Matchett and Rogers are appealing but they assume that the true needs of the particular set of circumstances can be established and furthermore that the optimum can be located. However, it is helpful in that they hint at one of the central difficulties of design, which will be referred to again below, namely that in design the task of identifying problems may be as great as or greater than, the task of 'problem solving'.

However, there is something missing from all of the above definitions, surely design is more than a mere exercise in optimisation. In the experimentally based research embodied in this thesis there were few opportunities to express subjective responses. This however is one, and the author's preferred definition (that of Norman Foster) is presented below. It embodies the priciples of: (i) optimising many variables to satisfy needs; (ii) of the whole being more than a mere assembly, and also (iii) that design is not a process at all.

> "Design is really a tool. It is a means of integrating and resolving the inevitable conflicts that range from public/private to socially acceptable/commercially viable, in order to reconcile the artistic aspects of making a building with cost, time and quality control. By trying to optimise all the givens within a consistent framework of values upon which design decisions are based, we try to arrive at a whole which is more than the sum of its parts."
>
> Norman Foster (1980)[12]

## A Three-Way View of Design

In his influential text first published in 1970, Christopher Jones presented an analytic, although conceptual, view of design in the context of his work on design methods.[3] He proposed that while working on a problem the designer was engaged simultaneously in three types of activity.

1) Creativity; or the designer as a black box.
2) Rationality; or the designer as a glass box.
3) Control over the design process; or the designer as a self-organising system.

Clearly they are only separable for the purpose of discussion but they do seem to sum up rather well the type of thought processes required.

### Designer as a black box

The main characteristics of black box design are:

(a) The output of the designer is governed not only by the inputs received from the problem in hand, but also from past problems and other problems. Each new task is viewed in the 'light of experience'.

(b) His capacity to produce outputs relevant to the problem depends on his being given time to assimilate and manipulate within himself images representing the structure of the problem as a whole.
During a long search for a solution he may perceive a new simpler way of structuring the problem - the 'leap of insight'.

(c) Intelligent control over the form in which the problem is fed into the human black box is likely to increase the change of obtaining relevant output.*

Designer as a glass box

Most of the formalised design methods produced in the '60s and '70s for the design of buildings come under this heading, they tend to envisage the designer as a human computer acting only on the information that is input, and then following through a planned sequence of evaluating synthetic and analytical steps and cycles until he recognises the optimum solution.

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* Empirical evidence which would seem to support this was reported by Eastman working in the U.S.A. in 1970. It is discussed in section 2.5.

The more common characteristics of the glass box methods are:

(a) Objectives, variables and criteria are fixed in advance.
(b) Analysis is completed or at least attempted before solutions are sought.
(c) Evaluation is largely logical.
(d) Strategies are fixed in advance.

Designer as a Self-Organising System

As the designer works at his problem, various avenues will be explored as possible sources of solution. There are far too many for each to be fully evaluated, so as work continues on the central task, the designer needs to constantly enquire of himself whether this route is likely to prove fruitful or not. In fact there appear to be two choices:

(a) Make a black box (arbitrary) choice of routes to be explored.
(b) Plod away at the impossible task of evaluating each proposal separately.

In reality it seems that designers often take neither of these two, but work on their problem by dividing the available design effort into two:

1. That which CARRIES OUT the search for a suitable design.
2. That which CONTROLS AND EVALUATES the pattern of search (Strategy control).

By doing this it is possible to replace blind searching through alternatives with an intelligent search that uses both external criteria and the results of partial search to find short cuts across unknown territory. Strategy control seeks to relate the results of small pieces of search to the ultimate objectives even if these are in a state of flux.

The above view of the activities of the designer is based on a development of Jones' approach to design methods. As mentioned earlier, the dearth of empirical work means[3] that there are as many views as writers and little means to judge rationally which are the more valid. It has been presented here to add to the 'character sketch' of the design process which is being built up in this chapter.

## 2.3 DESIGN METHODS

The 1960s and early 1970s produced a number of 'design methods', formalised methodical approaches to design. None of these methods found regular use among building designers. It is of course debatable whether there can be such an entity as a 'design method'. This is referred to again later. However inappropriate the methods were for practical use, they did reveal something about the design process. The earlier methods were very mechanistic and rational. In the '70s the tenor of the debate became softer with increased emphasis on user participation in the design process. There is little doubt that the two methods which most of all captured the public imagination were those of Alexander [9,13] and of Jones.[3] They are worth considering briefly.

### Alexander's Method

Based entirely on rationality, the essence of the method was as follows:

> "The form is the solution to the problem.
> The context defines the problem.
> The ultimate object of design is form.
> We need to fit the form to its context." [13]

Alexander saw the process of achieving fit between form and context as a negative process of neutralising the incongruencies or forces which carried misfit. As an apology for using a method to achieve this, he drew the analogy that there are limits to a person's capacity for mental arithmetic so that he needs to set bigger problems down on paper in a logical way.

Set theory was used as an analytical tool, the designer attempted to 'organise' his view of the problem by 'decomposing' the problem into a tree-like hierarchy of its subsets. For a real problem the hierarchy would be very large with many hundreds of elements. The aim was to identify the discrete sub-problems of a decomposition. Independent solution of the sub-problems so identified would result in a solution to the design problem.

Although mathematically elegant, the method proved to be unworkable in practical terms. It did however make an important contribution to our knowledge of the design process. It took the view that the design process was a highly complex tree-like hierarchy where each component interacted with many others. Shortly afterward Alexander rejected his method completely [14,15] and moved on to a user oriented approach where the designer uses his knowledge to assist the user to design his own building. [16,17,18]

Jones Method of Systematic Design[3]

This was an attempt to logically represent the overall design process. It was not specifically directed at architectural design. The main stages are summarised below:

| | | | |
|---|---|---|---|
| 1. | ANALYSIS | 1.1 | Random list of factors |
| | | 1.2 | Classification of factors |
| | | 1.3 | Sources of information |
| | | 1.4 | Interactions between factors |
| | | 1.5 | Performance specifications |
| | | 1.6 | Obtaining agreement |
| 2. | SYNTHESIS | 2.1 | Creative thinking |
| | | 2.2 | Partial solution |
| | | 2.3 | Limits |
| | | 2.4 | Combined solutions |
| | | 2.5 | Solution plotting |
| 3. | EVALUATION | 3.1 | Methods of evaluation |
| | | 3.2 | Evaluation for operation<br>for manufacturer<br>for sales. |

The analysis stage is a divergent process where the problem is explored and a list made of all the relevant factors. This listing and classification of factors is intended to assist in the definition and organisation of the problems and sub-problems to be solved. Performance specifications are written in order to separate the problem from the solution, the requirements and factors are rewritten as performance specifications with no reference whatever to shape, materials and design.

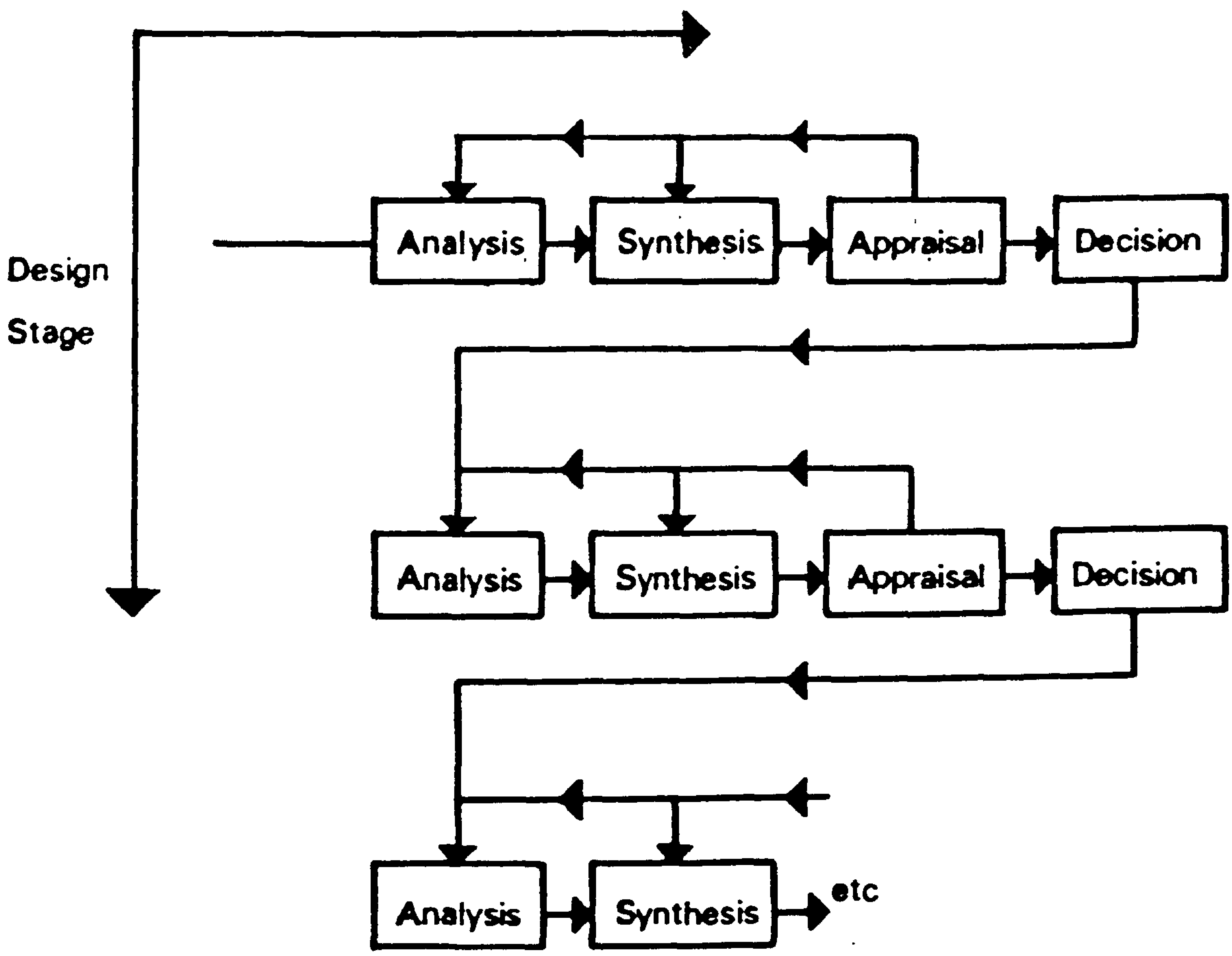
The synthesis stage is one of convergence. It is the black box stage in this design method. The method aimed not at finding a single solution, but at establishing a range of solutions and clarifying the points where they fit or do not fit the specification. Evaluation was taken to mean any method by which deficiencies in the solution chosen may be detected before it becomes prohibitively expensive to correct them.

The method was presented as a means of resolving the conflict between logical analysis and creative thought. He attempted to keep logic and imagination apart by external means, i.e. by keeping an external written record of all the ideas at various stages while at the same time allowing the mind freedom to produce ideas, solution hunches, etc., without confusing the process of analysis. The method does give a mechanistic representation of the process of design, but clearly it is not the kind of method which many designers would find it pleasing to work through in detail because of its sequential and severly logical nature.

However, the contribution made by Jones' method is that it concentrates attention on what has become known as the 'analysis synthesis appraisal loop'. This loop, which was first proposed by the Building Performance Research Unit and developed by Maver, is one of the few views of design upon which most writers agree.[19,20] It has underpinned most research and development in computer aided architectural design for the past 13 years. It is summarised in figure 2.1. Neither Jones nor Alexander gave any formal recognition to the iterative nature of the design process. The analysis synthesis appraisal loop makes up for the short-coming.

## Design: a procedural approach

Regardless of whether a particular design method is used or not, most working building designers advance through broadly similar procedural stages. As we have seen, it is normal practice to reduce the total problem to a number of design sub-systems in order to render the design of the total building into a manageable process. Wilson has indicated the wide use of this approach by pointing out that it has become formalised procedurally by specialist designers dealing with distinct sub-systems, e.g. services designers, structural designers and also by the nature of the generally accepted fee structures and forms of documentation.[21] This was portrayed in diagramatic form as



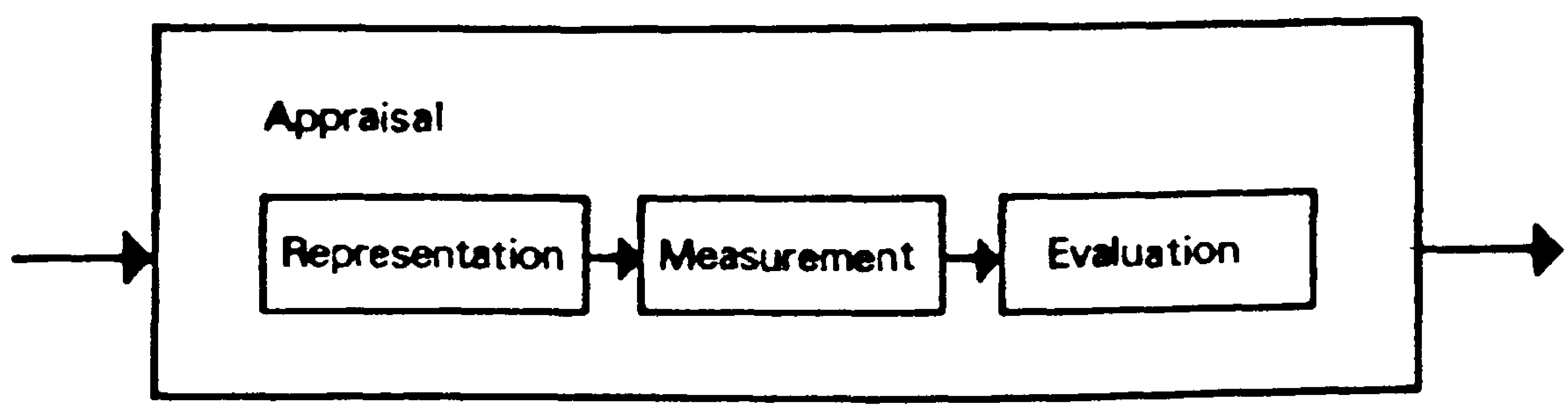




Fig. 2.1 MAVER'S 'MODEL OF THE ARCHITECTURAL DESIGN ACTIVITY' – from MAVER[20]

in figure 2.2.

This consideration of the design process being tackled as a series of discrete sub-problems, while indicating fertile ground for the generation of sub-optimal overall solutions, does at the same time have considerable relevance for economic modelling. Namely detailed economic models for particular sub-systems will not by their nature be alien to the methods of a practising designer. This is referred to in detail in Chapter 4.

Before drawing together the issues discussed above, the results of some experimental studies will be considered.

## 2.4 EMPIRICAL WORK

As pointed out earlier, there have been relatively few reports of experimental studies of the design process and the behaviour of designers. The literature search of publications on building design and the journal "Design Studies" yielded about ten reports of this nature - most of which have been reviewed by Lera.[22] It should be stated, however, that the vast literature of cognitive processes in psychology was not searched as thoroughly or knowledgably as it would have been by a professional psychologist. Two of the most significant reports will be discussed briefly

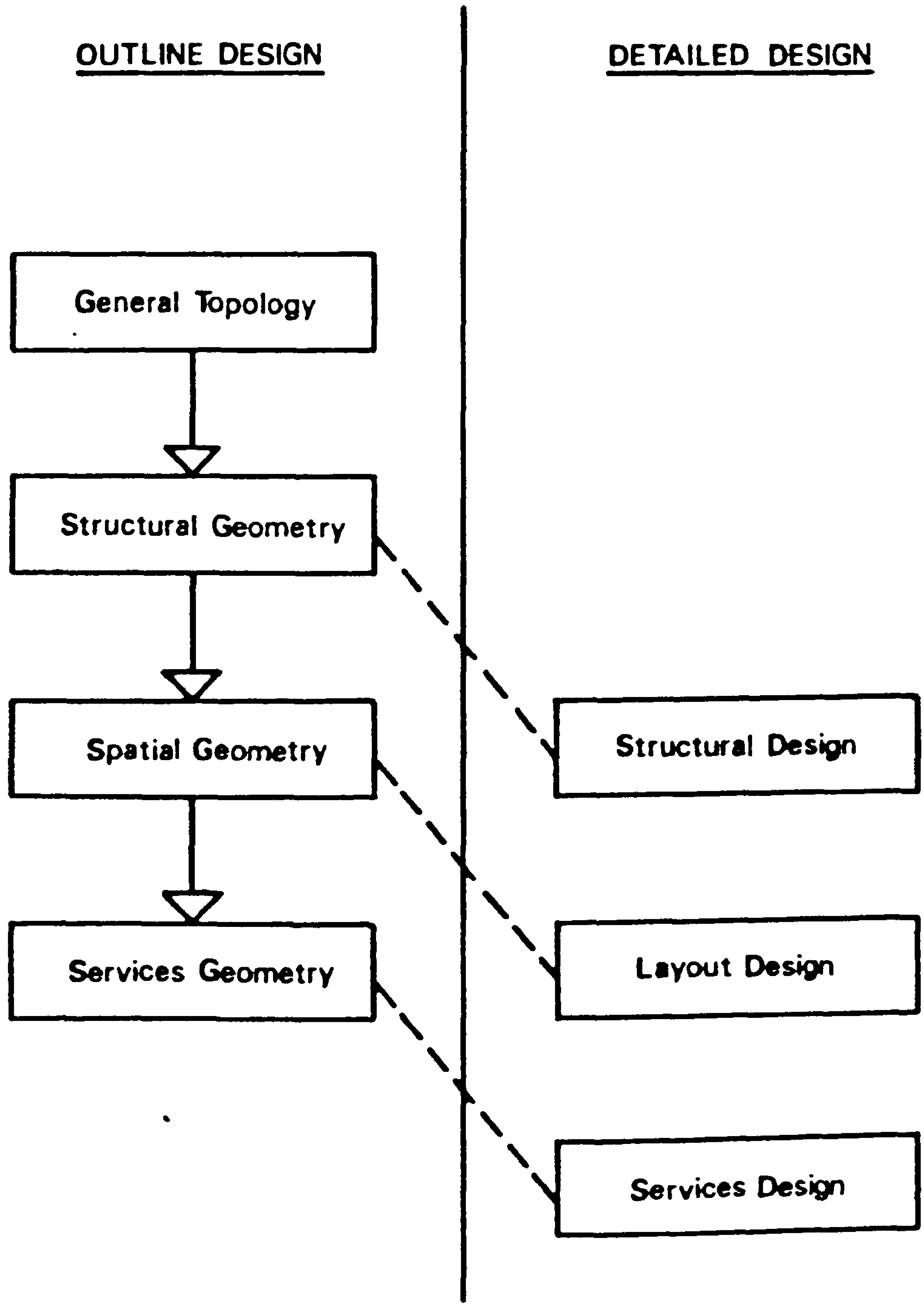



Fig. 2.2 THE HIERARCHICAL NATURE OF THE DESIGN PROCESS – from WILSON [21]

here (and in a simplfied form), as they add to the issues already presented earlier in this chapter.

Eastman, whose work at Carnegie-Mellon was reported in 1970, was one of the first to study the work of designers under controlled experimental conditions.[23] He considered the forms of representation which were used by building designers, i.e.

Words

Numbers

Plans

Flowcharts

Sections and Perspectives.

He concluded that there was a significant correspondence between the types of constraints which were identified by designers when working on a problem and the form of representation which they used. The most often quoted example being that in the design of a bathroom it was only when a section was drawn that the ability of a child's hand to reach the taps became an issue to be solved in the design solution.

Simmonds of Oxford Polytechnic in the United Kingdom reported in 1980 on work carried out with 12 graduate students of Architecture in an American University.[24] He considered the decision-making strategy of the students at three different levels, only one of which (the overall level) will be discussed here. At the overall level he found that there was a wide variation in the way that the subjects went about solving design problems. Some analysed the problem, generated solutions and then considered implementation of the design. Other subjects generated solutions, used the solutions to derive problem definitions which were then tested against the brief. Others began by considering the resources available and the constraints on their use.

From these results we may derive the following general conclusions with respect to the building design process and the behaviour of designers.

(1) The number of solutions evaluated varies from designer to designer.

(2) The nature of the solution eventually chosen is related to the representational technique used in carrying out the design problem.

(3) Designers use a variety of representational techniques and also use different logical sequences in carrying out the design.

(4) If the above are true, there must be more than one 'correct' solution to each design problem.

The correctness of the answer depends on the way the problem was solved. There is an analogy with mathematical problems using, say, mental arithmetic, paper and pencil and computer, where increasing degrees of accuracy are required for the answer to qualify for being called 'correct'.

(5) Conclusion number (2) above has major implications for CAD and CAAD. The increasing use of program software based representational techniques by architects may change the type of solution reached to certain problems. Work needs to be done to check if the change is always for the better.

## 2.5 SYNTHESIS: BUILDING DESIGN

The discussion above has revealed many of the salient features of building design, the exploration or problem finding nature of the early stages followed by a synthesis and a proposed solution. The iterative nature of design has been mentioned but historically this problem has been dealt with inadequately. An example of this iteration is where a definite decision is made regarding the type of lights and light fittings say for an office accommodation relatively late in the design, the heat gain resulting from this decision could be outside the range assumed by the services designer, who may then find that the air-conditioning or heating plant may need to be adjusted to take this into account.

The truth may be that it is not possible to deal with this type of interaction exhaustively and in a methodical way. In order to allow for all cases, the minimum number of decisions to be anticipated would be the total number of combinations of all of the decisions made separately. The number of possible solutions becomes very large indeed and the effect of each could not be appraised without resort to very powerful computer aids. Iteration is necessary as the solutions to certain sub-problems create new problems and alter the feasible space for other sub-problems, some of which may already have been 'solved'.

The later work of Alexander[16,17,18] and proposals made by Krauss[25] and Gill[26] attempt to deal with the problems of non-linearity and the interactive nature of the decisions. The method as observed by Krauss was a dialectic or "to'ing and fro'ing" between the design problems and their solutions with continual iteration and adjustment of previous solutions. With each iteration more was learned about the nature of the problems. Gill suggests an 'adoptive approach' which is in conflict with those who have sought to derive a design method but does serve at a general level as a description of the design process.

"A decision process which has no long-term action other than heading off undesirable trends is more likely to achieve good results than a process which seeks to steer society in a pre-determined direction, selected on inadequate grounds."[26]

Finally, it should be recognised that very few designers will carry out the task in the same way and even if they did it might not be possible to show that this was indeed the case. It is for this reason that the descriptions of the design process which have endured have tended to be at a general and procedural level and not at a detailed level. Examples of this kind are the "RIBA Plan of Work"[27] and the descriptions of Maver,[20,28] and Jones[3]. The RIBA Plan of Work has the major fault of not acknowledging the iterative nature of the process, but otherwise it provides a very general description of the movement towards the detailed design solution. The approach based on the analysis synthesis appraisal loop takes account of all the problems raised above at a general level.

An often asked question is "is building design (or design generally) an art or a science?" The design methodologists of the '60s and '70s seemed to suggest the latter. The issue does have relevance here due to some recently published work. It has been argued that the idea of rational design as it is understood, i.e. conforming to the 'orthodox areas of science and deductive logic' is not appropriate or helpful.[29] Lionel March has criticised the 'Popperian models' as 'pernicious'.[30]

> "Logic has interests in abstract forms. Science investigates extant forms. Design initiates novel forms."[30]

Indeed it has been shown that the concept of 'scientific method' itself is in a state of 'epistemological chaos'.[31] Furthermore, Cross, Naughton and Walker of the Open University have recently presented an attractive view of design (when applied to building design) namely that, design is a technological activity[31] identified by these fundamentals.

1) Practical tasks. Technology is oriented not towards understanding but towards actions or solutions to defined problems.

2) Different kinds of organised knowledge are used, i.e. - Scientific knowledge
   - Craft knowledge
   - Design knowledge
   - Organisational knowledge
   - Managerial knowledge

3) The activity takes place in an organisational setting.

In conclusion, the various issues discussed in this chapter may be drawn together as follows.

The dominant characteristics of building design are:

(i) It is very complex and possesses a large solution space.

(ii) The problem to be solved is ill-defined.

(iii) The process is iterative due to the large amount of interdependency among decisions.

(iv) The solution reached depends on the techniques used and the way in which the designer approached the problem. These vary from designer to designer, thus it may be said that, to a degree, design is personal.

This then is the context in which the economic models discussed later exist.

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# CHAPTER 3

## ECONOMIC MODELS IN BUILDING DESIGN

3.1 Introduction

3.2 Systems and Models

3.3 Economic Models in Building Design

3.3.1 a proposed categorisation

3.3.2 deductive models

3.3.3 inductive models

3.3.4 optimisation models

3.3.5 stochastic models

3.4 Conclusion

## 3.1 INTRODUCTION

In this chapter a range of economic models for use in building design is presented. With regard to the models of this type produced in the United Kingdom, the review is exhaustive and includes the literature up to 1983. Some models from Europe and the United States are also presented. The review is preceded by a short discussion on the nature of models per se, together with some pointers to the literature where the definitive sources of information may be consulted.

The models discussed below are referred to in common parlance as 'cost models', a brief digression on the terminology is appropriate here. It will become clear that some models are concerned with building prices (in the economic sense, of market prices and tender levels) and others with the cost of buildings. The difference between the two is significant. 'Price' is that which is received by the vendor. 'Cost' is the sum of the payments to the various factors of production. Models of building price need to incorporate relationships which take into account market forces, in true 'cost models' this is not always the case. These concepts are defined and discussed more fully in chapter 4, it may be stated here that the term 'economic model' has been used throughout this thesis in order to avoid describing as 'cost models' certain models which are in fact models of price. It is accepted that the term used here is not perfect either, in that it may be confused with the 'econometric models' of economics generally, this is however regarded as a lesser evil, as they are often in fact specialised forms of this latter type of model.

## 3.2 SYSTEMS AND MODELS

### 3.2.1 Taxonomy of Models

Current approaches to modelling in problem solving generally are based on systems theory. A full outline of systems theory is outside the scope of this work, a definitive treatment has been given by Ackoff.[1] Suffice it to say that a system is an interdependent group of items forming a unified whole. Systems are composed of parts which are themselves systems or "subsystems". For example, the human body may be viewed as a system of interdependent limbs. Each limb is a system of cells, each cell is a system of chemicals in solution, etc. The relevance of this to modelling is that in solving a problem it is possible to chose a level of detail, more importantly, there is usually a level of detail (often called 'decomposition' or 'disaggregation') which is more appropriate than others for a given problem.

A model is generally accepted as being a representation of some observable system or phenomenon which exists in the real world and is represented for purposes of display or analysis. Thus a fashion model, a photograph or a computer program are all models. In operations research and decision analysis the definition is refined somewhat, such that a model is a representation of reality made sufficiently explicit for one to be able to examine the assumptions embodied within it, to manipulate it and experiment with it, and most important of all, to draw inferences from it which can be applied to reality.

It is counterproductive if, in order to achieve this, attempts are made to construct a model which resembles reality exactly, one may as well study reality. The point of constructing a model is clarification of the dominant aspects of a system. The model, therefore, is an idealised representation of that which is being studied. The generally accepted taxonomy of models which best shows the structural differences between model types, is that given by Churchman, Ackoff and Arnoff and outlined below.[2]

i) Iconic Models:

Iconic models are essentially scale-transformations of the real world system which they purport to represent, they are 'look-alikes'. For example, an architectural model represents a scaled down version of a building, with, for all intents and purposes, identical shape, colour, layout, etc. Although as with all models certain details are absent from the model, for example, heating, cooling and waste disposal installations. Sometimes there may be a loss of dimension, for example in a photograph, which is a two-dimensional representation of a three-dimensional subject.

ii) Analog Models:

Analog models are at a higher level of abstraction than iconic models, the properties of the real-world system under consideration are transformed. A common example in building economics is the cash-flow curve, where the property 'elapsed time in the project' is represented by the distance along a horizontal line. Similarly the property 'expenditure on the project so far' is represented by the distance along a vertical line.

iii) Symbolic Models:

The most abstract form of model, the symbolic model, is a mathematical representation of the phenomenon. A classic example is Boyle's law of gases which is expressed as:

$$P \propto \frac{T}{V}$$

where P, V and T are the pressure, volume and temperature of the gas.

The importance of models in general problem-solving can hardly be understated. The intellectual and cultural evolution of man took a great leap forward when for the first time he became able to construct an image of something that would happen in the future, when he became able to anticipate. An early representation by what we would call a model was in the cave paintings.[3] There is evidence that these paintings were used in ritual re-enactments both as a rehearsal in preparation and as an aftermath in celebration.[4]

Both Mumford and White have held that language is probably the most powerful model of all,[4,5] that language in fact was man's earliest model of the universe itself. The use of such models being the main reason why man's cultural and intellectual evolution to date have taken only a fraction of the time of his biological evolution. However, whether language is itself a model is debatable. It may be a 'meta-model' or a medium for modelling. In fact it could be viewed as the material which is used to build the models while the models themselves remain cognitive phenomena.

Turning now to the use of models, Tate and Jones of the Open University identified five different uses of models from a systems viewpoint.[6]

1. To communicate facts about the system.

2. To communicate ideas about the system.
3. To generate new ideas for designing or operating the system.
4. To predict how the system will behave in different circumstances.
5. To provide insights into why the system behaves as it does.

However, the distinctions are rarely so well-defined and models are often used for combinations of the above purposes. Many models predict behaviour without offering much, or any, insight into cause and effect. This should be discouraged, but it is often unavoidable. Many methods of predicting future trends, for example, increases in building tender prices or consumer demand, merely assume that current tendencies will continue. It is less than ideal to predict future behaviour without attempting to gain some understanding of why such behaviour should occur. A model which lacks some such understanding will, if some important factor in the mechanism of cause and effect changes, fail.

Guidelines for the general philosophy of model-building were clearly important background work in this research, but they are not germane to this review. A full treatment of these areas is given in references (7) to (10).

### 3.2.2 Economic Models in Building Design

The central purpose of this chapter is to present a review of previously published economic models in building design. Models have been discussed so far only in the most general terms, it is necessary now to consider in particular the process of modelling economic problems in building design.

Cost estimating in the construction industry is shrouded in mystique and plagued with low quality data*. Two problems for the application of economic models in building design have been outlined by Wilson.[11] The first is that since design takes place a considerable time before construction, economic modelling of the impact of design decisions involves forecasting the future economic situation, a notoriously difficult task even with good data. Secondly, the procedures in the United Kingdom and in many other countries mean that there is a very distinct separation between design and construction in terms of both task and personnel. This creates problems of conflicting perception of economic impact.

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* The quality of recorded economic data and the issues it raises are discussed in more detail in the next chapter.

The central problem to be addressed by economic models in building design is that of translating the decisions of the designer into some form of economic measure. The issues have been summarised by Wilson as follows.[11] To the designer the economic measure E may be expressed as:

$$E = F_1 (V_1, V_2, V_3, \ldots\ldots\ldots\ldots V_n) \qquad \ldots[3.1]$$

where $V_1 \ldots V_n$ are the designers decisions or design variables.

However, to the contractor the economic consequences of the building defined by the design variables $V_n$ are viewed as follows:

$$E = f_2 \left[ \sum_{i=1}^{n} R \quad (I + D)_i \right] \qquad \ldots[3.2]$$

where I is the indirect cost and D is the direct cost associated with each resource i.

Clearly the contractor views the building not in terms of the architectural form created but rather in terms of the resources it consumes, that includes the amount of materials and labour needed and also the indirect cost and overheads of various kinds necessary to carry out the work. The reconciliation of equations [3.1] and [3.2] is the central issue in the application of economic models to building design decisions.

## 3.3 ECONOMIC MODELS IN BUILDING DESIGN: A REVIEW

### 3.3.1 A Proposed Categorisation

A careful survey of the literature of the field revealed nearly forty published works which presented economic models applicable in building design. Some additional publications presented approaches to, or accounts of, estimating procedures in building design. Although not strictly 'models', some of the latter will, where relevant, be mentioned. The models are presented in groups. In each group one or two models will be described in some detail to give the characteristics of that particular group and the other members of that group of models will be briefly noted. The categories under which this review is presented are as follows:

i) Deductive models
ii) Inductive models
iii) Optimisation models
iv) Stochastic models

The categories were chosen merely for convenience of presentation of the models, they are open to debate and are not presented as a definitive classification. A more suitable classification for general use is presented in the following chapter. Some models display characteristics of more than one group, generally the models were placed in the group which most closely described their dominant features.

In the United Kingdom the function of providing economic advice during the design process has traditionally been undertaken by the quantity surveying profession. To that end, it has evolved procedures based on the needs of the various forms of building contract. Similarly, since the early 1960s it has developed various techniques of cost estimating during the design process. Examples are the cube method, storey enclosure method and functional unit method. These methods, although variously titled, are merely procedurally different, being based on the same assumptions and identical data. As the research embodied in this thesis is not linked to any one profession, a review of quantity surveying techniques would be out of place, in any case this has been well done elsewhere.[12,13] Accordingly, these methods are treated as one model and dealt with once only.

### 3.3.2 Deductive Models

Deductive models are models which are derived from collections of data by using the techniques of statistical analysis (usually some form of regression technique is used) to infer model relationships.* An instructive example of this group was presented in 1974 by Kouskoulos and Koehn of Wayne State University in Detroit, Michigan.[14]

The method was presented as a 'predesign cost estimation function'. It was based on a sample of 38 buildings which was widely based, and appeared to be, a random sample, rather than one designed to take into account the range of values of the variables. This has implications for the model which are commented on later. The structure of the sample is presented in table 3.1.

The function proposed was:

$$C=-81.49+23.93V_1+10.97V_2+6.23V_3+0.167V_4+5.26V_5+30.9V_6 \quad \ldots[3.3]$$

where

C = some cost measure of buildings (in the derived model C became the dollar cost per unit floor area)

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* A full discussion of the nature of deductive models is given in chapter 4.

| BUILDING TYPE | No IN SAMPLE |
|---|---|
| Office Building | 10 |
| Bank and Office | 1 |
| Housing, Apartments | 1 |
| College Building | 4 |
| Renovated Office Building | 1 |
| Health Science Building | 1 |
| Telephone Centre | 1 |
| Hospital | 1 |
| Hospital Addition | 3 |
| Chemistry Laboratory | 1 |
| Small Garage | 1 |
| Dental School | 1 |
| Home For The Aged | 1 |
| Medical School | 1 |
| Union Hall | 1 |
| High School | 1 |
| County Correctional Centre | 1 |
| County Jail | 1 |
| College Dormitory | 2 |
| Foundry | 1 |
| Factory | 3 |
| Total in sample | 38 |

Table 3.1 STRUCTURE OF SAMPLE IN KOUSKOULAS AND KOEHN MODEL[14]

$V_1$ = locality index; based on cost of living and wage differentials and taken from a publication on building construction cost data[15]

$V_2$ = Price index; compiled in a similar way to $V_1$ from municipal statistics

$V_3$ = Building type; an index compiled from the cost differentials among the various building types

$V_4$ = Height index; measured by the number of storeys

$V_5$ = Quality index; this attempts to measure: (i) the quality of workmanship and materials used in the construction process, (ii) the building use, (iii) the design effort, (iv) the material type and quality used in the components. $V_5$ was derived from the expression

$$V_5 = \frac{1}{K} \sum_{i=1}^{K} I_i \, C_i$$

where k is the number of building components, C is the portion of cost of the $i^{th}$ component and I is an integer between 1 and 4 (corresponding to fair, average, good and excellent) arbitrarily applied to that component.

In the derived model the number of building components k was 8, these were the building use (multi-tenancy, single tenant, mixed, etc.), building design (minimum, average, high loads etc.), exterior wall, plumbing, flooring, electrical, HEVAC, elevator.

$V_6$ = Technology index; this attempted to take into account extra costs of special types of buildings, or the labour and material savings resulting from the use of new techniques. $V_6 = 1$ for normal situations, $V_6 > 1$ for extra costs (i.e. chemistry lab = 1.45, bank = 1.75) and $V_6 < 1$ for savings as a result of technology.

Indices for these six independent variables were applied to the sample of buildings, a least-squares analysis was carried out on each of the linear equations which, when solved, simultaneously gave the function shown in [3.3].

Work of a similar nature has been carried out by Park, again in the U.S.A., and applied to the estimation of civil engineering projects.[16] A more detailed deductive model applied to just one building sub-system has been presented by Gould at Loughborough University.[17] Coincidently the sample size was 38 buildings. The building sub-system investigated was the heating, ventilating and air-conditioning installation, which was also the subject of a model presented in Holland in 1968.[18] The Dutch study found a relationship between the number of rooms and the cost of the installation in housing projects. The relationship was significant enough to estimate the cost of the installation.

The sub-system concrete frame in multi-storey buildings has been the subject of deductive models presented by Buchanen and Bowen.[19,20]

Flanagan and Wiles have developed similar models using regression techniques for lift installations.[13,21] Both models sought to predict the cost of the lift installation based on data such as the numbers of floors, the speed of the lift and the number of passengers to be transported. McCaffer has presented a number of examples of models for cost estimation based on regression analysis.[22]

In summary, deductive models have been presented both for the whole building and for particular building sub-systems. Most of the models reviewed above have relied on the use of the regression analysis technique, with cost as the independent variable.

### 3.3.3 Inductive Models

A detailed explanation of the nature of inductive models is given in chapter 4, section 4.1, which deals with classifications of model types. Here, the term indicates that the models presented in this section are all models where the economic measure (cost or price) is derived from an additive function. This function in some way breaks down the resource implications of the particular building design or sub-system design, applies to each some economic data relating to the amount of the resource used and then sums across all the resources to derive the relevant result. The traditional quantity surveying technique of cost estimation during the design process, by applying 'unit rates' to quantities of finished work, and the more abstract version of the same process, elemental cost planning, are examples of this group.[23]

The COCO cost model was developed during the early 70s at the Property Services Agency.[24] COCO stands for Cost Of Contractors Operations, it is a computer based model and operates by simulating a contractors planning and estimating departments. Further, it looks at a proposed design solution in terms of the plant and labour, evaluating and comparing proposed design solutions. With the exception of the related type of model proposed by Flanagan, this is the only model of its type.[13] This type of model has definite limitations at the strategic and predesign stages and it is here at these stages that the majority of the cost commitment is made. The COCO model specialises in the area of location of plant, frame erection times, efficiency of utilisation of tower cranes and consideration of the constraints imposed by the site on the contractors. Thus its main use can be seen as the appraisal of particular proposed design solutions in terms of initial construction cost. It is worth noting that during the design stage the client will not be setting constraints in terms of contractors operations but in terms such as lettable area, ancillary areas, circulation area etc. The main use of the COCO model would be relatively late in the design process, because of its lack of sensitivity to fine adjustments in early design decisions.

GOAL[25] is an example of a complex Computer Aided Design package which includes an economic model of the building to facilitate appraisal of the proposed design in terms of capital cost performance. The model simulates the traditional estimating practice in common use, the user sets up files of unit rates which are then linked to quantitative information. However, the speed of the computer means that the design process is not interrupted and the designer gains access to a central data-base.

The models above are essentially for price prediction and for the general appraisal of design solutions.

An example of a more detailed model is that derived by Moore and Brandon.[26] This concerned itself with the effects of some design variables on the cost of an in-situ reinforced concrete frame. Essentially this model was a natural development from the work of the Wilderness group who reported in 1964 on an exercise which had been initiated in the mid 1950s. Using standardised 1956 prices they studied 1,195 buildings considering the cost relationships for the following: storey height; floor loading; column spacing; number of storeys. This study considered only steel frames, graphs and nomograms were produced indicating the relationship between each variable and cost,[27] in effect a parametric model. The main drawback of the Wilderness report was that the limited number of relationships which were identified were static and soon became out of date.

Brandon and Moore[26] attempted to solve that aspect of the problem by linking a program for structural design to a database containing rates for the various items of work in the frame. The rates were designed so that they could be updated regularly.

The model was designed to provide two types of investigation.

(i) The exploration of the effect of bay area and length/breadth ratio of a building with slabs spanning in two directions.

(ii) The exploration of the effect of changing the number of storeys and shape of building on the frame cost using a fixed bay size and length/breadth ratio chosen from (i).

This model did not consist of a function relating design variables with cost, rather it linked a measurement and estimating program to a program for performing structural calculations for an in-situ concrete frame. Although the model was designed to carry out parametric studies, the nature of its own internal logic was inductive.

Smaller scale studies of a similar nature were carried out in the U.K. by Southwell[46] who considered compartmentation in particular, and by Flanagan and Norman who studied the relationship between cost/price and the height of buildings.[47]

A large computer based model has been developed by Logcher for price prediction of housing contracts in Israel.[28] This model was designed to take account of the iterative and hierarchical nature of the design process. This process starts with a small set of very broad and general objectives but as it continues the specificity of the objectives increases and choices are made concerning the level of satisfaction required for the objectives. As a basis for judgement the designer collects and compares as much data as possible about his problem. Sources for this data include codes of practice, legal regulations, the designer experience, and constraints implicit in the clients brief. COSTMOD treats a cost estimating problem as the construction and costing of a hierarchical tree of cost components.

Powell and Chisnall have developed a computer program BECON which replicates the traditional elemental estimating process with a data file of historic data which facilitates probablistic analysis of the results.[29] As the design progresses there is a facility for the generation of building quantities and the production of more detailed estimates. A model by Townsend, although similar in nature, achieved a simple simulation of the entire design process by taking into account the statutory constraints on design decisions.[30] The latter model was restricted to office buildings, but contained enough detail for simple parametric studies of particular design solutions, to be produced. Newton has presented a similar model although with a more sophisticated approach to the treatment of the economic data for the various building components.[31] This model recognised that the price for units of work is dependent on what Newton refers to as 'the context'. Before running the model the user builds up a "knowledge-base", by defining the value of the items of data for different contexts. The model then selects the appropriate value for each context.

Some inductive models are built specifically to carry out parametric studies, i.e. studies of the relationship between the physical parameters of the building (or sub-system) and cost. For example, Regdon studies the effects of eight parameters on the cost of European public housing (i.e. apartments in blocks up to 20 storeys).[43]

1785 dwellings were considered, the parameters investigated were:

1. Average dwelling area.

2. External wall area per square metre of floor.

3. Horizontal structures (by floor thickness).

4. Internal vertical structures.

5. Area utilisation ratio (total dwelling area to gross built area).

6. Number of dwellings, on a floor level, per staircase.

7. Floor to ceiling height.

8. Number of storeys.

The eight parameters were found to be sufficient to estimate the future cost of such apartments, graphs were produced showing the influence of each parameter on building cost and their order of importance.

Meyrat, working in Paris (again in a large-scale study) with hundreds of hypothetical dwellings designed to the standards and constraints for French public housing, carried out a sizeable parametric study.[44] Parameters investigated were the structural design and the marginal square metre. Unlike many of the optimisation models presented earlier, this study grew out of a very practical model, namely A.R.C.

A.R.C. was a method of predesign cost estimation developed in France in the mid 1960s.[45] It was used in practice for about a decade, mainly for apartment blocks. Public housing of this type comes under rigorous control and there are strict limitations on the provision of space for various functions such as circulation, storage space, etc. within each apartment and block. The cost is broken into two categories, the cost of each apartment (fabric, services and fittings) represented by

$$Pc = (S \times rH) + (L \times D_L \times rL) + P_N \qquad \ldots[3.4]$$

where,

- Pc = Cost of One Apartment.
- S = Floor Area.
- $D_L$ = Total length of internal partitions within the floor area S.
- rH = Minimum cost/$m^2$ of horizontal works, i.e. floors, ceilings, etc.
- rL = Cost/$m^2$ of vertical divisions, (half of the partition is taken where it is shared).

$P_N$ = Cost of services in the flat, heating, sanitary, water, etc. not including service costs to common areas.

L = Storey height.

The cost of the common areas, circulation, staircases, etc. was represented by a series of expressions. The model was used by the public authorities for the planning and design of public dwellings (apartments).

Clearly this is a very simple model, but given that such items as S, DL and the level of provision of services to provide the cost $P_N$, are all clearly constrained in the regulations and standard specifications for public housing, it was a useful price prediction tool for use before detailed drawings were produced.

Finally, Birrel has presented a study of cost estimating for bidding which, although not strictly a model in the sense of the others included here, is at the same time of interest.[33] The essence of his study, carried out in North America, is that it presents construction cost estimating as an information handling process. This is of course the essence of any inductive computer model but presented in isolation, in a non-computer environment as in this case, it serves to focus the mind on the inadequacy of many of the current methods.

### 3.3.4 Optimisation Models

Optimisation models construct a feasible solution space, given certain model constraints and simplifications and then, with certain criteria preset as evaluation tools, the space is searched to locate the point which optimises the given criteria. Models of this nature require rigorous and formal definition of the problem and become rapidly highly complex for anything other than simple problems.[34,35]

Two important optimisation models were produced by Wilson in the mid 1970s. The model for thermal design of office buildings warrants further attention. In modelling terms the problem, although complex, was at the same time well-defined. Of some importance is the fact that it was a working life-cycle cost model, thus taking into account both initial and recurring costs. Only one other of the models presented in this chapter is a true life-cycle cost model. The model of Wilson and Templeman was constructed in terms of heat supply and heat losses.[36] This takes account of intermittent heating. The objective function was the total discounted costs of the entire heating and fuel cost, plant cost and insulation costs. The cost function used to represent fuel cost was:

$$\text{Total fuel cost} = DF[C_1+C_2.P.Q_s(T+t_1+\ .t_2)]£ \qquad ...[3.5]$$

where

$DF$ = discount factors.

$C_1$ = annual standing charge.

$C_2 = \frac{WY}{F} \times DW \times WF \times FP.$

WY = heating season in weeks/year.

E = plant efficiency.

DW = occupancy in days/week.

WF = weather factor.

FP = fuel price.

T = plant time constant.

$$\text{Total plant costs} = \underbrace{a + b\,(p.Ws)}_{\text{boiler}}\ \underbrace{Q\,(d/e)(p.Qs)£}_{\text{emitters}} \quad ...[3.6]$$

where

a, b = boiler cost regression co-efficients.

d = average radiation cost in £/$m^2$.

e = average output rating of radiator surface in W/$m^2$.

The cost function for insulation was obtained by plotting thermal resistance against the cost of providing it, using different insulation materials. This gave a large cloud of points with a dense lower edge. The lower bounding curve was mathematically approximated and this equation was used to provide the cost of insulation. An optimisation algorithm was then applied to the thermal model. The model has been formally constructed with objective and measurable variables. It is capable of manipulation and of providing a sensitivity analysis of changes in design parameters.

An optimisation model for the same (thermal design) sub-system, presented in 1970 by Gupta, chose as the criterion of optimality, the minimum discomfort of the occupants in the absence of custom-designed environmental control systems.[37]

Optimisation models at the overall building level but which deal comparatively crudely with particular sub-systems, have been presented by Brotchie and Lindsey in Australia and Clarke of the Asian Institute of Technology in Bangkok, Thailand.[38,39,40] The important contribution of these models is that they attempt to deal with the problem of combining the optimal subsystem solutions in such a way as to produce a global optimum.

Dudnick and Gero[53,54] have investigated the use of linear and dynamic programming techniques, while not formally presented as economic models, both techniques were acknowledged as in some way helping to provide more economic and efficient designs.

Radford and Gero have considered optimisation in multiple criteria problems,[41] proposing the use of 'trade-off diagrams' and dynamic programming. The results have been too highly constrained by the simplifications necessary to render the problem computationally tractable to be of practical use in design as yet. Russel and Arlani focussed attention on the derivation of objective functions for optimal building design.[42] They identified five main steps in the optimisation process, which are well known but worth mentioning here:

1. Identification of the decision variables and the relevant constraints.
2. Mathematical formulation of the decision problem.
3. Determination of appropriate objective function(s).
4. Selection of a mathematical programming algorithm to determine the optimal values of the decision variables.
5. Execution of sensitivity analysis.

Further they also indicated that for a given design problem, different objective functions may lead to different alternatives being identified as optimal. The most useful objective function was that which maximises net present value (NPV) which clearly lends itself to life-cycle cost models.

### 3.3.5 Stochastic Models

Stochastic models, in the context of this research, are models which are designed to take account of the economic risk involved in making any predictions during the design process. The necessity for some form of risk analysis has been increasingly recognised during the past 15 years due in part to the political and economic instability of the period. The techniques of risk analysis have surprisingly only been applied in building economics since the early 1970s and much work remains to be done.[48,49,50]

Wilson has recently presented a study which seeks to identify limitations of the widely accepted probabilistic techniques used in stochastic models.[11] In a case study he concluded that the influence of correlation among variables was not significant in his case, but that much further work was required to investigate any limitations of probabilistic techniques which may manifest themselves in building economic applications. Legard[51] has presented a very simplified analysis of a theoretical probabilistic model of construction cost. However, an idealised model combined with the use of a rectangular or uniform distribution renders the results less important, to the problems of stochastic modelling, than could have been the case.

A highly detailed model for cost estimation in residential rehabilitation has been presented by Chapman at the National Bureau of Standards in Washington D.C.[52] A combination of probabilistic techniques and cost functions enables a potential investor to identify an optimal 'retrofit' strategy which complies with relevant codes.

In 1981 Russel,[55] then at Concordia University in Montreal, presented a methodology for measuring risk and incorporating it into design decision making by means of a first and second moment or mean and variance description of life-cycle cost. The basic life-cycle model was stated as:

$$LCC=\sum_{i=1}^{M}[C_I+(1-Y)(O_{id}O_{it}+M_{id}M_{it})+R_{id}R_{it}+A_{id}A_{it} - Y\sum_{j=R1}^{Ts} B\ V_{ij}C\ CA_i e^{-rj}] \quad \ldots[3.7]$$

where

$LCC$ = life cycle cost.

$M$ = number of building sub-systems.

$C_i$ = capital cost of the $i^{th}$ sub-system.

$Y$ = combined federal and provincial income tax rate.

$O_{id}$ = operating cost of the $i^{th}$ sub-system at time zero.

$O_{it}$ = present worth function of time varying operating costs per dollar of expenditure.

$M_{id}$ = maintenance cost of the $i^{th}$ sub-system at time zero.

$M_{it}$ = present worth function of time varying maintenance costs per dollar of expenditure.

$R_{id}$ = cost at time zero of aperiodic major repair costs for the $i^{th}$ sub-system - these costs are capitalised.

$R_{it}$ = Present worth function of time varying aperiodic repair costs per dollar of expenditure.

$A_{id}$ = Cost at time zero of alteration or retrofit costs (capitalised).

$A_{it}$ = Present worth function of time varying alteration of retrofit costs per dollar of expenditure.

$BV_{ij}$ = book value of $i^{th}$ sub-system in $j^{th}$ year.

$CCA_i$ = Capital cost rate allowance for $i^{th}$ sub-system.

r = after tax discount rate of the investor, including an allowance for long-term inflation rate.

The quantitative treatment of risk consisted of, firstly, calculating the mean (LCC) and variance ($\sigma^2$LCC) of the life cycle cost.

This involved three steps:

1. Estimate the mean and standard deviation or coefficient of variation V for each of the components in equation [3.7]. A combination of experience and subjective judgement may be needed to compute .
2. Estimate the correlations between each of the components. Analysis of existing data may need to be supplemented with subjective judgement here also.
3. Process the results using standard statistical formulae.

Clearly the above calculations rest on the assumption that the risk attaching to each component is normally distributed. Once these calculations are complete the alternatives may be ranked by a variety of methods.

## 3.4 COMMENTS AND CONCLUSIONS

Comments.

(i) Deductive Models.

These in general suffer many of the problems of statistical analysis. Correlation itself does not establish causality. The output of such models may not be extrapolated beyond the limits of data in the original sample. In the models of this type presented earlier, insufficient attention was given to the size and structure of the sample, also there was an underlying assumption that the relationships were linear. There was no evidence of any consideration of sampling theory in the design of the samples. Indeed the samples appeared to be relatively (in statistical terms), small and random.

This would cast doubt on any conclusions from such models. In general, deductive models are of use in the early stages of design but they become rapidly weaker as the design progresses and more information becomes available. It is not possible to manipulate such models to consider the effect of changing any design decisions. Therefore their use is limited to a type of black-box prediction, without enabling the designer to learn anything new. None of the deductive models surveyed gave any consideration to the time period for which the model would be valid. It is known that regression-based models deteriorate over time. The relationships between variables change over time, updating the output of the model by means of an index is an inadequate approach. The data itself also becomes out of date and updating the original data by means of an index gives only a limited life to the model. It is not known how fast or by how much they deteriorate in building economics applications. This is one of the questions which will be considered in this study.

(ii) Inductive Models.

In computerised form, inductive models of total building cost have a lot of potential in building economics, especially in the generation of flexible and up-to-date parametric studies, examples of which have been produced from the models of Newton and Townsend.[31,30] However, there are a few attendant problems. In manual form, these models which operate at the relatively coarse level of approximate quantitites, are far too slow to be of much practical use to a designer. This is one of the main criticisms of traditional quantity surveying techniques. In elemental cost planning, the turnaround time for receipt of economic advice by the designer is so slow (measured in days and sometimes weeks) that relatively few alternatives can be fully appraised. Computerised models circumvent this problem, but there still remains the problem of the data used in the model. No assessment of the limitations of the data was given in any of the studies presented. Inductive models generally do not perform well in the early stages of design, but become rapidly more useful as sketches are produced and information builds up. A change-over system between deductive and inductive models may be appropriate in a global modelling system. Whether or not this is the case, attention should be directed towards the relationship between the model and the design process. Is the level of detail of information required by the model to produce one output, appropriate to the stage of the design process? Sometimes this is dealt with by including default values which the model takes for certain variables until the designer has made a firm decision.

(iii) Optimisation Models.

Well designed optimisation models are very powerful tools for locating optima on the basis of clearly defined constraints and criteria. However, in problems where the decision criteria are complex (i.e. the cost is not the only criterion a building designer must consider), the computational aspects of mathematical optimisation rapidly become unmanageable. Successful optimisation models have been built for particular building sub-systems, but much work remains to be done on the problem of the global optimum of a set of highly interactive sub-systems.

(iv) Stochastic Models.

This group of models is gaining in importance, as both client and professional advisors seek to evaluate the risk attached to decisions. Probabilistic and mathematical simulation techniques are well known, but have only infrequently been applied in building economics. However, work is continuing in the field of assessing the limitations of these techniques and exploring the use of new techniques.

Conclusions.

Although the models were presented in four distinct groups, this is not how they emerged in the literature. In fact, the studies above were mostly carried out in an unco-ordinated fashion with each researcher solving the problems relevant to the particular modelling application in hand. Much could be gained by taking an overall view of economic models in building design, and assessing their strengths and weaknesses per se. This research is a first attempt at the latter.

Models resemble reality in an approximate way. The purpose of a model is not to describe reality, but to reduce it to a more manageable form, losing much of the minutiae of reality, but hopefully retaining the general form in a way that is more easily understood. They can be regarded as a translation of reality into a different language with fewer words, and which only addresses itself to the features of reality which are relevant to whatever problem is being studied.

Further, Wilson has proposed that models are sometimes simplified by:[56]

1. Converting discrete variables into continuous ones.

2. Translating non-linear functions into linear form.
3. Eliminating some constraints.

The most powerful computational techniques that exist are for linear functions dealing with continuous variables. Clearly, such simplifications as those listed will tend to increase the level of abstraction of the model from the reality of the problem, and if used, they should be made explicit.

The problem of the limited life of models has been indicated earlier, no quantitative work has been undertaken in this field yet. Similarly insufficient attention has been given to understanding the relationship between the economic model and the design process. The theoretical limitations of the various modelling techniques are known in building economics, but little or no quantitative work has been undertaken.

Accordingly in the next chapter, some features of the models reviewed here will be examined exhaustively and criteria for measurement will be established so that such quantitative research may be carried out.

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# CHAPTER 4

# CRITERIA FOR MEASUREMENT OF THE PERFORMANCE OF ECONOMIC MODELS IN BUILDING DESIGN

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## 4.1 A Taxonomy of Models

### 4.1.1 Introduction

There are at least three useful ways of considering the range of model types. Firstly, in terms of economics one may place a model in the milieu of cost, value or price prediction. That is, whether the model is concerned with predicting, on behalf of the owner or designer, the tender price of the building or, on behalf of the contractor, the sum cost of the resources he needs to construct the building or, on behalf of say the users, the 'value' to them of the building (being taken as a function of utility and scarcity). Cost price and value may be viewed as objectives of models. Secondly, models may be grouped together in terms of the use to which they are put. For example, one may group together all models used by contractors to monitor job progress financially, all models used professional advisors to predict the market tender for buildings and all models used by central government to measure the effect of legislative and building code alterations. Thirdly, models may be considered in terms of the nature of their own internal logic the way they do whatever it is that they do. For example, whether the model simulates the consequences of a proposed design solution using causal relationships or whether it uses deductions from data stores of statistically analysed historic information.

In considering the issues relating to economic theory, the discussion which follows is set against the background of a conventional western market economy unless otherwise referred to. While this simplifies the exposition of the arguments, it must be recognised as less than complete in terms of economics.

### 4.1.2 Economics

Value.

Value, in common parlance, is the intrinsic worth of a good. Most people would allow that it cannot always be measured in money terms, instances of this are items such as archaeological finds and works of art. (A work of art may well have a price attached, but it will be shown later that price often bears little relation to value.)

Scarcity affects value (in an indirect way; it affects one of the many components of value). Normally when scarcity increases, so does value. The usefulness of an article also affects value. Hence, the value of a sheepskin coat to a person on a Mediterranean beach in midsummer will be different from the value of the same item to the same person stranded in the Himalayas in midwinter. The value of an article, therefore, gives an indication both of its scarcity and its utility when compared with others.

Theoretically, one would expect people to be willing always to pay more for a more useful article than for one which is less useful. Clearly this is not true, and is illustrated by the well known paradox of value which compares the value of water (low value - high utility) with that of a diamond (high value - low utility).

This paradox arises when one considers utility and scarcity, but in reality there is much more to value than that: value is the power to serve man's needs or desires. Some of these needs will be objective (the capacity of the good to do something) and some will be subjective, differing from person to person depending on the varying importance attached to the good in question.

The exchange value of a good is the amount of some other good for which it can be exchanged. Under the barter system, this meant that any particular good had as many exchange values as there were different goods to exchange with it. This has now become rationalised by using a generally accepted means of exchange, which today is money. ('Money' is not the only solution to a 'generally accepted means of exchange' and criterion for this are discussed later).

Value, then, can be regarded as a complex vector made up of the above components. Further, it is also influenced by conditions of demand and quantity available. If you want something desperately, then its value to you is increased.

Cost.

The cost of a commodity, whether it be a simple one like a sheet of timber or a complex item like a building, is the sum of all the payments (whether money or otherwise) made to the factors of production* engaged on the production of that commodity. Costs can be divided into fixed costs and variable costs. The former being those that remain the same over a large range of output, the latter being those that change with every adjustment of output. The term 'cost of production' has meaning only when it is related to output. For example, the cost of a motor car depends on whether the manufacturer is producing 50, 100 or 500 units per week. The term is also ambiguous since it has several different meanings, the cost of production for a given output may be the total cost, whereas for a single unit it is clearly the average cost. If a firm is already producing 100 units a week and decides to increase

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* Factors of production are defined in economics as Land: Labour: Capital: Entrepreneurship. Land may be defined as natural resources, labour as human resources, capital as money, machinery, plant, equipment and any man-made components, and entrepreneurship as the risk-taking, process of organising the other factors of production. For a more complete discussion see Lipsey[1] or Allport and Stewart[2].

production to 101, the cost of producing the extra unit may be much less than the average cost. On the other hand, if a re-arrangement of production lines and shifts is necessary then it may be much greater than the average costs. The additional cost, whether it is greater or lesser than the average, is known as the marginal cost.

Whichever particular type of cost is being considered, the essential meaning remains the same, that is the sum of all the payments to the various factors of production. This appears deceptively simple, it will be shown below that present day methods of calculating 'costs' are incomplete.

Price.

Price is the amount (of money usually) that someone is willing to pay for some particular good. It can be either determined by the interplay of supply and demand in the market situation, or else be fixed by the entrepreneur or the authorities. There is not always a very strong relationship between price and cost. Consider a highly simplified example, if a developer builds an office block and the cost to him is £1 million (i.e. the sum of all the costs he pays for the site, professional fees, contractors, etc.) the price he can now expect to sell the building (or let the space) does not relate to the cost that he has paid for it, but rather to the conditions of demand and supply, and how much profit someone else feels he can make by buying or leasing the building. A potential buyer may calculate that if he were to buy the building and manage it and let the space, it would produce an income of £x per annum for the next 15 years, and that for an income of that amount over that time he may be willing to pay £2 million initially. It may be less or more than what the developer wants, but the buyer's calculations for the price he wishes to pay are not based on the developer's cost but rather on the buyer's own potential for making profit.

There emerges from the above one other important point and that is that one man's price is another man's cost. In short, cost is the amount paid by the buyer, price is the amount received by the vendor.

## The Relationship between Value and Price.

The history of value theories did not begin with the classical economists of Adam Smith's era. Aristotle[3] was not only able to distinguish between value in use and value in exchange, but also the fact that the latter stemmed somehow from the former.

Adam Smith developed what was to become known as the labour theory of value. His definition of value was based too much on utility, and thus he was not able to solve the paradox of value, about the diamond he said it has "scarce any value in use; but a very great quantity of goods may frequently be had in exchange for it".[4]

Smith felt that the real price of everything (its value in exchange), what everything really costs to the man who wants to acquire it is the toil and trouble of acquiring it. If the price was expressed in money or in other goods by barter, then these were merely representative of the amount of labour that was locked up in the good in question.

J.S. Mill began to answer the paradox by taking a much wider (and nowadays generally accepted) view of value. Mill felt in 1848 that the utility of a good lay not just in its power to 'do' something, but also in its capacity to satisfy a desire or serve a purpose.[5]

The theory of value is still, in this century, the subject of much debate.[6,7] Modern economists hold the view that value in exchange does not come from total utility but rather from marginal utility of the extra increment demanded. In economic terms this can be stated:

> "The response of quantity demand to change in price (i.e. the elasticity of demand) depends on the marginal utility over the relevant range and has no necessary relation to the total utility of the good."

There is a school of thought which holds the view that it is possible to regard the price for a good as a measure of its value in general, making the concept of value and price interchangeable. Price, while in some way linked to value when it is originally set, becomes largely unrelated to value when the forces of supply and demand begin to operate on it. Price can be defined as the money obtainable from a person or persons willing and able to purchase an article when it is offered for sale by a willing seller.

Thus 'price' is equivalent to market value, at a given time, but market value cannot be taken as equivalent to value per se. As has been indicated above, market value or price relates to the degree of marginal utility accruing to the one who demands. This will set the price he is willing to pay. Whereas the value itself in its true sense must relate to the combination of the total utility of the good and the subjective view of the person who is considering it. The value as a building to the owner, occupiers and the community has been proposed as being a function of three qualities; exchange, this would equate with market value as discussed above, utility, or usefulness for its purpose; and merit, the power to satisfy.[10]

Expression of Price and Cost.

For convenience price needs to be expressed in terms of a medium of exchange. Under the barter system a good would have many prices in terms of the different things it could be exchanged for. Cattle, shells and tobacco were variously used as money and eventually, pieces of metal of a specified weight and quality. The function to be fulfilled was merely that of avoiding the awkwardness of barter.

Adam Smith laid down an ideological basis for expressing exchange value, "A commodity which is itself continually varying in its own value can never be an accurate measure of the value of other commodities".[4] Money clearly does not fit this model, as it is continually changing its value. Using units of labour as discussed earlier does not fit either. The value of, say, one hour's labour depends on whether the person performing it is young or old, whether he is working strenuously or at a slow pace, different perceptions of what is 'hard work' among different races, etc. Labour, as a measure, is of little more or less use than money, any preferences for the use of either measure are merely on political grounds. In this respect Marxist and Capitalist economies face similar problems, with the exception that labour as a measure would appear more meaningful than pieces of paper and silver.

There is a more recent school of thought which suggests that units of energy should be used as a measure, the reasons being that they are a sought after and scarce resource. There are many different sources of energy, which are, in the main interchangeable. If any one becomes scarce, prices begin to rise and impetus is given to industries to use alternatives. In the past eleven years in particular political events, and violent clashes between cultures have given rise to many short term and medium term adjustments in the price of energy sources. However, the only real shortage would be if all resources were in danger of becoming exhausted and world demand were rapidly reaching that point.

The long term movement towards the extinction of oil, coal and natural gas supplies can be looked at as a primer for the development of the technology to harness energy efficiently from the sun, wind and waves. If and when this occurs we will have energy sources which, for all intents and purposes, will be limitless. Until this moment arrives we will have a mixture of energy types, some renewable, some not, and this would not be a good vehicle for the expression of value or any of its associated concepts.

Cost is that which must be given in order to acquire produce or affect something. It has been referred to earlier as the sum of the payments made to the factors of production. However, a consideration of the methods by which accountants and managers calculate 'costs' in modern systems would lead to a redefinition of costs as being "that which the entrepreneur cannot avoid paying".[8]

Modern industries still do not include in the cost of what they produce such items as the disposal into the air of effluents or the loading of the land with solid wastes. These costs cannot be avoided, hidden and heavy costs are passed on to the community where they are either met by increased taxation and by public spending or else they are not paid for at all, resulting in destruction of amenity, which in itself is a cost. If the nature of these diseconomies is considered, it will become apparent that any attempt at a precise delineation of the issues is fraught with problems. There are three areas to be examined; the atmospheres; airs and climates, the hydrosphere; rivers, lakes and seas, the lithosphere; soil, rocks and land. The complex interaction of these throughout the ages has given us the planet in its present form.

It is relatively easy, say, to decrease pollution in one of these areas, but very difficult to ensure that other life systems are not endangered. There are no single simple solutions, each of the three systems above is made up of many sub-systems and interact with the others in a complex set of interdependencies. The instance of energy, discussed earlier, is just one sub-system.

It is clear that in order to calculate real costs more sophisticated estimates of the degrees of impact on the environment are needed.

'Cost Models' in the Context of Economics.

The money paid by the client to the contractor is the contractor's price for providing the building. However, the same money is the cost of the building to the client in the larger scheme of things. The client will hope to gain a price for the building space he now possesses either by letting the space or by using it himself and offsetting the rental costs he would have had to make elsewhere. The money he pays to the contractor is just one of the costs of the building. Other costs the client have to pay are land costs, professional fees, etc.

The contractor's costs are the payments he incurs while erecting the building, this will include wages and salaries to staff working on the particular job, plant costs, materials, interest charges on any monies he has paid but but not received from the client. The nature of contractors' costs are exremely complex, relatively few contractors have an accurate picture of what their real costs are.

The majority of the models presented in chapter 3 are deterministic. It is clear from the above that no form of price prediction can be fully deterministic in a market economy. Further it would seem preferable to accept the stochastic nature of estimates of building costs and prices rather than to use pseudo-deterministic figures. Of the two types, price prediction models will be much more indeterminate and therefore the importance of some recognition and measurement of uncertainty is increased in this type of model. Possible ways of dealing with this are discussed below.

## Economic Response Models.

The term 'economic model' is used throughout this work in order to avoid any confusion caused by the differences between cost and price models. This has been referred to in chapter 3 and discussed above. However, the models under consideration here are not solely concerned with the prediction of price or cost, their fundamental aim is that of improving building designs and in the last resort of assisting in the location of optimal design solutions, whether by formal mathematical optimisation or by informal optimisation involving simulation of solutions and appraisal of the results. The nature of this task is the comparison of alternative solutions to the same design problem, hence one is interested only in those components of the economic model which change as one or more design variables are altered. Any factors which do not change between solutions or certain sets of solutions need not be considered, with the result that in effect we are dealing with differential models. Examples of factors which may remain the same across certain sets of design solutions are preliminary, time and method related charges, profit requirements, tactical and strategic considerations.

When these factors are left out, then what remains is merely an index of the factors which change. Money units give the name "economic model" but in reality they are used merely because it is convenient and consistent to locate up to date money values for many resources, such as materials and labour. If there were an accessible and consistent red-bead or energy unit scale for the wide range of resources used in building, then these could with equal validity be used. Some difficulties relating to the use of such scales have been mentioned above. Models of this nature measure the response to the adjustment of design variables. In an attempt to refine the terminology and to take into account the existence of differential models, the term economic response models may be used.

### 4.1.3 Applications of Models.

As stated in chapter 3 all economic models in building design must address themselves to the problem of relating the designer's decisions (or the design variables) to the economic consequences to the contractor of assembling and synthesising the resources necessary to physically construct the design. (Cf. equations [3.1] and [3.2]). Within that constraint, most economic models in building design are designed and built for one of the following uses.[33]

i) To predict the monetary price which the building owner will have to pay for the building, this is referred to as tender price prediction.

ii) To present the consequences, according to a predefined economic criterion, of alternative sets of design variable values. Thus to enable design solutions to be compared and to assist in the selection of the optimum (with respect to the defined criterion.)

iii) To predict the economic impact, regionally or nationally, of changes in building design codes and regulations.

The first type of model is referred to as a macro model, it deals with the whole building. Model types (ii) and (iii) are, inevitably, referred to as micro models. Type (ii) models are differential models and type (iii) models concern themselves only with matters relating to the particular code or regulation under consideration, and thus it is usual for both of these to be concerned only with particular design subsystems, hence the reference to "micro models".

### 4.1.4 Modelling Technique.

The formulation of an economic model depends on the stage in the design process at which it is required, as it is this which determines the amount of detail available both for the design variables and for the economic data required. As the design progresses it is normal to break the overall design down into a number of design subsystems. Traditionally these are often tackled by specialist designers dealing with, for example, the structure, the services, the landscaping, interior decoration etc. This results in a design hierarchy which is of great importance to the makers of economic models, if they are to be of use in the design process. Fig. 4.4 is an attempt to represent one such hierarchy. There is no one structure or hierarchy, the figure is intended to illustrate that there are design subsystems, that these are interelated and that the process moves from a situation of little or no detail to one of very great detail at the completion and quantification of the design.

At inception there exists very little information specific to the project itself and most decisions have to be made by analysis of data relating to other similar projects. Reliance on this general or default data reduces as the design develops and more project specific data comes into existence. It is this change in the nature of the available information which leads to the two main approaches to economic modelling in building design, namely deductive models used at the early stages and the more detailed inductive models used later.

Deductive Models.

In applied economics generally, and particularly in the economics of building design, there is little chance to carry out the controlled experiments which are so important to research in the physical sciences. This is a severe disadvantage, due to the large size and unique nature of individual buildings, experimental analysis of the manipulation of certain variables and observations of the effects on other variables is rendered well nigh impossible. For these reasons, when there is little information available which is specific to the project in hand, reliance is placed on data which pertains to other projects perceived to be similar. Deductions drawn from this type of analysis are then applied to the project in hand.

This type of model relies on the method of that branch of statistics known as 'classical statistics' which is concerned with the analysis of 'sampled (objective) data for the purpose of inference'.[9] The central techniques are those of correlation and regression analysis. Due mainly to the wide availability of computer software packages, these techniques are often misused, high correlations are taken to indicate causality, regression equations are used to make predictions outside the limits of the original data. These problems are among those discussed in the next section.

Deductive models often take the form of cost expressed in terms of some functional or design unit such as floor area, theatre seat, hospital bed, etc. The assumption being that as the number of units increases the cost will increase linearly. Clearly this is a big assumption and consequently such unit cost models should be treated with great caution.

Finally it should be noted that deductive models are 'passive', they rely on what has gone before and hence it is not possible to learn about, for example, particular combinations of variables which were not contained in the original sample.

## Inductive Models.

An inductive model will compute the consequences of a set of design decisions in terms of a physical design solution and by linking this to some form of detailed economic data, produce an economic measure of the result. This approach to modelling seeks to apply the detailed analytical methods of the contractor's estimator at the design stage. The usefulness of this approach at the design stage was severely limited until the introduction and wide availability of fast computing facilities, the calculations involved, while relatively simple, are quite lengthy.

Inductive models contain exact and not functional relationships as in deductive models. For example, in STEPS the economic model for staircase design which is presented later, given values for certain design variables, such as occupant loading, number of floors served, desired tread and riser size, the model calculates a design solution which satisfies these values in the light of any given set of building regulations. The model therefore contains a detailed description of the solution including the physical dimensions of staircase and stairwell, enclosing walls, landings, smoke lobbies, etc. This numeric description is highly manipulable. It may, on the one hand, be resolved into further detail producing quantitative measurement of the physical components of the solution, which may then be linked to economic data for detailed evaluation of the solution or, on the other hand a design decision may be altered and the entire solution re-calculated to expose all of the possible effects of that decision.

In this way inductive models are 'causal' models. They are also referred to as 'simulation' models in the sense that they simulate the proposed design solution. There is some similarity to the use of the word 'simulation' in systems and operations research models, however the term is sometimes confused with mathematical simulation techniques as used, for example, in experimental physics where the technique, by definition, involves measurements of the degree of uncertainty in the results. Simulation models in CAD do not automatically take this form, therefore the word inductive is a more concise description of this type of model.

The economic data used in inductive models may be at varying levels of detail from operational level (for example, 'lay foundations' or 'erect internal partitions') to resource level (measured for example in numbers of manhours and quantities of material required to complete the task). The economic measure in inductive models is derived by a summation of the cost generating subsystems. For some purposes, all subsystems do not have to be measured, as mentioned earlier, factors which do not change between certain sets of solutions may be ignored. The economic measure which results is neither cost or price, but is an index of economic response, the model becomes a differential model. This trait may be very helpful in a pragmatic sense when dealing with complex design problems. For example the model for the heating and air-conditioning subsystem presented later does not need to take account of the design and layout of the ductwork system when the relationship between the proposed operating strategy and the capacity of the installed cooling and heating plant is being explored for a particular building.

Clearly inductive models are more manipulable in relation to the deductive models discussed earlier. It is relatively easy to explore what happens if a certain variable or group is altered, but there are also attendant problems. The speed of the response is entirely reliant on computer hardware and software, this will become less of a problem as software becomes more reliable and machine independent. These models are complex and extremely time consuming to build and test, because of the high level of detail required. (The air-conditioning and staircase models mentioned above collectively took two man-years.) Finally, the detailed and accurate nature of the model itself frequently exposes the weaknesses, inconsistencies and gaps in the available economic data, and like a chain the model is only as good as its weakest link.

## 4.2 A Critical View of Economic Models in Building Design

### 4.2.1 Problems Identified: A Conceptual Framework.

At this point it is worth recapitulating briefly, on the overall approach of this thesis. The work is concerned with that subset of CAD models known popularly as 'cost models', but referred to here for reasons set out earlier, as 'economic models'. Further, the work takes the form of a series of experiments designed to quantify and assist in the evaluation of the performance of certain models. The models presented in chapter 3 are wide ranging and there is a diminishing marginal benefit to be gained by a detailed criticism of each one individually. For the purposes of the experiments outlined in chapter 8, it is important to give careful consideration to the establishment of which factors should be measured. The models presented in chapter 3 are criticised in detail under several headings below. These are the factors which, to the best of the writer's knowledge and based on the conceptual framework outlined below, seem to be important and about which we have little 'real' knowledge. By the latter is meant that while for example, we know it to be generally true that specific identical items selected from different current data sources will not have identical values, has the effect of this for specific data sources been measured and evaluated in a working economic model? Is it possible to enumerate how sensitive a certain model is to its data source? There is no previous work of this nature in this field, as far as can be established. Therefore the list of factors under which the robustness of the models is discussed below, and which are later used in the quantitative experiments, should not be viewed as exhaustive but rather as a preliminary working set which do enable some new quantitative work to be carried out.

In order to establish these factors, consider the context of the economic models under discussion here. As has been shown in chapter 2, the designer is in the position of juggling many decisions at the same time and of attempting to optimise the overall result of decisions affecting all of the design subsystems. This work is concerned with improving the decisions regarding the economic subsystem and with examining the techniques used to make these decisions. Thus the economic model may be viewed as part of a chain which leads from raw data through some kind of model and output and on to a 'decision' maker. This is illustrated in fig. 4.1. A chain is only as strong as the weakest link, in the diagram the chain is dismantled for analytic purposes, with the suggestion that not only should each link be examined, but also its connection with adjacent links. This suggests five kinds of factors to be considered. These factors fall into two areas, the modelling environment and the decision environment, and are illustrated in figure 4.1. They may be described in more detail as follows.

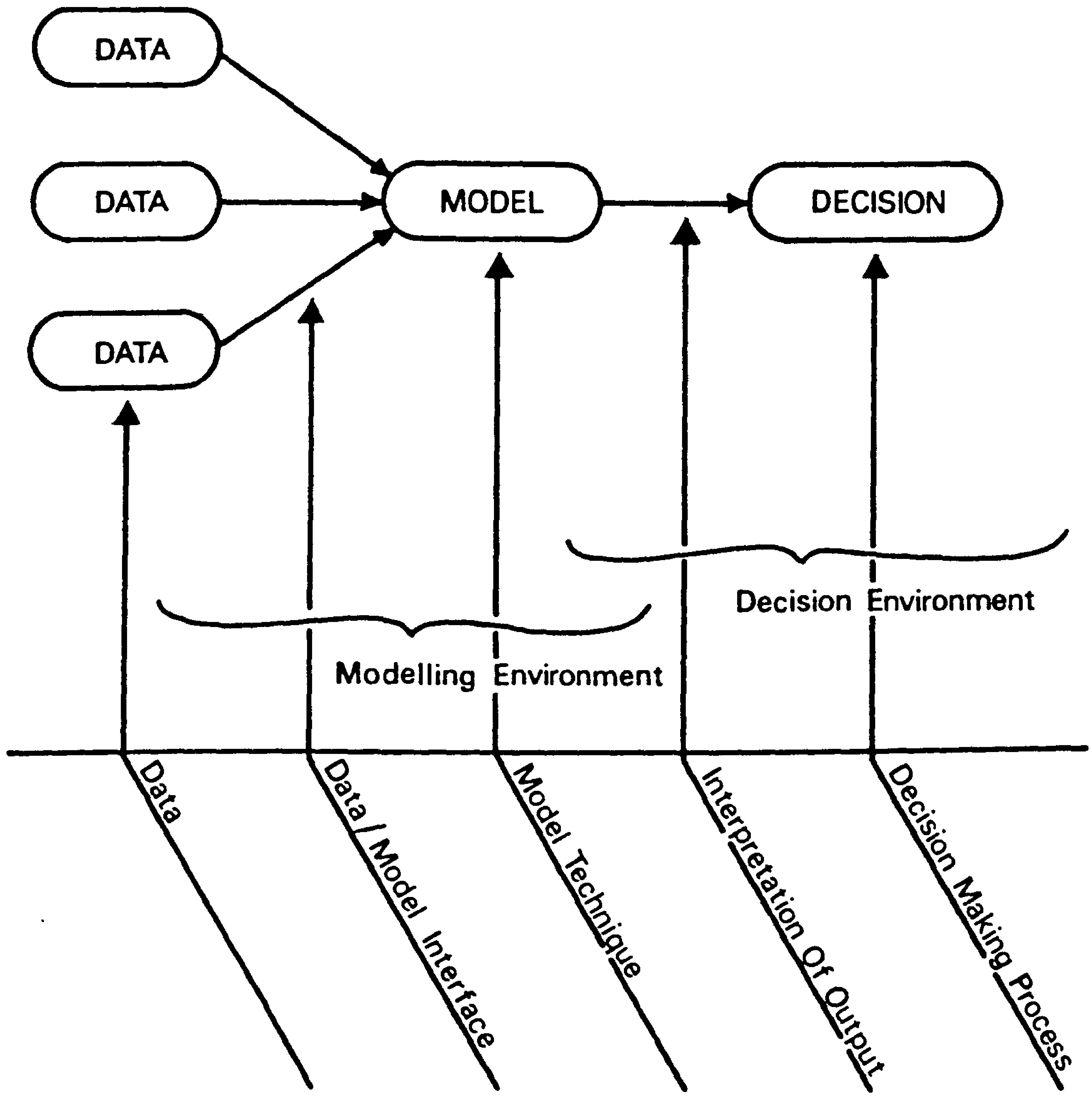



Fig. 4.1 THE DECISION AND MODELLING ENVIRONMENT

Modelling Environment.

(i) DATA: The source and the nature of the data have an impact on the validity of the model.

(ii) DATA/MODEL INTERFACE: The matching of the model to its data is dependent upon the degree of development of the design. Data suitable only for the early stages of design should not be used in models intended to be applied later and so on.

(iii) MODEL TECHNIQUE: The modelling technique used has an impact on the validity of the model. Each technique has its own strengths and weaknesses.

Decision Environment.

(iv) INTERPRETATION OF OUTPUT: How does the designer perceive the output of a model, is objectivity possible? How may the output be interpreted in relation to the age of the model. Do the relationships still hold? How has the model been updated?

(v) THE DECISION: The internal mechanisms of human decision making are as yet relatively unknown and the subject of much research. The experimental studies are often very situation specific and there are many issues left to be resolved in the area of human decision making and problem solving.[36] Such work is outside the scope of this research.

### 4.2.2 Data

Introduction: The Use of Data.

Rational decisions are usually made in the light of the information available at the time of the decision.[11,12] In the construction industry, cost estimation of all types is usually based on 'past experience' projected forward. 'Past experience' is recorded in the various forms of economic data available and also the sum of the experience of the decision makers. Whether or not sophisticated economic modelling techniques are used, reliance is based on some form of historic data as a basis for input to the decision making process. Clearly the more reliable and accurate the data the greater the chance of making a good decision, all other things being equal.

In the construction industry historic cost data is put to four main uses:[13]

(i) Forecasting.

Forecasting is the estimation of the absolute cost of construction activity, large or small, to be performed at some future date.

(ii) Comparison.

Financial comparisons are made between design alternatives or different design strategies for a particular building or component. The aim is to assess the different financial implications of varying design decisions.

(iii) Balancing.

This is the balancing of expenditure between various elements of a building. It is an attempt to set up individual mini-budget figures for the different building elements.

(iv) Analysis of Trends.

This is carried out in order to get a picture of what is happening to prices and costs in the industry over time so that historical data may be updated to the present or projected forward.

However, in the 'real world' things are not nearly so clear. There are very few absolute facts. Before examining the cost data used in the construction industry it may be helpful to consider briefly the nature of 'data' from an Operational Research viewpoint.

A skilled person making a managerial decision, or preparing a plan or a model of a system will, at the outset, question all information, even that which purports to be a 'fact'.

It is not sufficient to be aware of a 'fact', one must know what the 'facts' mean and how they fit together. It is possible that a 'fact' or piece of data as it stands suppresses precisely what it is most necessary to know in handling a particular problem. The information may not contain details of the value judgements or other imponderables that were involved in the data collection.

It may not be safe to use data that was originally collected for some other purpose, as the purpose behind data collection alters the facts that are collected. For example, in planning the time to be allowed for say erecting timber stud partitions, it would be unreliable to base a decision on the bonus records, as tradesmen tend to decrease the time logged against tasks in a bonus scheme and increase the time logged on non-bonus tasks while keeping the total time unchanged. This clearly renders the recorded times less useful for the purposes of project planning.

People frequently use what a statistician would call an estimate as if it were a cast-iron fact. An 'average' figure is merely a representative of a family of figures. It has attached to it a level of uncertainty, it does not exist on its own and can have little meaning or practical use unless it is combined with other measures of the family of figures from which it comes. Similarly, the user of data must be aware that maxima for wholes computed as the sums of maxima for parts cannot be correct in a world governed by any degree of chance, an oversimplification, but one which is redressed below.

It is clear then, that all users of data in a decision-making, planning or modelling sense, must be aware of both the reliability and the variability of that data. A forecast or decision will have at least the same uncertainty as that pertaining to the data on which it was based. It has not been traditional in the construction industry to acknowledge explicitly the uncertainty of cost data in decisions and forecasts made from such data. Consequently decisions and estimates are frequently given as figures which purport to be determinate when, in fact, that is an impossibility given the data on which such results are based.

A survey of the sources of data and the varying nature of data from each source is presented in Appendix I, together with an analysis of the way in which building costs are generated. Familiarity with these areas is essential to the understanding of the issues presented below. The most important conclusions of the study are:

(i) Identical items do not have identical values when one source of data is compared to another. The practical meaning of this is that, all other things being equal, the output of a model will change when the source of data used is changed, even though the items selected from each source are identical.

(ii) Building cost data is generally presented in a deterministic way, the analysis of Appendix I indicates that this is not compatible with the way that building costs are generated.

The following subsections present a discussion of how the data is derived and appraise the quality of data, finally conclusions are drawn with respect to the models presented in chapter 3.

How is the economic data derived?

The answer to this question depends largely on the tendering process. There are many types of tendering processes, the most common in the U.K. being the competitive tender based on bills of quantities measured independently according to the Standard Method of Measurement (S.M.M.).[14] Briefly, the procedure is as follows; each of the competing contractors receives a bill of quantities and perhaps a set of drawings. The contractor then proceeds to seek quotations from materials suppliers for the materials, from subcontractors for the subcontracted work, and to estimate his own labour and overhead requirements. The overheads include the cost of non-working foremen, the provision and maintenance of site services and security, a portion of the central office costs, and any financial charges. A profit markup which reflects the contractor's desire to win the project is then added to the summation of the costs. A "tender form" is completed by each contractor and lodged with the client or client's representative on or before the last date for receipt of tenders. The tender form is in fact a legal offer to carry out the project for a specific price and in a specific time. No other details are given. The tender forms are opened by the client and his advisors and usually, if there is no obvious error, the lowest tender is accepted. Under the traditional procedure the contractor is then infromed and asked to submit the priced bills of quantities. As likely as not, the contractor will have arrived at the tender figure without pricing the detailed unit rates of the bill of quantities. He then proceeds to break down the tender figure into all of the measured rates contained within the bill of quantities. Tactical manouvers take place at this stage, for example, if it is suspected that the extent of certain parts of the project may be reduced low rates will be applied, and vice versa in the case of areas where the work may increase. If the contractor wishes the project to be self-financing he may increase the rates for work at the beginning of the project and reduce in the same proportion the rates which occur late in the project. Thus leaving the tender figure is left the same but while generating a proportionally high income at the beginning of the project, which will then finance any cash outlays needed later on and save interest charges. This is known as "forward loading".

The client's cost advisors (usually a firm of quantity surveyors) will perform a "cost analysis" of the accepted tender. The rates contained in the priced bill of quantities will be gathered up and allocated over the building 'elements'. The bill of quantities under SMM 6 contains lists of unit rates of finished work gathered into trade sections as shown in tables 4.1 and 4.2. The cost analysis presents the building costs allocated to the building 'elements' as shown in table 4.3. Clearly the rates from any one trade section may be appropriate in more than one element. For example, reinforced concrete will occur both in foundations and possibly in a structural frame.

Quantity surveyors use elemental cost analyses for the cost planning of future projects and when more detail is emerges, the rates contained in bills of quantities are appropriately adjusted for time, quantity and quality are used to calculate rates for use in cost planning by approximate quantities.

| | |
|---|---|
| A GENERAL RULES | M ROOFING |
| B PRELIMINARIES | N WOODWORK |
| C DEMOLITIONS | P STRUCTURAL STEELWORK |
| D EXCAVATION & EARTHWORK | Q METALWORK |
| E PILING | R PLUMBING & ENGINEERING INSTALLATIONS |
| F CONCRETE WORK | S ELECTRICAL INSTALLATIONS |
| G BRICKWORK & BLOCKWORK | T FLOOR, WALL & CEILING FINISHINGS |
| H UNDERPINNING | U GLAZING |
| J RUBBLE WALLING | V PAINTING & DECORATING |
| K MASONRY | W DRAINAGE |
| L ASPHALT WORK | X FENCING |

Table 4.1 TRADE SECTIONS

| | | | | | £ | |
|---|---|---|---|---|---|---|
| | **ROOFING** | | | | | |
| | **Plant** | | | | | |
| 1. | The Contractor is to allow here for bringing to site and removing from site all plant required for this section of the work. (SP7: WC14: E4) | | Item | - | - | - |
| 2. | The Contractor is to allow here for maintaining on site all plant required for this section of the work. (SP7: WC14: E4) | | Item | - | - | - |
| | **Slate or tile roofing** | | | | | |
| 3. | Marley 'Mendip Smooth' roofing tiles to 75 mm lap fixed with approved clips to and including 38 x 25 mm treated softwood battens to timber at 338 mm gauge. (SP7: WC14: E4) | 62 | $m^2$ | 4.82 | 298 | 84 |
| 4. | Form small opening not exceeding 0.50 $m^2$. (SP7: WC14: E4) | 1 | No. | .46 | | 46 |
| 5. | Extra for eaves finish with eave filler clip. (SP7: WC14: E4) | 13 | m | .30 | 3 | 90 |
| 6. | Extra for verge and undercloak bedded and pointed. (SP7: WC14: E4) | 2 | m | 2.09 | 4 | 18 |
| 7. | Ridge tile to suit general tiling bedded and pointed in mortar. (SP7: WC14: E4) | 5 | m | 3.74 | 18 | 70 |
| 8. | Vented ridge tile by Rite Vent Ltd., bedded and pointed in cement mortar and including connection to 127 mm flue pipe. (SP7: WC14: E4) | 1 | No. | 14.08 | 14 | 08 |
| | **Underlay** | | | | | |
| 9. | Reinforced bituminous felt underlay to B.S. 747 Type 1F lapped 150 mm horizintally and 300 mm vertically and fixed with galvanised clout nails. (SP7: WC14: E4) | 62 | $m^2$ | .85 | 52 | 70 |
| 10. | Holes for pipes. (SP7: WC14: E4) | 2 | No. | .06 | | 12 |
| | To Collection | | | £ | 392 | 98 |

Table 4.2 TYPICAL PAGE FROM A BILL OF QUANTITIES

**1. Substructure**

**2. Superstructure**

2.A. Frame

2.B. Upper Floors

2.C. Roof

2.D. Stairs

2.E. External walls

2.F. Windows and external doors

2.G. Internal walls & partitions

2.H. Internal doors

**3. Internal finishes**

3.A. Wall finishes

3.B. Floor finishes

3.C. Ceiling finishes

**4. Fittings and furnishings**

**5. Services**

5.A. Sanitary appliances

5.B. Services equipment

5.C. Disposal installations

5.D. Water installations

5.E. Heat source

5.F. Space hearing and air-conditioning

5.G. Ventilating system

5.H. Electrical installations

5.I. Gas installations

5.J. Lift and conveyor installations

5.K. Protective installations

5.L. Communication installations

5.M. Special installations

5.N. Builder's work in connection with services

5.O. Builder's profit and attendance on services

**6. External Works**

6.A. Site work

6.B. Drainage

6.C. External services

6.D. Minor building works

**Preliminaries**

Table 4.3 BCIS Table of Elements

The data which is published in the sources mentioned in Appendix I is of two types.

(i) Cost analyses (of real projects submitted by subscribers) published by the B.C.I.S. (Building Cost Information Service).

(ii) Unit rates for measured work. These "price book" rates are designed to replicate as far as possible the current going rate in bills of quantities.

Synthesis: The Quality of Data.

The process of cost generation, recording and the eventual derivation of what is euphemistically called 'data' is riddled with inconsistencies. There is a discernable trend for research in this field at present to apply itself to the refinement of the techniques of 'cost' modelling viz., this work and that of Morrison and Newton, all in the past twelve months.[15,16] Clearly much detailed work addressed to the quality of data used in such models is needed. From the discussion of the previous sections and the study presented in Appendix I, four central issues with respect to data may be distinguished.

(i) Data transformations.

(ii) Cost-planning as a self-fulfilling prophecy.

(iii) Data incompatible with cost generation.

(iv) The variability of data.

These issues, although all present and interacting at the same time, will be dealt with individually for the purpose of analysis and comment.

(i) Data transformations.

Data, by its very name, purports to be objective. However it was proposed, early in section 4.2.2, that there are imponderables and subjective elements involved in data and its collection.

This subjectivity, it is suggested, creeps into the data under discussion here in two ways, firstly during the recording of the event, and secondly during subsequent transformations of the data to produce 'information' for various procedural requirements. The most common example of 'misinformation' occuring at the recording stage is that of the records for the time taken to perform various tasks in a project, some of which are included in bonus schemes and some which are not, as discussed earlier.

Two major transformations of data occur. The first is when the sum of the resource costs is spread over the unit rates to produce the priced bill of quantities with the attendent 'loading' and tactical decisions. The second is when the unit rates are subdivided and clustered into element costs. These processes are summarised in figure 4.2. To complete the picture of the 'cycle' of use of this data it should be added that the elemental rates tend to be used by quantity surveyors for cost planning at an early stage in the design when there is little detail. Later on, at sketch design stage, unit rates based on similar bill of quantity items from comparable projects are used in conjunction with approximate quantities to produce more detailed cost plans.

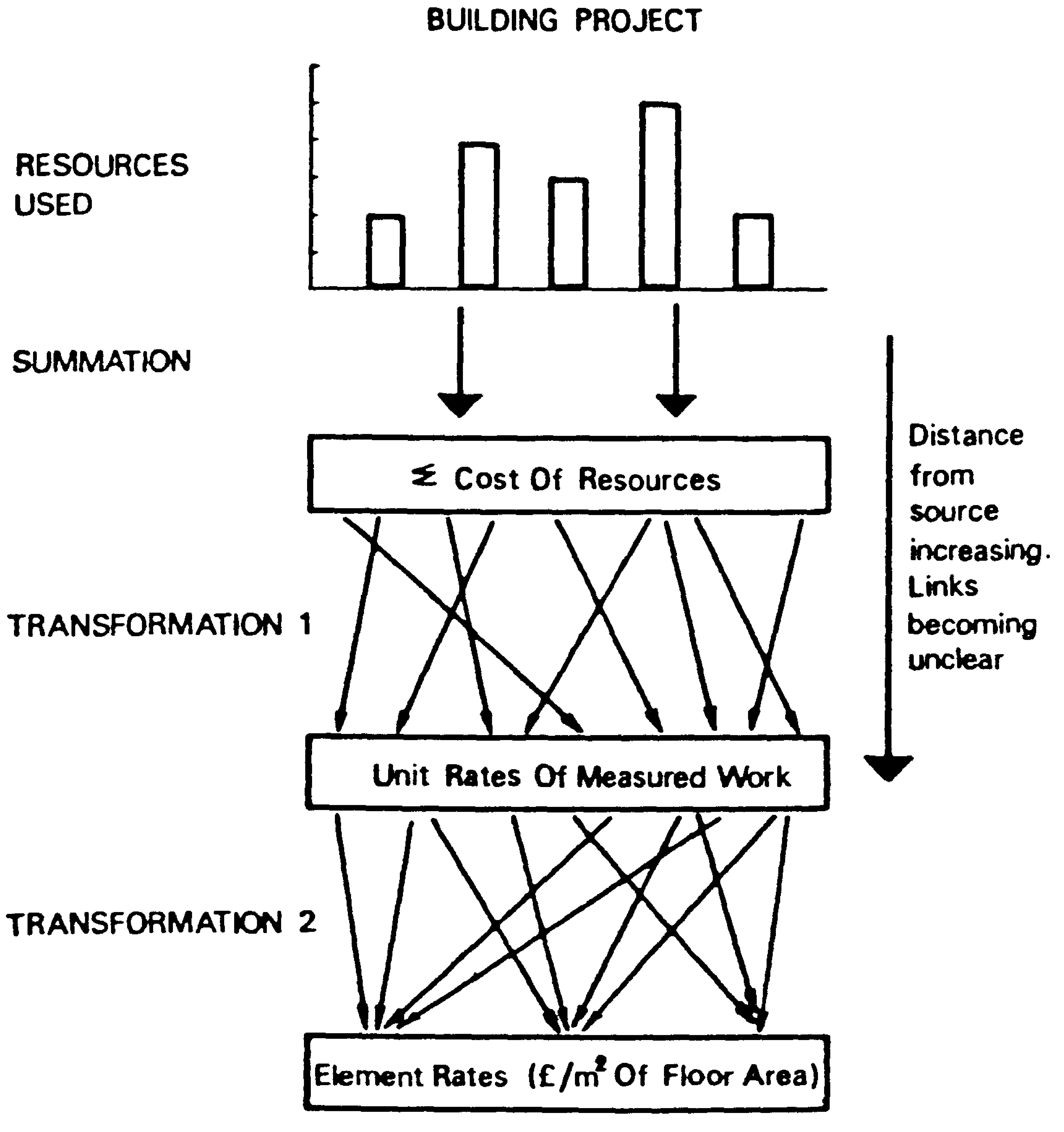



Fig. 4.2 DATA TRANSFORMATIONS

(ii) Cost planning as a self-fulfilling prophecy.

Clearly, much apparently firm information is produced from data which may reasonably be regarded as suspect. On the other hand existing practice seems to keep many professionals happy, the accuracy of estimating both by contractors and by professional cost advisors has been the subject of much research itself. This work has been well-reviewed elsewhere.[18] Clearly 'the answer' depends on both what exactly is being measured and the technique of measurement among other things, but the most comprehensive of the recent studies shows that the mean deviation of cost planning predictions of the lowest tender is just under 10%.[19] Although far from perfect this figure seems quite good in the light of the quality of the data on which such predictions are based. However it is suggested here that the conventional view of the process of cost planning confuses the issues and a plausible reason is proposed to explain why the accuracy given above is not worse.

The traditional view of cost planning is that it moves through states of increasing accuracy, beginning with fairly low accuracy at the inception stage and then as sketch designs are produced, elemental cost planning takes place and eventually cost plans from approximate and then firm quantities. Hence, so the story goes, at the latter stages with much more detailed information the accuracy of the cost planning (or cost estimating by the quantity surveyor) is much greater than at the beginning.[13] This view assumes that the end point, the accepted tender, is the target on which one has eventually "homed-in". An alternative view and, it must be said at the outset, one for which there is little empirical evidence but which seems to fit the patterns of the process, is that cost planning is a self-fulfilling prophecy.

'Cost planning as a self-fulfilling prophecy' in real terms implies that the tender figure is fixed from the first time that a budget is given. As the design proceeds more information builds up about the project, if the project is perceived to be deviating from its preplanned financial course, the control function is exercised and adjustments are made to the design to bring it back into line. Eventually, the accepted tender will be sufficiently close to the cost plans and estimates. This prompts the question, how close will the building be to the one which was desired? If the object of the whole exercise is good design one must guard against the tail wagging the dog. The procedures as they are now make it very difficult for the cost planner to be shown to be wrong. It is relatively easy to keep the figures in line if the design is altered to suit. For example in a report on the Holy Innocents Church Orpington, the project quantity surveyor said of the accepted and competition winning design,

> "We therefore hypothesised that a building of only half the floor area would be possible..."[26]

The dimensions of the church design were appropriately reduced by the architects and,

> "The final negotiated figure (including PCs based on quotations) was still marginally higher than the budget".[26]

(iii) Data incompatible with cost generation.

The main inconsistency in the data is that although as has been pointed out earlier, cost is generated by the use of resources, the economic data generally available and used for cost modelling does not represent cost in this way. It has been shown that it is possible to link economic information directly to resource usage in such a way that there are considerable advantages in designing, planning and controlling construction projects.[20] As well as being incompatible with resource generation, unit rates have been shown above to be subject to a degree of tactical adjustment in the preparation of tenders, which although leaving the tender unaffected, produces a high level of distortion in the actual rates themselves. This can be shown by an examination of the co-efficients of variation for unit rates from priced bills of quantities.

(iv) Variability of data.

The co-efficients of variation of bills of quantity rates for similarly described items of work are much greater than figures for whole identical buildings. Beeston suggests that the co-efficient of variation for identical buildings in the same location would be about 8½%, he gave typical figures for the trades within bills of quantities as follows: [21]

| | | | |
|---|---|---|---|
| Excavator | 45% | Joiner | 28% |
| Drainlayer | 29% | Roofer | 24% |
| Concretor | 15% | Plumber | 23% |
| Steelworker | 19% | Painter | 22% |
| Bricklayer | 26% | Glazier | 13% |
| Carpenter | 31% | All Trades | 22% |

This variability has been exemplified in the published data as shown in table 4.3.

This would support the idea that bills of quantities rates are merely a notional breakdown of the overall price and are tempered with so many tactical considerations (forward loading, special discounts with certain suppliers, etc.) as

| No. | Item | Building Specification Cost Index | Building Cost File | Q.S. Weekly Datafile | Building Trades Journal Estimating Supplement |
|---|---|---|---|---|---|
| 1 | Trench excavation n.e. 1.50 m deep by hand | 5.57 | 6.06 | 4.64 | 6.92 |
| 2 | Planking strutting to trenches n.e. 1.50 m deep | 0.74 | 0.50 | 0.72 | 0.75 |
| 3 | Bulk hardcore filling | 7.05 | 7.98 | 5.42 | 9.02 |
| 4 | Concrete (1:3:6) in foundations over 300mm | 25.81 | 22.99 | 23.77 | 27.95 |
| 5 | Concrete (1:2:4) in beds 150 mm thick | 5.62 | 4.81 | 5.12 | 4.56 |
| 6 | 12mm dia. bar reinforcement in foundation | 0.40 | 0.37 | 0.37 | 0.34 |
| 7 | Fabric reinforcement A252 in bed | 1.90 | 1.49 | 1.47 | 1.46 |
| 8 | Formwork to vertical walls | 9.83 | 8.76 | 7.84 | 6.68 |
| 9 | Half-brick wall in common bricks | 8.06 | 6.72 | 6.31 | 7.15 |
| 10 | 100 mm block wall | 5.85 | 5.21 | 5.39 | 5.07 |
| 11 | Hessian based dpc | 3.03 | 2.84 | 2.33 | 1.76 |
| 12 | 265 x 165 roofing tiles | 9.83 | 10.26 | 10.71 | 9.83 |
| 13 | Three layer felt roofing | 5.53 | 6.16 | 5.29 | 5.47 |
| 14 | 50 x 100 softwood plate | 1.09 | 1.02 | 0.85 | 0.85 |
| 15 | 50 x 100 softwood partition | 1.21 | 1.68 | 1.19 | 1.33 |
| 16 | 25 mm softwood roof boarding | 6.39 | 6.82 | 5.43 | 5.39 |
| 17 | 762 x 1981 hardboard flush door | 10.14 | 9.67 | 9.45 | 13.00 |
| 18 | PVC soil and vent pipe | 4.91 | 3.55 | 3.37 | 2.33 |
| 19 | Two coats of plaster on wall | 2.91 | 2.30 | 2.39 | 2.60 |
| 20 | Plasterboard and skim to ceilings | 3.43 | 3.06 | 2.78 | 2.72 |
| 21 | Two coats of render on walls | 3.29 | 2.30 | 2.29 | 2.35 |
| 22 | 25 mm floor screed | 2.17 | 2.16 | 1.68 | 2.28 |
| 23 | 4 mm Float Glass n.e. 1 $m^2$ | 12.14 | 9.04 | 7.06 | 10.49 |
| 24 | Two coats emulsion on wall | 0.85 | 0.85 | 1.00 | 0.80 |
| 25 | K.P.S. and two coats of oil | 2.33 | 1.67 | 2.06 | 1.63 |
| 26 | 100 mm flexible jointed drain pipe | 2.34 | 2.49 | 1.65 | 1.75 |

Table 4.3: Sample of common bill items and prices (April 1979).[17]

to render them very unreliable for any form of cost planning.

It is known that prices tend to be distributed about their mean in a skewed way, high prices tending to be further above the mean than low prices are below it. This can be taken into account in a statistical analysis.[22] When variability in prices is due to a combination of several distinct causes, each of which has its own co-efficient of variation, the overall co-efficient may be calculated by adding the squares of the individual co-efficients and taking the square root of the total.

The practical meaning of this is that when preparing an estimate using published data adjusted for the circumstances of a particular project, it would be possible to calculate the co-efficient of the adjusted rate. Unfortunately this would not be the panacea for all cost modelling or estimating problems, because when causes of variability are removed, for example by adjusting for them, the effect on the overall reliability is small as the combination and separation of co-efficients of variation is by squares. But at the very least it would enable a more explicitly realistic picture of the data to be presented than is the case at present.

However, statistical methods alone do not provide the full answer. The variability, imprecision and uncertainty present in the data are the result of complex phenomena which deserve further consideration. The issues are relevant here because they have a bearing on how these traits are measured in the later experiments.

The nature of the imprecisions in building cost and price data.

The plural of 'imprecision' is used advisedly in the above sub-heading. This section will demonstrate conceptually the presence of two different types of imprecision, probabilistic and possibilistic. Probabilistic imprecision is that which may be explained by probability theory, i.e. given a statistical knowledge of the distribution of certain historic events, it is possible to predict the frequency of occurrence of future events. These events are not assumed to be 'random' (although some recent work, mistakenly assumes this to be the case)[16] some outcomes will have a higher likelihood of occurrence than others as one would expect. Possibilistic imprecision on the other hand is that imprecision (or 'fuzz') of outcome predictions which depends on the imprecision (or 'fuzz') attached to the information used to make the prediction. Both of these theories will be explained in greater detail when the methods of measurement of imprecision, in experiments with models, are considered in chapter 8. Initially we need to concern ourselves with the nature and existence of these two phenomena. To this end the examination of a case will help to concentrate the mind.

Consider an estimator predicting the cost of the labour content of the foundation and substructure for a multi-storey building. He reads the drawings and soil survey reports and may visit the site. In this way he conceptualises the work to be carried out and under what conditions it will be carried out. On the basis of the information he has been given and of his view of the rquired work and method of work, he adjusts the labour output rates recorded in past projects which are comparable.

Consider now the actual carrying out of the work at some later date (assuming that the contractor has won the project). A reasonable scenario for this would be the following; assume that the work takes place in the month of September as originally planned. However when the ground is opened up it is found that the conditions are not as was suggested by the soil survey report based on trial holes. In fact conditions are such that the substructure is substantially redesigned and the amount of piling work is doubled, resulting in the need for a second piling rig and gang to be imported to the site. Further, it turns out that the month of September is unusually wet and great difficulty is experienced in moving the heavy piling equipment around the site. Consequently many men are under-employed while waiting for the machinery to be relocated. In summary the amount of the resource labour turns out to be in excess of what the estimator originally expected. Why?

The two circumstantial reasons for the increased labour requirements were that the unexpected soil conditions necessitated increased piling work, and secondly that the unusually high rainfall caused ground conditions to deteriorate and the work generally to be slower than would normally be expected for the month of September. It is suggested here that the first phenomenon is possibilistic and could usefully be dealt with by fuzzy-set theory. The soil report was based on the trial holes, the inputs to the decision were 'fuzzy' and possibility theory seeks to provide a means of deducing "the fuzz on the outputs, given the fuzz on the inputs".[23]

On the other hand, if the meteorological data for the locality of the site is studied, we may find that the mean rainfall for the month of September is say 50 mm and that the actual recorded rainfall seems to be normally distributed about this mean with a standard deviation of say 10 mm. The rainfall is not random, it is far more likely to be 50 mm than 150 mm, on the other hand there is no 'fuzz' on the inputs we have access to the actual recorded rainfall for the area for each September since records began. 'No fuzz on the inputs' but that does not make the information precise (or 'crisp' in fuzzy jargon), we know that the pattern of rainfall appears to be according to a distribution (which we have assumed here to be 'normal', this does not have to be the case, other distributions may easily be dealt with). The probable future scenario may be reasonably forecast using a probabilistic computational technique such as Monte-Carlo simulation. The project could be simulated many times with respect to rainfall, replicating the observed distribution of rainfall. Using cumulative probability it is possible to estimate the risk of any level of output not being achieved. The estimator may chose the level of risk he considers acceptable and base his estimate accordingly.

Finally before summarising and concluding from the above, it is important to be aware of the limitations of the method of exposition of the arguments. The latter has been entirely conceptual and anecdotal, there is no empirical evidence to support the co-existence of the phenomena. Neither, it must be said is there sufficient empirical evidence to suggest that the imprecision in the data is entirely probabilistic,[24] as assumed by Fine and others, or, possibilistic,[16] as assumed by Newton. None of the three approaches could be described as a model of imprecision in the data, rather each approach seeks to provide a conceptual framework for assisting in the discussion and measurement of the imprecision.

In summary it is suggested, somewhat inelegantly, that in building economics as in many other fields, the above are parallel phenomena and not mutually exclusive, a view which Zadeh himself takes in the general case.[25] However the measurement of the imprecisions depends on the quality and power of the tools or computational techniques available. This is discussed separately in chapter 8, where the evaluations carried out on the models are described. This section has been concerned merely with proposing a description of the nature of the imprecisions. Measurement of the latter is a different issue.

Conclusions.

The title of this section is 'Problems Identified'. Each subsection will conclude by applying the preceding material to the groups of models presented earlier in chapter 3, in order to identify any weaknesses.

(i) Deductive Models.

Most of the deductive models presented in chapter 3 were not accompanied (in the initial report of the model) by a critical appraisal of the data used. The sample used in the Kouskoulas model has been presented (see table 3.1). In statistical terms it is a very small, random sample. For reliable conclusions to be drawn from a random sample with many diverse members, the sample needs to be large. Reliable conclusions may be drawn from a smaller sample if it has been designed in order to extract the maximum of useful information. For example, in this case if one wanted a model to fit the case of 'all buildings', the sample would need to be selected so that each member had a weighting in the sample which approximates to its weighting in the population from which the sample is drawn.

None of the studies reviewed in chapter 3 presented any tests of the models sensitivity to its data. The data used in the samples for the models was generally normalised for time by applying an index of some kind to all the members, thus bringing them all to the same date in economic terms. The use of indices forms a separate issue and is discussed later, but the practical implication of this use of indices is that any vagiaries or inconsistencies, and particularly any factors which reduce the comparability of the sample members, become built-in to the model. It is known that tender prices for construction projects are not derived in perfect/theoretical market conditions.[27] The market for many types of project is quite localised, the market for the same project in a city 200 miles distant would contain a different set of potential bidders, although there may exist some members common to both. Thus the market conditions under which tender prices are derived vary in relation to geographical distribution. Market conditions also vary with time. At time $t_1$ there may be 12 potential bidders for a particular project, at time $t_2$ there may only be nine, as in the intervening period three bidders may have won other projects which stretch them to their full working capacity. Clearly an index applied to 'normalise' prices gained under differential market conditions takes no account of the real effect of the dimensions of both time and geographical distribution.

(ii) Inductive Models.

Quality of data was again a relatively unimportant issue in the reports of the inductive models presented earlier. With one partial exception the models assumed that the economic data used was determinate, thus disregarding Beeston's advice:

"A single item of data can never be relied on because it is only one member of a wide-spread distribution of such items, any one of which could have arisen by chance. The only way to increase reliability markedly is to average several of such items."[28]

One model[16] allowed that the value of a rate would vary according to its 'context', but the different values were to be specified deterministically by the user for each such context. Again no studies were presented to test the sensitivity of the models to their data sources. Inductive models may use data varying levels of aggregation, from the actual resource costs used by COCO, to the unit rates for items of measured work used by Townsend to the elemental rates used by the BCIS.

(iii) Optimisation Models.

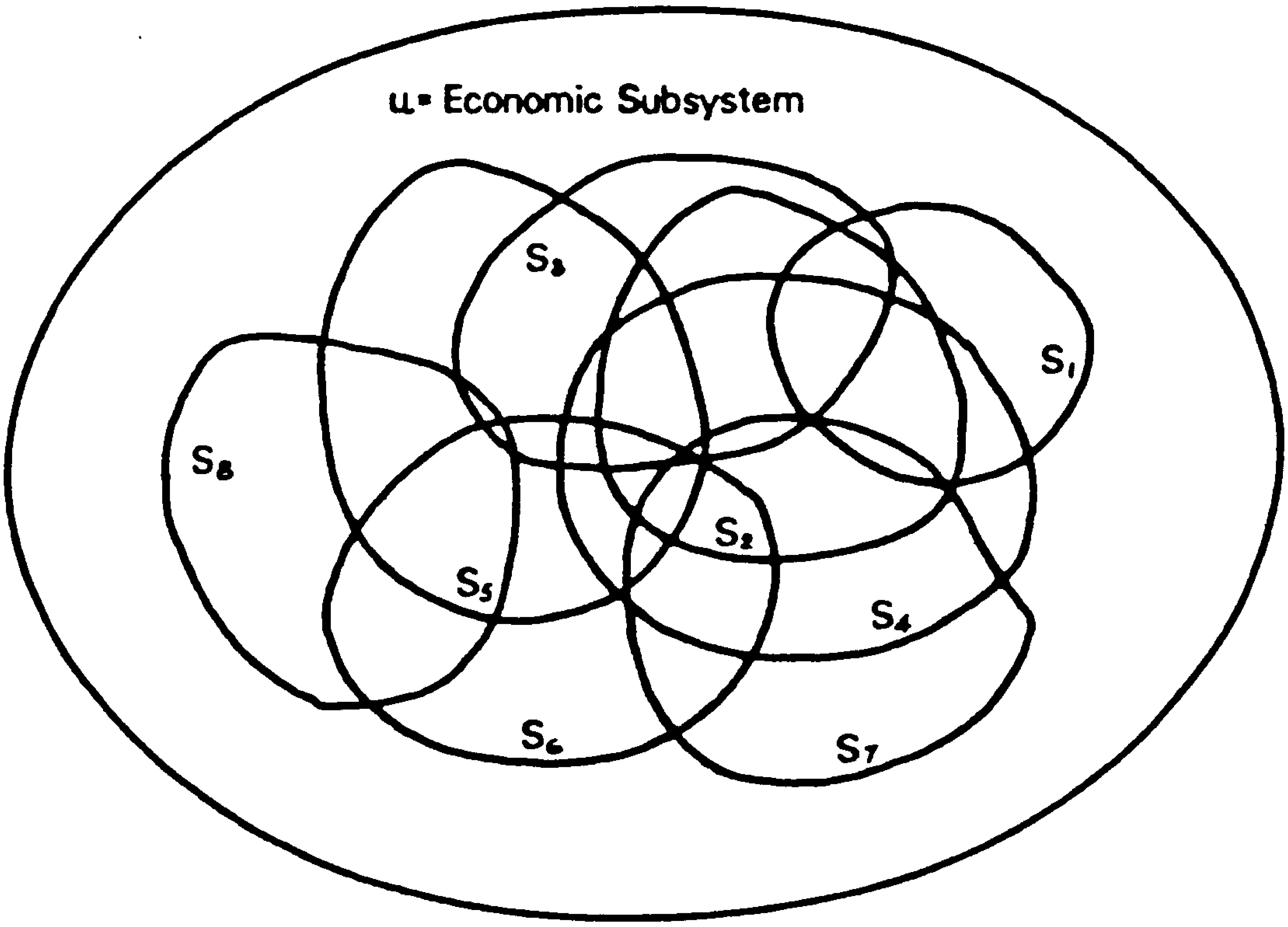
The problem of the quality of data was not neglected completely in the studies which presented optimisation models. In particular Wilson and Templeman[29] made use of an interesting method of reducing the logistic complexity of collecting and choosing from data which applies to various methods of satisfying certain performance criteria. Generally though the studies concentrated on the formulation of objective functions and the techniques of optimisation leaving the data unassessed.

(iv) Stochastic Models.

Stochastic models by their nature question the validity of given data in seeking to measure the imprecision of the model outputs which is accounted for by the unreliability attached to the data used. However the answers are not clear, due mainly to the limitations of current computational techniques. Traditional techniques of mathematical simulation assume the independence of events, this is not the case in reality. Thus, although the indeterminate nature of economic data is acknowledged, its measurement and evaluation is less than perfect, this is discussed in more detail when the techniques of modelling are considered.

### 4.2.3 Data/Model Interface

As alluded to in section 4.2.1, the issues of importance at this interface arise due to the tension between the data and the model caused by the state of development of the design. The design process was examined in detail in chapter 2, that treatment will be developed slightly further here. Before this however, consider the relationship between the economic subsystem and the other design subsystems. The complexity is increased as the economic subsystem is not similar to the other subsystems which concern the designer, rather it is the environment in which all other subsystems exist. This may be illustrated as a set diagram and is presented in figure 4.3. The




u= Economic Subsystem

$(S_1, S_2, S_3 \ldots\ldots S_8) \in u$

and

$S_1 \cap S_2$
$S_1 \cap S_3$
$S_1 \cap S_4$
$S_1 \cap S_7$

and

$S_3 \cap S_4$
$S_3 \cap S_7$
$S_3 \cap S_5$
$S_3 \cap S_6$
$S_3 \cap S_8$

and

$S_7 \cap S_6$
$S_7 \cap S_5$

and

$S_2 \cap S_3$
$S_2 \cap S_4$
$S_2 \cap S_6$
$S_2 \cap S_7$

and

$S_4 \cap S_4$
$S_4 \cap S_5$
$S_4 \cap S_6$
$S_4 \cap S_7$
$S_4 \cap S_8$

Fig. 4.3 INTER-RELATIONSHIPS AMONG DESIGN SUBSYSTEMS economic subsystem forms the environment or universal set of which all the others are members. In the schematic diagram only eight subsystems are shown, the interrelationships for subsystem $S_1$ are shown at two levels only. Clearly if the first and second level intersections were considered for all eight subsystems, the presentation would become highly complex. It was shown in chapter 2 that a comprehensive model of the design activity enabling any quantification of these interdependencies among subsystems has not yet been presented. Hence an alternative approach is called for.

One possible candidate is a post-hoc representation of the design activity. It was shown in chapter 2 that there are as many design methods as there are designers. Empirical evidence was presented which showed that the particular route through the design problem, chosen by the designer, depended, among other things, on the method of representation the designer used. The only tangible evidence of the design process is the finished design. A post-hoc representation attempts to show which decisions would have had to have been considered for the design solution to have been reached. The order in which they are considered will vary from person to person, but they have had to be faced at some stage in order to produce a design solution. This representation may take the form of a hierarchical tree as shown in Figure 4.4. Movement down through the hierarchy is not temporal, it was shown in

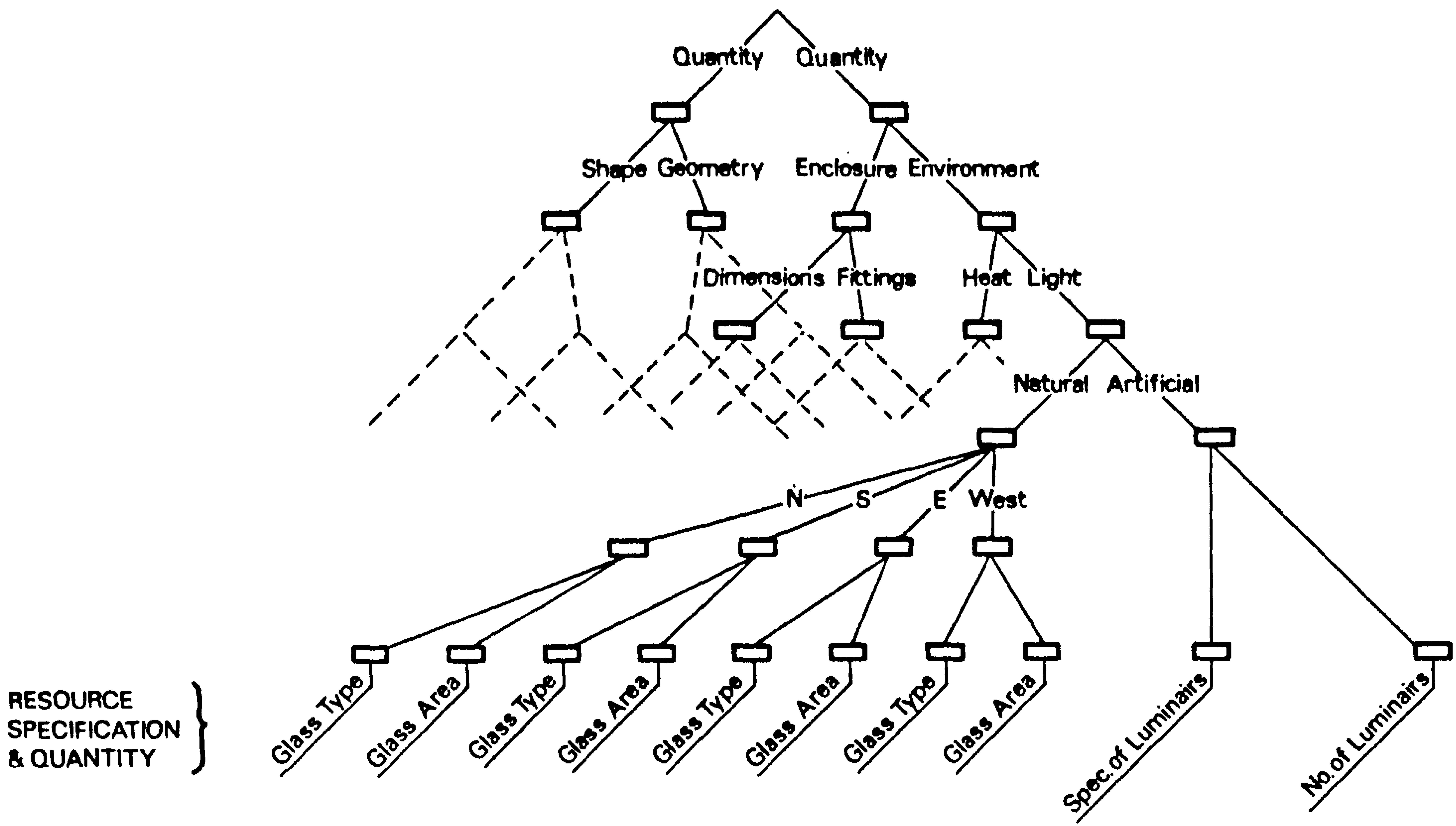



Fig. 4.4 POST-HOC REPRESENTATION OF DESIGN HIERARCHY

chapter 2 that some designers may start at the bottom with a solution and work upwards, some may begin at the top with the brief and work downwards, others may begin with partial solutions and move around the hierarchy at random.

There are many limitations associated with the hierarchy as a method of presentation, it does not deal very well with the complex inter-relationship among decisions which maybe considered using set-theory as in figure 4.3. Further it is an apparently rigid representation not appropriate to the design activity. However, if it is not considered as a model of the design process but rather as a post-hoc representation of the range of design decisions, which is particularly useful for the evaluation of 'design cost models', then it has some merit. It shows the rapid progression from a position of little or no information on the proposed design, to a state of having large amounts of information.

This movement away from a situation of little information has major implications, in particular for the use of deductive and inductive models. The utility of these types of model at different stages of the design is illustrated schematically in figure 4.5. As more detail is acquired about the design problem, the feasibility of using inductive or simulation models increases and the usefulness of deductive models decreases. The reasons for this are discussed in more detail in section 4.2.4.

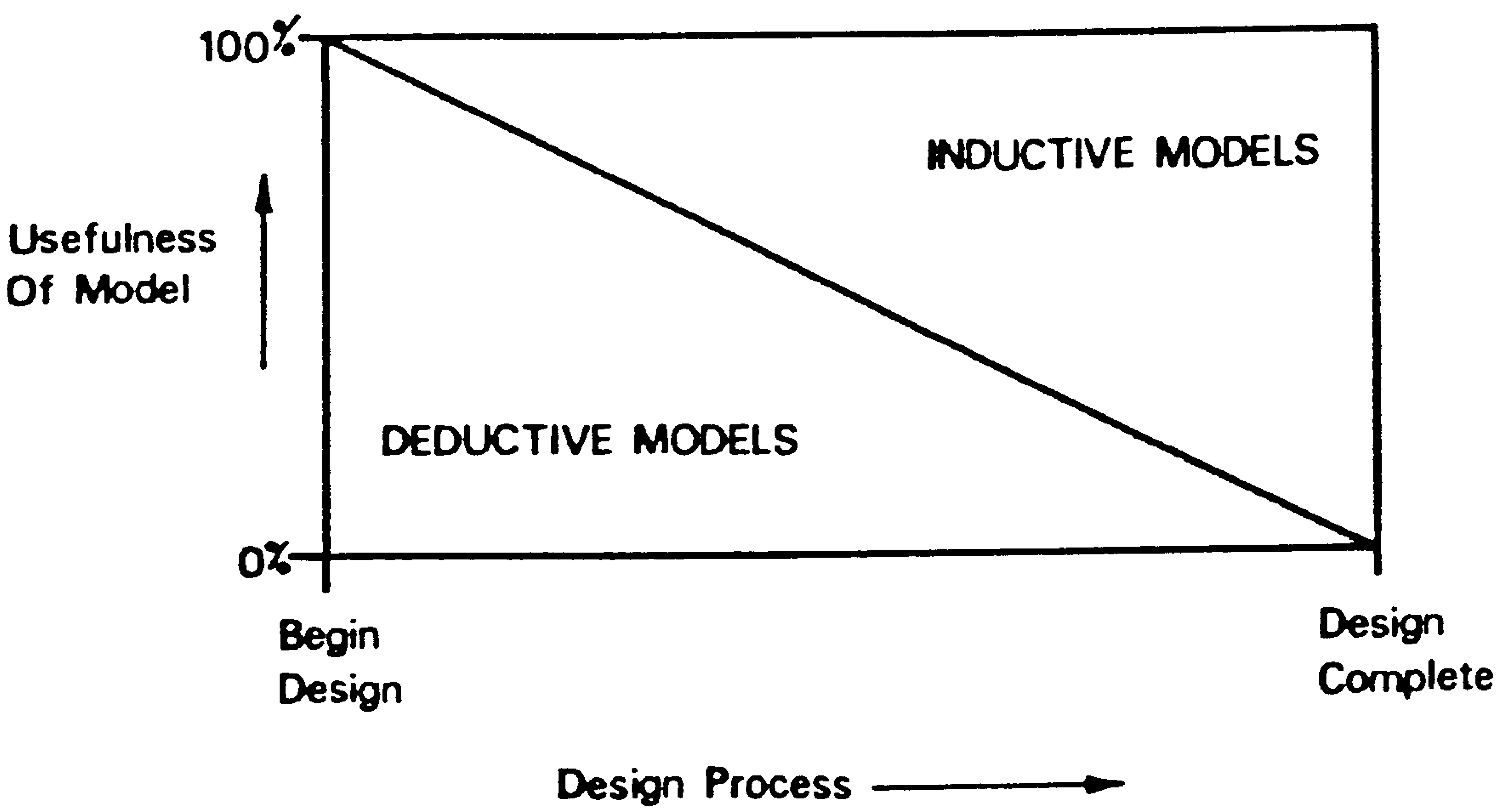



Fig. 4.5 USEFULNESS OF DEDUCTIVE AND INDUCTIVE MODELS IN THE DESIGN PROCESS

The relevance of the above discussion to the data/model interface may be exemplified as follows. Consider the inception of an office project, the designer is required to provide 5000 $m^2$ of lettable office space on a particular site. At this stage of the design detailed economic data on the current cost of resources such as labour, plant hire, etc. are of little relevance, what is needed is data of a coarser nature, for example, the current construction cost per $m^2$ of lettable area. The data used must be tuned to the stage of the design and the modelling technique used. In this context consider the models as presented in chapter 3.

(i) Deductive Models.

All of the deductive models presented are of use only in the early stages of design, they give guidance usually on the possible market price. As the design progresses and the designer produces trial solutions, more detailed data is required and deductive models become less useful as they cannot utilise such data. In summary, as design progresses, deductive models become less useful.

(ii) Inductive Models.

Inductive models may be applied almost any time during the design process. Their usefulness increases as the design progresses. The exception is that there is rarely enough information available at the inception of a design to facilitate the use of an inductive model. It is not insignificant that the majority of the inductive models presented earlier were used for tender price prediction. This has been the traditional use of such models. The increasing availability of computer facilities has enhanced the power of inductive models, this is manifested in particular in the models of Townsend and Newton[30,16] which are capable of producing useful parametric studies. Developments of this nature increase the usefulness of inductive models at the earlier stages of design. The usefulness of inductive models generally increases as design progresses.

(iii) Optimisation Models.

Optimisation models, although frequently highly constrained and inflexible in themselves are, as a group, capable of being applied at any stage of the design process, this indeed is one of their most attractive features. For example the optimisation models of Gero and Dudnick were designed for early use and that of Wilson and Templeman was designed to be used much nearer the completion of the design.

(iv) Stochastic Models.

There is nothing about the current computational techniques of stochastic modelling which confine their use to any particular stage of the design process. As with the other groups of models, the limiting factor is again the availability of suitable data given the existence of such data, stochastic models may be used at any stage of the design process, this range of application is exemplified by the stochastic models presented earlier.

### 4.2.4 The Modelling Environment

Modelling Techniques.

This discussion of the techniques of modelling falls into three sections:

Deductive Methods.
Inductive Methods.
Stochastic Methods.

Each of these methods has strengths and weaknesses in particular applications. These will be discussed here in the general case in order to provide a suitable framework for the evaluations in chapters 8 and 9.

## Deductive Methods.

Deductive models are models derived from the statistical analysis of sample data. The techniques themselves are well known and are relatively easy to apply in building economics.[9,31,32] The central concern of this type of analysis is the relationship between variables. Three aspects of the theory are relevant, correlation, regression analysis and sampling theory.

### (i) Correlation.

The traditional measure of association between two variables has been the correlation co-efficient r which for n sets of x and y is given by

$$r = \frac{\sum x_i . y_i}{n.Sx.Sy} \qquad \ldots[4.1]$$

or for computational ease

$$r = \frac{\sum x_i y_i - n\bar{X}.\bar{Y}}{\sqrt{\sum x_i^2 - n\bar{X}^2}\sqrt{\sum Y_i^2 - n\bar{Y}^2}} \qquad \ldots[4.2]$$

The co-efficient r is a pure number lying in the range $-1 \leq r \leq +1$, it takes the value +1 when all the points lie exactly on a straight line, the sign indicates whether the slope is positive or negative. The drawback of this co-efficient is that it is so well known that its limitations are often forgotten. These are as follows:

(i) Linearity, the expression above checks for a linear association between the variables, variables which are associated in a curvilinear way may show a low correlation co-efficient.

(ii) A value of r close to 1 shows high correlation but does not show causality, both variables may be directly linked to a third unmeasured variable. There are many examples of such spurious correlations.

(ii) Regression Analysis.

This is a form of analysis which attempts to predict the value of the dependent variable, given the value of the independent variable(s) by means of the regression equation. The equation, whether for the simple linear case or for multi-variate curvilinear relationships, is estimated by the method known as 'least squares'. It is this latter method which gives rise to many of the limitations of deductive models.

Consider the simple case of two variables, a scatter diagram is plotted and a 'best fit' line is attached to the data minimising the squares of the distances of each of the points to the line. The equation of this line is then the model for the relationship. The limitations of the technique are therefore:

(a) Outlying data points on scatterdiagrams have a disproportionately high influence on the derived model.

(b) The derived model is only valid for the range of historical data included in the sample.

(c) Simple regression assumes linearity.

(d) The technique deals only with continuous functions, many relationships in building economics are stepwise or discrete functions.

(iii) Sampling Theory.

Deductive models are based on samples. Deductions are made from samples and inferred to be true for the populations from which the samples are drawn.

Sampling theory consists of a number of methods which assist in ensuring that the sample used for analysis does in fact resemble closely the population about which inferences are to be drawn. Taken to its most meticulous, as in the case of opinion polls, good sampling methods can assist in greatly reducing the size of sample needed to draw valid conclusions. One such method, applicable to building economics, is in quota sampling, where knowledge of the population being sampled is used to determine the quotas of the buildings in various groups.*

There should also be a relationship between the structure of the sample and the number of variables to be taken into account in the deductive model. The sample should be

* Reference was made to the absence of this method in the Kauskoulous model presented in chapter 3.

designed factorially with respect to the variables, so that there are two members of the sample for each possible combination of extreme values of variables, and hopefully the same for many values in between.

## Limitations of deductive methods.

The points discussed above have the following implications for deductive models. They are totally reliant on historic data. Extrapolation may not be made beyond the range of the sample. Great care should be exercised in making inferences from ill-designed samples. There is an assumption of linearity underlying simple regression and linear correlation theory, for this reason attention should be focussed on any gaps in the sample data and also on data which has a low correlation co-efficient. The nature of the technique used to fit models to data lends a disproportionate effect to 'wild' data.

## Inductive Methods.

The nature of inductive models has been described in general terms earlier. Here we are concerned with the techniques of modelling which are used in these models. Given that the resources required to construct a particular design solution are well defined, inductive methods are essentially additive in nature. The economic measure is calculated by a summation over the cost generating items.

$$E = \sum_{i=1}^{n} L_i + P_i + M_i$$

where

$n$ = the number of subsystems.

$L_i, P_i, M_i$ = the direct and indirect costs of labour, plant and material respectively for each subsystem.

It has been pointed out earlier that these cost generating items may be set at varying levels of aggregation. The individual resources may be itemised in appropriate units, for example steel in tonnes, plant and labour in hours required, etc. The resources may be aggregated into units of measured work, for example, per cubic metre of concrete in beams, including all plant, material, labour and overheads necessary to complete and position the item of work. They may be aggregated even further into 'element unit rates' which group all resources under about six elements such as 'substructure', 'frame', etc.

Modern, more powerful inductive models have two stages, of which the above is the second. These computer models are built such that they can translate design decisions (usually in the form of performance specifications) into the physical resource implications. In CAD terms they are known as 'simulation models', they simulate the solution. The differences in terminology are not important, the simulation process is well defined although very complex, it may be represented as follows:

$$S = \prod D_i . A_j . b_t$$

where

$S$ = the total of the resources necessary for subsystem/building.

$D_i$ = the design decisions.

$A_j$ and $b_t$ = the variables and constants needed to solve the technical design, examples are loading allowances on beams and thermal transmittances and shading factors for structural and service design.

The outcome of this function taken over an entire building should be the bottom line of the hierarchy illustrated in figure 4.4. While it has proved impossible so far to build a model which defines the hierarchy of design decisions for the general case, it is not conceptually difficult to simulate by computer the technical design process, given the performance and other decisions made by the designer and the appropriate codes of practice, regulations and 'design methods' for the various building subsystems.* Theoretically there is no limit to the number of variables or range of relationships which may be dealt with in this way. The problem reduces to one of the logistics of writing and testing vast computer programs which, given the manpower and equipment necessary, is not insurmountable. The models STEPS and MACE presented later carry out this simulation function at a very detailed level each for one subsystem. Other models such as those of Newton and Townsend simulate all subsystems but with less detail.[16,30]

Potential weaknesses in inductive methods centre around two issues in general. Firstly the compatibility of the model with the data, which has been discussed in detail earlier, and secondly, the constraints and assumptions built in to the model. The nature of inductive methods is such that these assumptions are not generally explicit and furthermore, unlike deductive methods the assumptions are liable to be different in each case, and are built in to the algorithms and routines in computer software. Clearly assumptions of this nature are not obvious to the user. Examples of the latter will be considered in some detail in chapter 8.

* Examples are, the accepted calculation method for services design in this country as set out in the CIBS guide.

Stochastic Models.

Knowledge of the fact that models in building design evaluation attempt to predict some future outcome, coupled with the prior assumption that a model is an abstraction of reality and, even a cursory consideration of the quality of the existing economic data, lead inexorably to the conclusion that the phrase 'deterministic model' is a conflict in terms. Whenever we predict the future we are making an assessment based on human judgement and available data, neither of which is perfect. Notwithstanding that, relatively few of the models in the literature were in fact stochastic models. The reasons for this are difficult to find, well developed computational techniques do exist for the measurement of uncertainty and have been used in physics and in applied sciences such as systems analysis and operational research for decades. The strongest brake on the application of these techniques would appear to be the fact that designers and building economists find it difficult to think in terms which imply an acceptance of risk and uncertainty.

There are two major approaches by which 'real-world' uncertainties may be taken account of in models. Firstly, by the use of some set of specially developed computational techniques, and secondly, the non-mathematical approach of the young field of 'knowledge engineering'. Knowledge engineering is an approach to the development of computer systems which have a lesser reliance on mathematical data and more on the use of the qualitative knowledge which would be used by the human decision maker, this involves systems which have some 'learning' facility or expandable 'knowledge base'. The applications are still relatively primitive, but the successes have in some cases been spectacular.[34,35] This specialised field is regarded as being outside the scope of this thesis.

The mathematical techniques of risk analysis are much more highly developed. Among the relatively few models which recognise and consider uncertainty in some of the values, the most commonly applied technique in building economics has been that of Monte-Carlo simulation. It is suggested that the technique has often been applied unquestioningly. For example one of its assumptions is that the events simulated are independent events. In building economics this is rarely the case. Secondly, the use of normal and rectangular distributions has been assumed as correct. Wilson has been able to confirm some accepted 'folklore' concerning the skewed nature of the distribution of labour and material prices, in a study conducted in 1981.[22]

In summary, the main issues which remain unsolved cluster around the problems encountered when computational techniques developed in other fields are applied in building economics without, at first, undertaking some experimentation to ascertain whether or not such imports are indeed suited to these applications.

### 4.2.5 Interpretation of Output.

In considering the interpretation of the output of models, two major issues present themselves. Firstly, is the problem of subjective interpretation of outputs generally, and secondly, is the problem of how output may be interpreted with respect to time. The latter refers to the age of the model and the means by which it has been updated to ensure its relevance to the present.

In the field of design optimisation models there has been much debate as to whether formal optimisation techniques should or should not be employed. On grounds of aesthetics there are good reasons for not using such techniques. If this is the case in a particular model, then the decision maker chooses his own combination of variables based on his or her individual perception of the importance of each.

It is known that generally, subjective estimates of probability differ from objective estimates by over-estimating low probabilities, and under-estimating high and compound probabilities (for example, the 'gambler's fallacy', the phenomenon where for many people the subjective probability of getting a head after, say, five coin tosses have been heads, is not 0.5). Or, in the words of Guildenstern, "a weaker man might be moved to re-examine his faith, if in nothing else, at least in the law of probability."[37] Techniques such as Bayes Theorem have been developed with limited success to measure subjective probabilities. The relevance of this to cost models is that the decision maker should be aware that his subjective perception of the relative importance of certain variables may not be entirely rational in that it may not lead to the optimum decision.

Turning now to the issue of the age of models, it is proposed that at least three questions are relevant.

(i) Do the relationships embodied in the model still hold? Clearly the answer to this question will be different in each case, depending on the problem modelled. It is suggested also that there may well be generic differences apparent among the various modelling techniques, whether the model is predominently deductive, inductive or stochastic.

(ii) Is the data used in the model still relevant? An example of this is where innovations in the manufacture of materials render the previous generation obsolete. Consider the situation of the old lathe and plaster technique of constructing ceilings being replaced by the use of large sheets of mass-produced plasterboard. The new material replaces the old because it is a more economic solution. A model containing the old data updated by means of an accurate price index would still be out of step with the current implementation of the 'real world'.

(iii) How has the model been updated? This question refers to the use of indices. Indices are based on assumptions which may reduce their accuracy over time. This issue is explored with some quantitative results in chapter 8.

## 4.3 Measurement of Performance: Proposed Criteria

### 4.3.1 The Criteria of Performance.

In section 4.2.1 and figure 4.1, the relationship between the designer and an economic model was conceptualised as a chain-like structure. Each link and intersection was then examined in the ensuing discussion. The framework was proposed, in the absence of any other way of rationalising the problem, as a preliminary working set of factors to be considered. This framework will now provide the basis for a set of criteria which will enable some objective tests to be carried out.

(i) Data.

It has been shown theoretically above that the quality of economic data is variable across the range of sources available. Also that the question of the sensitivity of models to their data source does not seem to have been investigated previously. There is a need for some experimental work to evaluate the importance of this issue.

(ii) Data/Model Interface.

It has been shown that the various modelling techniques have different requirements with respect to the level of detail of data required. There is a need for some objective evaluation of the need for 'tuning' models to data.

(iii) Modelling Techniques.

Three dominant modelling techniques were identified and examined. There is a need for some quantitative work to examine the effects of the assumptions of the various techniques in specific cases.

(iv) Interpretation of Output.

The central issues for investigation here are the effect of time, and the age of the model upon the interpretation of its output. Secondly, whether the output has any facility for recognising and evaluating the uncertainty in the input.

### 4.3.2 Rationale for Evaluating Criteria.

The criteria summarised above will form the basis for a rigorous examination of the performance of three models presented in the following three chapters. The objective is to ascertain whether any conclusions may be drawn from the quantitative results in particular cases and applied more widely to economic models in CAD. Chapter 8 presents the details of the assessments and the results, which are presented in sub-sections, apply to each of the models as indicated in figure 4.6. The significance and limitations of the results are discussed in chapter 9.

| | MODEL 1 | MODEL 2 | MODEL 3 |
|---|---|---|---|
| DATA | 8.2.2 | 8.2.3 | 8.2.4 |
| D/M INTERFACE | 8.3.2 | 8.3.3 | 8.3.4 |
| MODEL TECHNIQUE | 8 4.2 | 8.4,3 | 8.4.4 |
| OUTPUT | 8.5.2 | 8.5.3 | 8.5.4 |

Fig. 4.6 CHAPTER LOCATION: RESULTS OF EVALUATIONS OF PERFORMANCE

CHAPTER 4

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# CHAPTER 5

# MODEL 1: A SUPERFICIAL AREA MODEL

5.1 Introduction

5.2 The Model

5.3 Data

5.4 Conclusion

## 5.1 INTRODUCTION

The first of the three models used as vehicles for experiment in this work is a superficial area model that is embodied within the Building Cost Information Service (BCIS). The BCIS is a cost information service used by architects and quantity surveyors, neither of whom would normally regard it as a formal cost model per se, for this aspect of its nature is not obvious but will be explored here.

The BCIS was set up as a separate body by the Royal Institution of Chartered Surveyors in 1962. The original raison d'etre was to build up a data-bank of building cost analyses, which would be submitted by members and then made available to all other members. The objective however has only enjoyed limited success. The preparation of a detailed cost analysis from a traditional bill of quantities is a time consuming and thus expensive task, taking upwards of three days to complete. The vast majority of members are small practices who have not traditionally had access to computer facilities, thus they have been less than enthusiastic about submitting analyses, the relatively small number of available analyses render the service less attractive for new members, and so on in a downward spiral. The number of detailed analyses published annually has been in the region of 50 in recent years. On the other hand, these conditions have resulted in some positive consequences in so far as the BCIS now disseminates a very wide range of economic information of relevance to the building industry, briefly this includes the following:

General Information; this contains cost indices, wage rates, hire rates for equipment, details of new legislation and current cost limits, building activity statistics, general economic indicators and regional trends.

Publications Digest; lists new material relevant to building economics in the U.K.

Cost Studies and Research and Development Papers; these are detailed research papers presenting studies of particular aspects of building economics and cost planning methods.

Detailed Cost Analyses; cost analyses of projects presented in a standard form. For comparability these are discussed in detail in the next section.

Concise Cost Analyses; an abbreviated form of the detailed analyses.

This chapter is concerned only with a description of the way in which the BCIS models building cost, the strengths and weaknesses of the model will be tested in chapter 8.

## 5.2 THE MODEL

The BCIS model of building cost is derived by apportioning the building cost among "functional elements". Elements are generally defined as major parts of the building which always perform the same function irrespective of either their own specification or the building type.

Examples of elements are substructure (which whether raft, piler or strip foundation, still transfers the building loads to the ground below) and say, external walls (which enclose the building space, although there may be some variation in function here insofar as some external walls are loadbearing and others are not). There are many ways of defining elements. The BCIS model uses a "Standard Form of Cost Analysis" (see Appendix II) which operates at two levels. The first level contains six elements and the second level contains sub-elements for each of the six main elements giving a total of 32 elements. The six summary elements are as shown in table 5.1.

1. SUBSTRUCTURE

2. SUPERSTRUCTURE

3. INTERNAL FINISHES

4. FITTINGS AND FURNISHINGS

5. SERVICES

6. EXTERNAL WORKS AND PRELIMINARIES

Fig. 5.1 BCIS ELEMENTS

The detailed list is given in Appendix II. The elements bear some relation to the design process and to design subsystems as discussed in chapter 2. The cost of these subsystems or elements may be calculated separately and, in order to facilitate comparisons with other buildings of various sizes, the total for each is expressed per unit of gross floor area (G.F.A.)* of the building. Appendix II shows a summary sheet from a concise analysis by way of illustration. All BCIS cost analyses are based on the accepted tender for each project and thus each one is an analysis of the price for the project containing not only the costs of the resources required, but also profit and amounts for market and tactical considerations.

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* The BCIS have given an official definition of G.F.A. as follows:

"1. Total of all enclosed spaces fulfilling the functional requirements of the building measured to the internal structural face of the enclosing walk.

2. Includes area occupied by partitions, columns, chimney breasts, internal structural or party walls, stairwells, lift wells and the like.

3. Includes lift, plant, tank rooms and the like above main roof slab.

4. Sloping surfaces, such as staircases, galleries, tiered terraces and the like should be measured flat on plan.

Note: (i) Excludes any spaces fulfilling the functional requirements of the building which are not enclosed spaces (e.g. open ground floors, open covered ways and the like).

(ii) Excludes private balconies and private verandahs which should be shown separately."

This is fitting as the models main use is in the prediction of tender price. Elemental cost planning is used as such (although not always with the BCIS element scale) by the majority of quantity surveyors and architects in the U.K. It is worth mentioning, in passing, that most element lists allow for the cost of non-quantity related items (method related and time related items such as cranes, site hutsand site facilities, cost of non working foremen, insurance bonds, etc) to be dealt with separately as 'Preliminaries'.

Elemental cost planning and control procedures have been summarised in six stages.[2]

1. Preliminary estimate. This is very vague and is usually a general figure based on the recorded cost/$m^2$ of similar buildings. It is derived at the briefing stage and before any drawings have been produced.

2. Preliminary cost plan(s). One or more of these is produced to evaluate the architects early sketches. The method used is to identify a cost analysis in the data store in which the building has as many similar characteristics as possible to the project in hand. Three basic adjustments are then made to the chosen analysis. These are time, quantity and quality. Firstly the chosen analysis is updated to the present using some form of tender price index.

Next the elemental unit rates from the updated analysis are applied to the G.F.A. of the building in hand, the new totals are thus altered to take account of the different building size. Finally, the updated element rates are adjusted for each element to take account of any differences in the level of specification between the original building and the building in hand.

3. Cost Plan. A more detailed version of the above is then based on the final sketch drawings for the chosen scheme.

4. Cost checks. As the working drawings are produced they are checked against the elements in the cost plan so that if they begin to deviate from the original assumptions this will be noticed and may be corrected if necessary.

5. Tender reconciliation. The accepted tender is checked against the cost plan. Any cost over-runs are identified and appropriate reductions made. If all has gone 'according to plan' no hitherto unthought of over-runs should appear.

6. Post contract cost control. As the project is constructed on site, continual checks are made and incurred costs are monitored to ensure that each

element of the project is proceeding more or less as planned.

It is worth noting here the main assumptions embodied in the model. These will be examined in further detail and manipulated experimentally in chapter 8. These assumptions are:

(1) A central assumption of any model using unit rates is that there exists a linear relationship between the size or area of the building and its cost.

(2) All of the assumptions contained in the use of price indices have impact on models which rely heavily on being updated in this way.

(3) Each plan is produced usually by reference to only one other project, a statistically inadequate approach.

(4) Element unit rates are highly abstracted figures and the adjustment of an element rate to take account of differences in specification defined in terms such as "higher or lower quality" is a very subjective process. There is of course nothing wrong with this except when it purports to be less subjective than it really is.

In summary, consider a mathematical representation of the model, the preliminary cost plan may be defined as:

$$C = \sum_{E=1}^{6} (t.q.qu.R)_E \qquad .....[5.1]$$

where

E = the main element headings as in table 5.1.

t = the time adjustment, not all elements will suit the same index for example the services element will often be updated by a mechanical and electrical services price index and the other elements by a tender price index for building work which excludes these services.

q = the quality adjustment which attempts to account for differences in the level of specification of the element in the building chosen for comparison and that of the project in hand.

qu = the quantity adjustment. This is usually assumed to be linear, by merely substituting the new building area for the old one and not applying any adjustment for economy or diseconomy of scale.

R = the element unit rate or the cost of the element expressed per unit of G.F.A.

Consider now the detailed form of the model:

$$C = \sum_{E=1}^{32} (t.q.qu.R)_E \qquad .....[5.2]$$

Clearly there is much more information at this detailed level now including 32 elements (Appendix II contains an example). However, this extra detail is not supported by a refinement of the functional relationship. This in fact remains the same as each subheading is expressed in terms of unit floor area. The method of derivation may be different, at this stage approximate quantities may have been computed. This may be expressed as follows:

$$C = \sum_{F=1}^{N} (Q.r)+P+K \qquad .....[5.3]$$

where

F = The number of items of finished work, measured separately.

Q = The quantity of any of the items in F. The unit depends on the item (examples are $xm^2$ of internal partition, YNo. Internal doors ZM of drainage trench 1.00M deep, etc.).

r = The unit rate for each item of finished work F which includes usually for the materials, labour and overheads necessary to fix the work in place.

P = Preliminaries, indirect costs as described above.

K = An amount added to or taken from the total to take into account market considerations, etc.

## 5.3 DATA

The data used to compile the historic cost analyses which are then used to build the cost plans for new projects is derived from priced bills of quantities. The nature of this data has been discussed in chapter 4. It is worth repeating that although the tender figure is an earnest and realistic representation of the cost of the construction including profit, the unit rates are little more than a notional breakdown of this cost. Thus in a cost plan prepared using this model the data used to derive the element rates may be characterised by something less than consistency.

## 5.4 CONCLUSION

This short chapter has described a model which is used for tender price prediction. The main features of the model, its data and the assumptions on which it is based have been presented. These will be critically examined in the experiments later on, based on the criteria outlined in chapter 4.

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# CHAPTER 6

## MODEL 2:

## A MODEL FOR THE ECONOMIC EVALUATION OF BUILDING REGULATIONS

6.1 Introduction

6.2 Impacts of Building Regulations

- Building regulation system
- Income distribution
- Benefit-cost

6.3 Methods of Evaluation

6.4 The Model

6.5 Model Validation

## 6.1 INTRODUCTION

The model described in this chapter was built for the primary purpose of evaluating the economic impacts of building codes. As far as can be ascertained, little work of this nature has been carried out in the U.K. The problems involved in the measurement of the economic impacts of building codes have been considered in studies by the National Bureau of Standards in the United States and by the Danish Building Research Institute.[1,2] Building codes are in general complex and usually fragmented, for these reasons some of the more important issues relevant to their nature and the nature of their effects will be discussed prior to the presentation of the model.

## 6.2 BUILDING CODE IMPACTS

A generally accepted definition of building regulations has been given by the United Nations as follows:

> ".... building regulations are documents containing requirements for buildings laid down by an official body (Parliament, the government or the responsible authority) to ensure the safety, hygiene,stability and level of amenity compatible with environmental

and social requirements during the construction and throughout the lifetime of the building."[3]

Building codes and regulations are typically fragmented and diverse, this is exemplified by the fact that they stem from acts of parliament, national standards (British Standards in the U.K.), design guides, local authority by-laws, fire officers regulations etc. The set is not well-defined and is highly complex. Even within the national boundaries of one country there are problems of lack of co-ordination in different regions. The latter are of course far more pronounced in countries which have developed as federations, such as the United States and Germany. Fragmentation of these regulations exists however in most countries, due mainly to the fact that many 'official bodies' are concerned with buildings, building safety and the environment, including the national government, local planning authorities, the professional institutions of engineers and fire officers and the standards authorities who test and certify the quality of manufactured goods which are building components. The survey, presented below, of the regulations governing the size and number of escape staircases to be provided in office buildings in the U.K. showed no evidence of any form of harmonisation of regulations amongst the different fire authorities. It would seem also that the codes for this area, throughout the country, have not been developed upon consistent principles or decisions based on scientific data, but rather they appear to be rules of thumb for various regions which have become formalised as regulations and statutory requirements.

The impacts of building regulations are often indirect, they may be local, regional or national, they also depend on who is being considered namely the user, the investor, the national economy etc. The U.S. National Bureau of Standards proposed a taxonomy of impacts, which has been presented here in diagramatic form in figure 6.1.

Building Regulation System.

The real cost of establishing and running the institutional and administrative system necessary to process and enforce the regulations gives rise to the 'Building Code System Impacts', which may be further defined as having three components, namely:

Duplication Impacts.

Building Innovation Impacts.

Production Organisation Impacts.

Duplication impacts have two components, the public and the private/corporate. Public duplication impacts are the costs to the public authority of establishing and running the departments containing the officials who review plans

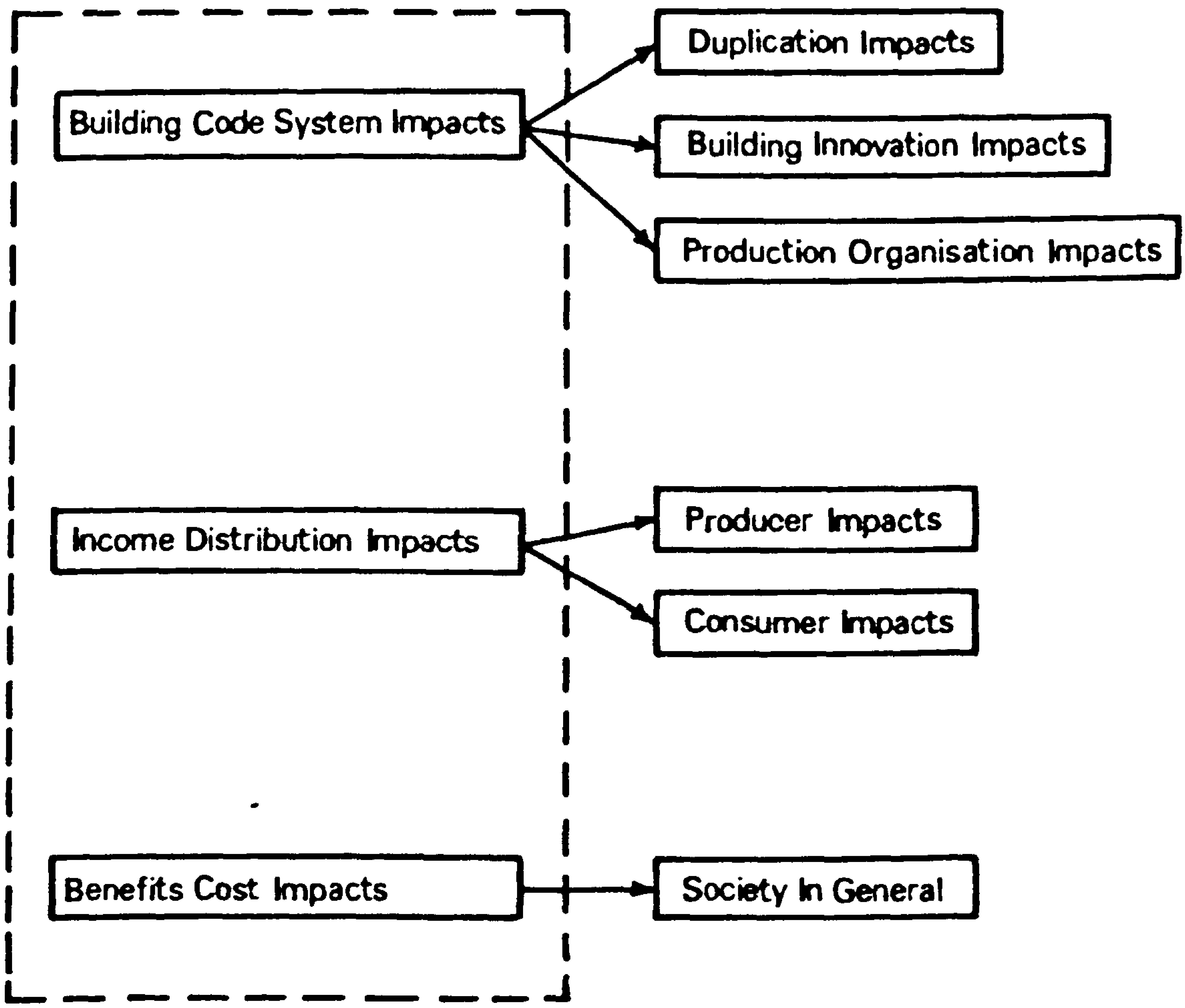



Fig. 6.1 THE IMPACT OF BUILDING CODES

and specifications for proposed projects. The private/corporate component is the cost of the charges paid by private individuals or building contractors or developers to the authority for the carrying out of such reviews. The latter component also refers to the money paid by manufacturers of building components for the testing and certification of their products to show that they comply with the various regulations and standards. All such charges are of course passed on to the consumer in some form or other.

Building innovation impacts refer to the costs of delays in the implementation of new innovations. This occurs where there is a time lag between the adjustment of codes and the introduction of new material or components. The monetary impact of this is difficult to assess but would seem to be higher in the U.S.A. than in European countries which operate the Agrement system of product certification.[4]

Production organisation impacts are those which affect the structure of the building industry. The training of staff skilled in checking proposed projects and certification and testing of products has implications for the Universities and Polytechnics. Differences between regulation requirements regionally and also internationally is a brake on the expansion of construction activity.

Income Distribution.

Income distribution impacts affect the economic situation of various interest groups in the economy. Producer impacts are those which affect interest groups on the supply side of the industry, namely: The Trade Unions, the Professional Institutions, the contractors and subcontractors, the manufacturers of building materials and components. Often-quoted examples of this type of impact are the problems experienced with certain forms of asbestos and with high alumina cement in particular applications, which occurred in the early 1970s. Both of these cases had clear implications, in the second case for the manufacturers, design professionals and contractors, in the first case, for the unions and the manufacturers. In both cases there were implications for the building users. It is worth noticing also that pressure from individual interest groups may be the stimulus for a change in a building code or regulation.

Consumer impacts are concerned with those who either buy or rent building space. Consider the market for housing, economic theory suggests that if the price is increased (in this case because of building codes and standards) then in the long term there will be a reduction of demand and eventually of supply, as a new equilibrium is reached. Clearly this is a vast over-simplification. In fact, many of the effects will be indirect as a complex process of substitution develops with demand switching to alternative forms of housing on the one hand and, on the other hand, changes will take place in the attitudes and expectations of families and extended families to sharing housing facilities. It is not possible to generalise as cultural factors are very important here.

Benefit-Cost.

Whereas regulation system impacts and income distribution impacts are concerned specifically with particular interest groups, benefit-cost impacts consist of the adding up of all of these individual impacts, positive and negative, economic and otherwise. The central problems are those of measuring in some way the effects of increased or reduced risk of building failure because of changed regulation requirements. Examples of relevant problems would be those of minimum provision of smoke detectors or minimum number and width of staircases for emergency egress. The impact of such regulations on society as a whole is usually measured using the techniques of cost-benefit analysis.

## 6.3 METHODS OF EVALUATION

Two previous approaches to the evaluation of building regulation impacts will be briefly summarised here in order to provide a context for the model presented below. Rawie in the U.S.A.[5] proposes a full cost-benefit approach which is summarised in figure 6.2. The third and fourth stages where the effects on building safety and performance and the net benefit ratio are estimated are subject to a degree of ambiguity, as would be the case in most cost-benefit analysis. This type of approach to building regulation impact evaluation inevitably leads to controversial decisions regarding economic evaluation of the 'statistical life'. Cost-benefit analyses of this sort are undeniably subjective.

Bonke et al, at the Danish Building Research Institute[2] took a similar approach and seemed to encounter similar problems regarding the impossibility of evaluating 'social' and 'indirect' consequences in a consistent and rigorous manner. They proposed a 'model' which may be more accurately described as a procedural approach and is summarised in figure 6.3.

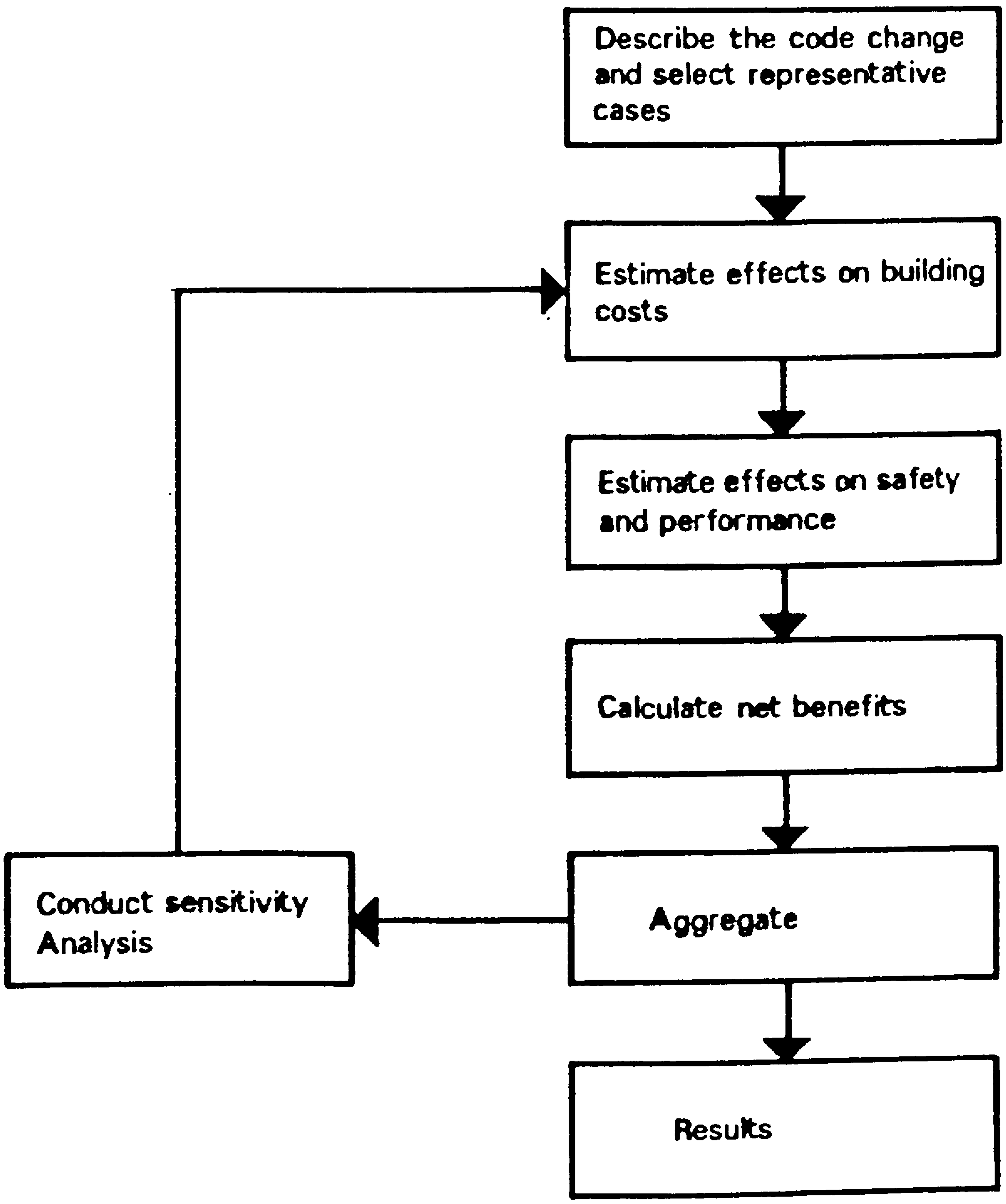



Fig. 6.2 BUILDING CODE IMPACT EVALUATION adapted from RAWIE [5].

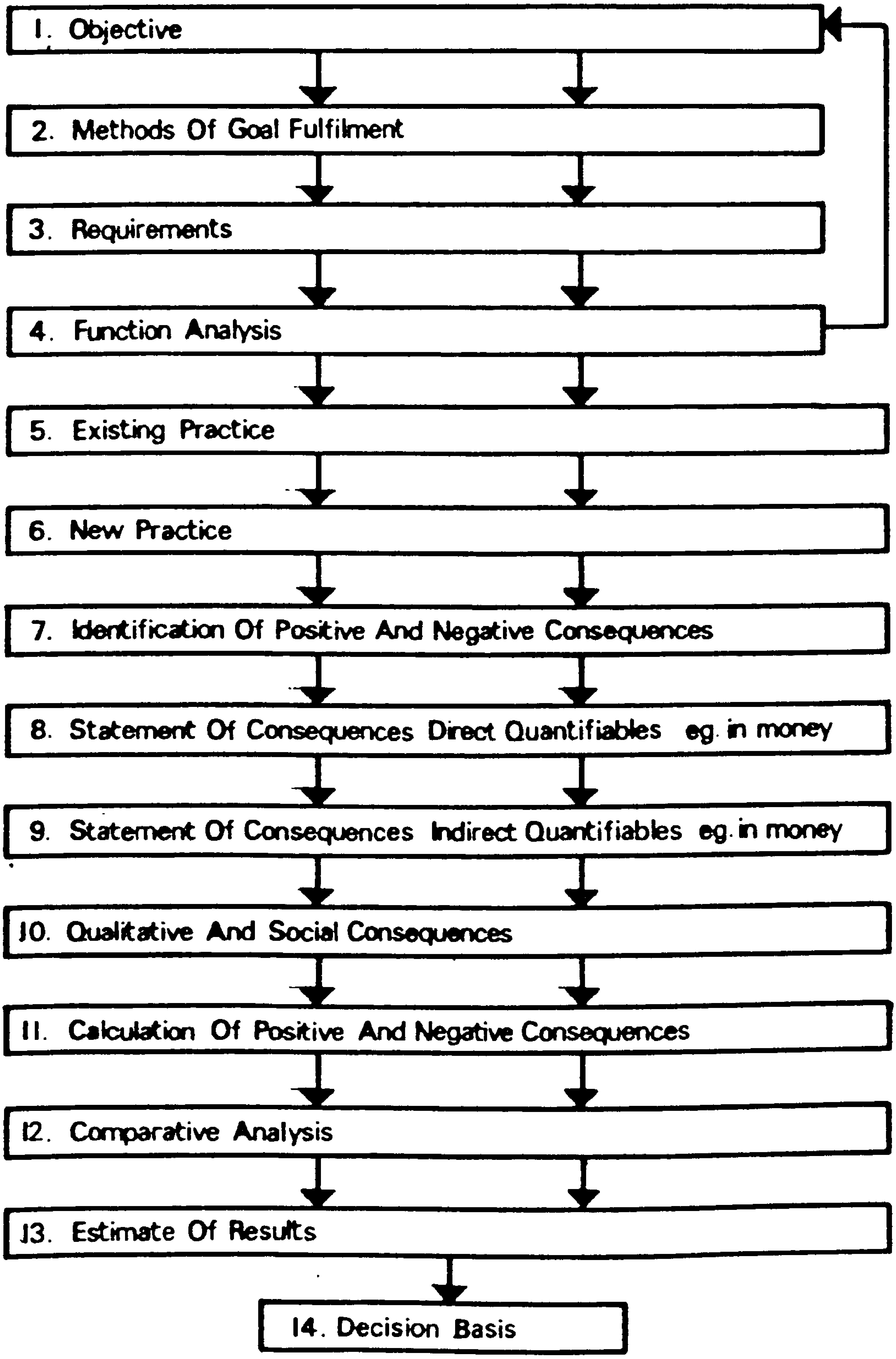



Fig. 6.3 "MODEL FOR CONSEQUENCE ESTIMATE," DANISH BUILDING RESEARCH INSTITUTE[2].

## 6.4 THE MODEL

Although the two previous approaches used the techniques of cost-benefit analysis to evaluate the impact of regulations on society as a whole, this research is concerned with the use of models in the design process so the problem of building regulation evaluation will be considered from a CAD perspective. The general tenor of this work demands also that subjective measurements within the model be avoided as far as is possible and left externally to the decision maker. Furthermore it seems preferable, as an example of a CAD approach to building regulation evaluation, to deal with one well defined problem exhaustively and rigorously rather than taking wider problems at a more general level. To this end the area chosen for consideration was the evaluation of the economic consequences of the various regulations in force regarding the provision of means of egress in case of fire in multi-storey office buildings.

Codes of practice and regulations for the provision of means of escape are generally related to the assumed occupancy of the building. Designers advisedly use a worst-case approach so the limitations of occupation density need to be considered. An examination of the regulations, codes of practice and statutes relating to occupancy loads in multi-storey office buildings in the United Kingdom shows that there is considerable variation.

Where layouts have not been agreed at the design stage, which applies in speculative development and also in many owner occupied buildings, very low values of maximum floor area per person are required. This sometimes results in a larger means of escape provision than would be required had the layouts been finalised at an earlier stage. In recent years occupancy loads have been falling as a result of increasing mechanisation of office tasks. The occupancy loads are based upon the gross floor area, excluding staircases and lavatories, and vary in the United Kingdom between $5m^2$ and $10m^2$ per person, as shown in table 6.1. In practice however, occupancy loads may normally be as low as $25m^2$ per person. A study by De Wolf and Henning[4] of 77 Canadian Government offices disclosed an average usable area of $18.6m^2$ per person.[6]

In addition to variations in occupancy load, separate means of escape legislation applies to the Inner London Boroughs, England and Wales except for the Inner London Boroughs, and also in Scotland. Further, office buildings are also subject to the provisions of the Offices, Shops and Railway Premises Act 1963, The Fire Precautions Act 1971, and Section 78 of the Health and Safety at Work Act 1974, as outlined in Figure 6.2.

Apart from the different means of escape provision in this country, research undertaken by Pauls[7] at the Canadian National Research Council has questioned the escape

| | Statutes/ Guidance | Occupancy | Qualifications |
|---|---|---|---|
| Health & Safety at Work Publication No. 40 | Guidance | $3.7m^2$ | Gross Floor area per person, excluding staircases, corridors, lavatories, etc., for individual rooms. |
| Building Standards Scotland | Statutory | $3.7m^2$ | As above. |
| Offices, Shops & Railway Premises Act 1963 | Statutory | $5m^2$ | Gross floor area per person, but excluding staircases, lavatories, etc. |
| Health & Safety at Work Publication No. 40 | Guidance | $5.1m^2$ | As above. |
| Building Standards Scotland | Statutory | $5.1m^2$ | As above. |
| British Standard Code of Practice No. 3 | Guidance | $7m^2$ | Gross floor area per person. |
| British Standard Code of Practice No. 3 | Guidance | $9.3m^2$ | Gross floor area per person, excluding staircases, and lavatories. |
| Greater London Council Code of Practice | Guidance | $10m^2$ | As above. |

Table 6-1 - OCCUPANCY LOADS IN STATUTES & CODES OF PRACTICE

| Designated Area | Statutory Instruments | | Guidance | |
|---|---|---|---|---|
| | Acts | Regulations | Codes of Practice | Recommendations |
| Inner London Boroughs | London Building Acts (Amendments) Act 1939 Sections 36-35. | | GLC Code of Practice Means of Escape in Case of Fire. | Health & Safety at Work Public-ation No. 40. |
| England & Wales | Offices Shops & Railway Premises Act. | Building Regs. 1972 & amends. | British Standard Code of Practice CP3. | Health & Safety at Work Public-ation No. 40. |
| Scotland | Offices Shops & Railway Premises Act. | Building Stds. (Scotland) (Consolidation) Regs. 1971. | | Health & Safety at Work Public-ation No. 40. |

Table 6-2 - STATUTORY INSTRUMENTS & GUIDANCE WHICH APPLIES TO MEANS OF ESCAPE IN OFFICE BUILDINGS requirements upon which, the United Kingdom regulations are based.

The complexity of these regulations suggested that the building designer was already severely constrained by the codes and should not be further inhibited by the model. To this end the approach was formulated in such a way that the design decisions are separated as far as possible from the problem constraints. However if the constraints clash with a design decision this will be made clear and allowances made for change. Figure 6.4 is a schematic representation of the model.

The model considers only multi-storey office buildings and is restricted to dog-leg staircases enclosed in a traditional stairwell.

It is apparent that there are two types of input to the model. Firstly, there are "design decisions", these are decisions which are under the immediate control of the designer, although they will normally be related to the designer's solution to the problems posed by other building subsystems. Examples of this type of decision are storey height and (within certain bounds) the catchment area to be served by the staircase. In terms of the model these are, of course, the independent variables. Before any dependent variables can be produced, it is necessary to take account of the problem constraints which bound the feasible solution space. In terms of STEPS these are known as "regulatory decisions". These decisions are not under the control of the designer (see Figure 6.4). Once it has been decided by the relevant planning or fire authority that a particular set of planning regulations apply, then the number of possible design solutions becomes constrained. The feasible space is now defined and the solutions within it can now be evaluated.

DATABASE.

The database for STEPS was designed so that it would be possible to test proposed solutions for sensitivity, not only to design and regulatory decisions but also to changes or relative changes in the database. Two types of data are held in this data file.

(i) Unit rates; which accurately reflect the relative costs of various construction components. Price book rates are used which are considered useful only for comparing solutions, not for cost or tender prediction.

(ii) Relationships; functions which are used in the methods of economic appraisal of solutions.

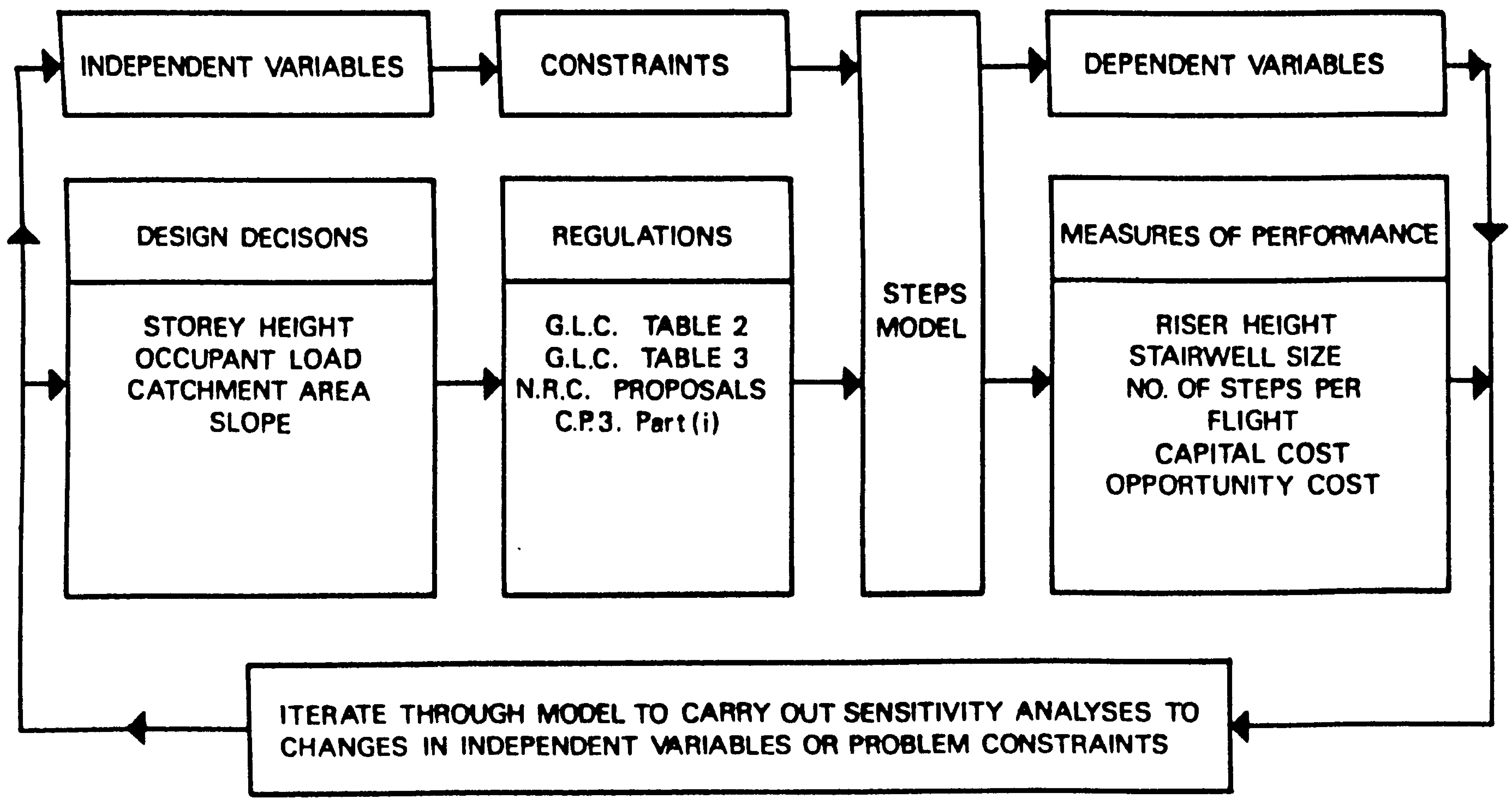



Fig. 6.4 STEPS MODEL — SCHEMATIC PRESENTATION

PAGE NUMBERING AS IN THE ORIGINAL THESIS

Evaluation of particular solutions is carried out using a life cycle model which incorporates the opportunity cost of the design solution. The opportunity cost is calculated with respect to an arbitrary datum of zero. Although clearly no proposed solution can have zero opportunity cost with respect to other solutions, the datum is necessary so that comparisons may be made between solutions. Its use has a further benefit in that it precludes the temptation to use the output for cost prediction.

In practical terms, the economic assessment is carried out by considering the amount of space taken up by the stairwell as non income-earning space. The nature of the commercial letting market for office space in the U.K. is such that the net lettable area of a multistorey building includes only the usable area and any linking corridors. Vertical circulation space is not income earning for the investor. Therefore there exists an opportunity cost which may be equated with the amount of rent which may have been earned had the space been lettable. Hence evaluation uses the capitalised lost annual rental from this space as a measure. As pointed out above, no solution would have a zero cost in these terms - i.e. there has to be some type of vertical movement space - but the model is not concerned with the absolute monetary value of any solution, but rather with the differential economic impact caused by different codes. A measure of this sort requires a common datum, the fact that it is arbitrary does not influence the measurement of the differences.

The model may now be stated formally.

$$LCC_r = [\sum_{i=1}^{M} C_i+(1-Y).(R_t.A)]_r \qquad ...[6.1]$$

where

- LCC = Life cycle cost.
- r = The particular code under consideration. In its current implementation the STEPS model can deal with four choices here.
- i = The number of items of finished work measured in order to complete the capital cost of the stairwell. The model computes all the dimensions necessary to construct the stairwell system needed to comply with the regulations. Currently this level of detail here is that 23 separate items are quantified.
- Y = The tax rate payable by the firm which benefits from the rental income for the floor space.
- $R_t$ = A present worth function applied to the rental income from one unit of floor space.
- A = The actual amount of floor space occupied by the stairwell system and thus lost to the investor as an income generator.

In the U.K. the corporation tax payable by firms does not generally change from region to region. Regional development assistance, when it does occur, usually takes the form of grants towards capital expenditure on buildings and equipment.

This being so, equation 6.1 may be simplified as follows:

$$LCC_r = [\sum_{i=1}^{m} C_i + (R_t . A)]_r \qquad \ldots[6.2]$$

Clearly this simplification would not apply in countries which have federal taxation systems such as the U.S.A. and Canada. Figure 6.5 is a simplified flowchart of the model.

## 6.5 MODEL VALIDATION

The validation exercise involved time consuming manual calculation of design solutions for comparison with the model. The model was dissembled into its constituent parts and these were checked separately, then the whole unit was tested. The procedure was as follows: The model allows the use of four sets of regulations. When the designer makes his early decisions and specifies which set of regulations apply, the model derives an outline description of the solution. It contains values for the number of staircases, their width, internal dimensions of smoke lobbies and stairwells, floor to floor height and riser to tread ratios. Each of these routines was tested separately for each of the four possibilities using two building sizes. The values from this are then fed into a routine which is common to all routes through the model, this is the routine which generates the detailed mathematical representation of the actual constitutional details. This was validated by manually designing and drawing up a detailed solution, and then manually 'taking off' the quantities of work involved.

When the exercise was first carried out the model was found to give results about 5% higher than manual calculations. Some amendments were made to the program and the discrepancy was reduced to less than 2%, this was considered small enough to enable the model to be used. Figure 6.6 shows some results of the model.

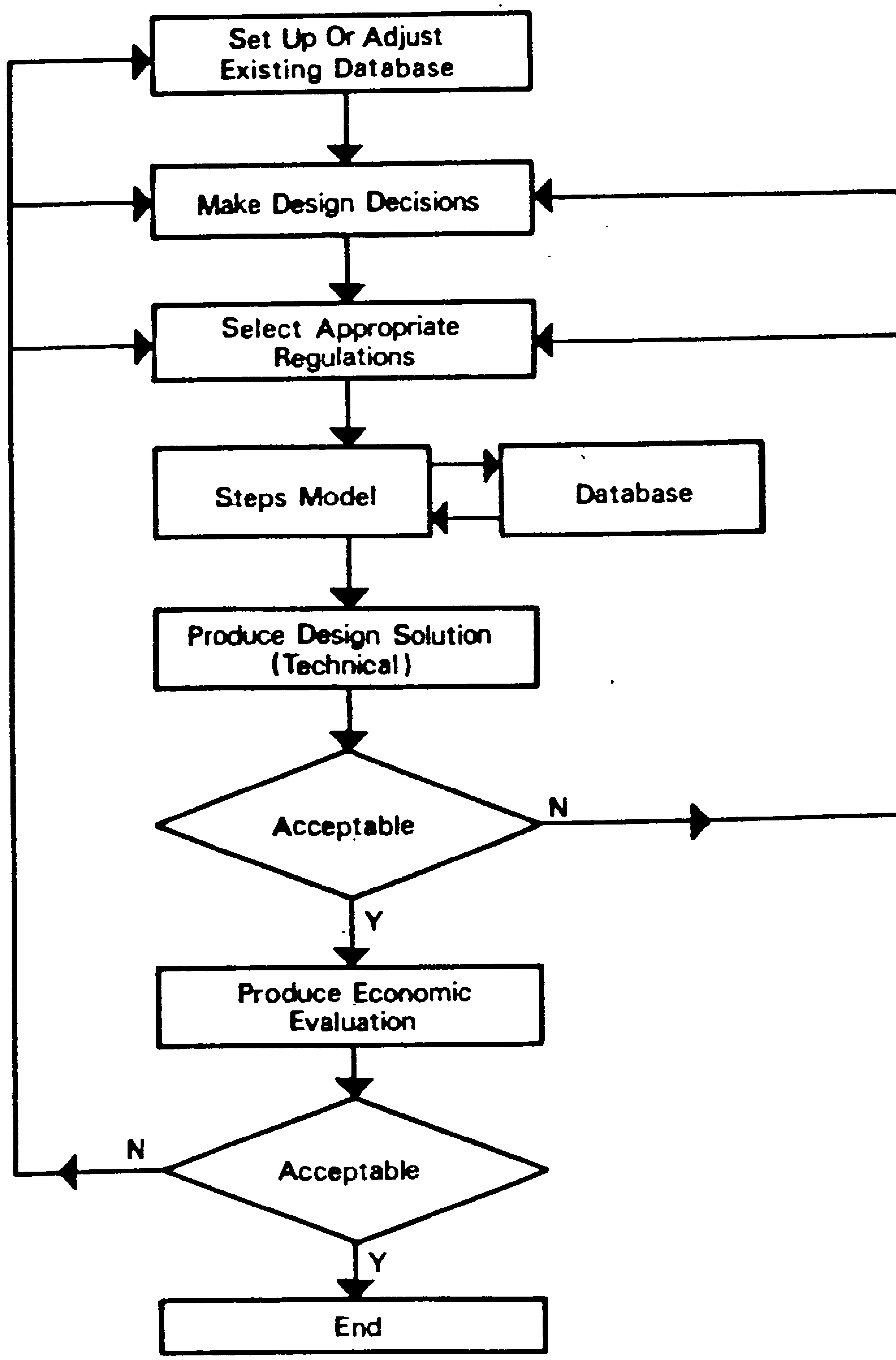
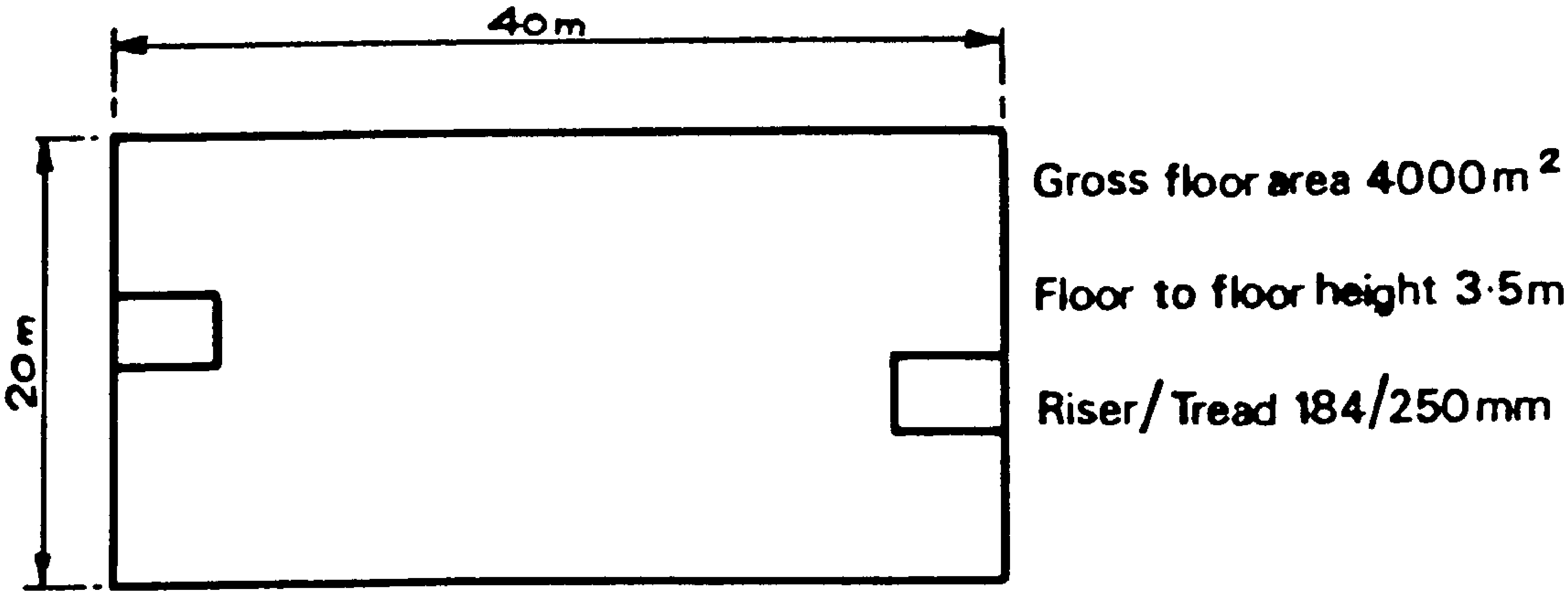



Fig. 6.5 STEPS MODEL SYSTEM FLOWCHART




TYPICAL FLOOR PLAN

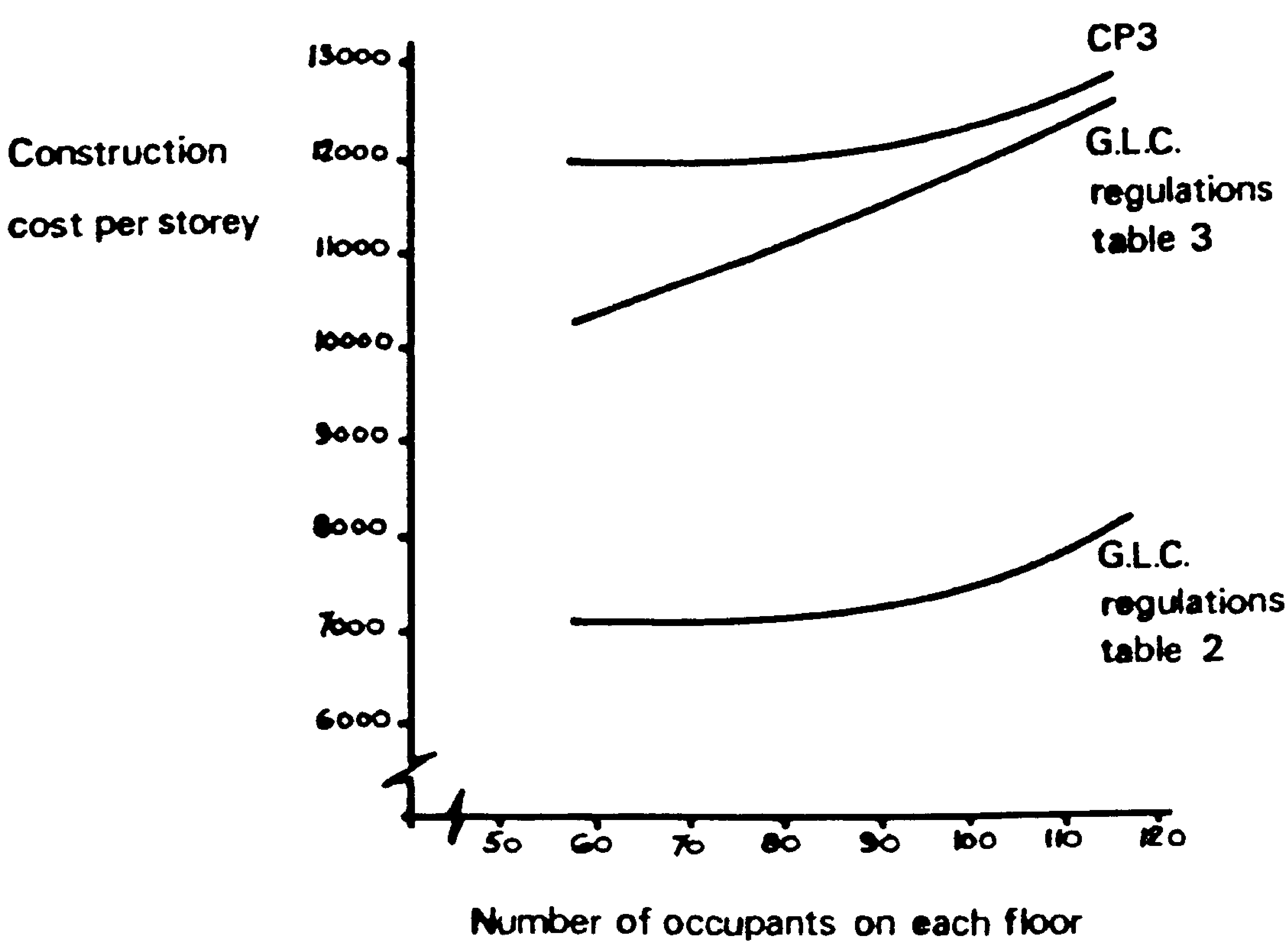



Fig 6.6 MODEL 2 : ANALYSIS OF SOME RESULTS

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# CHAPTER 7

## Model 3: A Model for Air-conditioning Design


7.1 Introduction

7.2 Design Conditions

7.3 System Design

7.4 System Economics

7.5 Model Formulation I

7.6 The Objective Function

7.7 Data

7.8 Model Formulation II

7.9 Constraints

7.10 Validation

## 7.1 INTRODUCTION

This, the third model presented here, is the most complex and detailed of those built during the research. The problem was to provide an economic model to assist in the informal optimisation of a design subsystem, namely the heating and air-conditioning installation of multi-storey office buildings. This corresponds to the third category of model proposed in chapter 4, section 4.1. Although the design of mechanical systems for the heating and air-conditioning of internal space is complex (both computationally and logistically in terms of the number of variables involved) it is, at the same time, relatively well defined. There are consistent units and scales of measurement and there is relatively little subjectivity involved (with the exception of individual perceptions of 'comfort'). The objective was to design and construct a robust model in order to learn more about modelling techniques. The advantage of choosing a well-defined subsystem with a high level of theoretical and practical knowledge and reliable design methods (both ASHRAE and CIBS were considered)* was countered somewhat by the technical complexity of the area. In order to formulate the model a

* ASHRAE; the American Society of Heating, Refrigeration and Air-conditioning Engineers. CIBS; the Chartered Institute of Building Services.

preliminary time-consuming study of the theory of 'comfort' and the range of types of air-conditioning systems was necessary. In the remainder of the chapter the following are discussed; the desirable design conditions, method of air-conditioning system design, the model formulation, data, constraints and validation.

Clearly this model is of a highly specialised nature and deals with a definite sub-set of the overall building design problem. However the problem area is not by any means an insignificant one, Watson has concluded that a current trend in the cost of new property development is for the cost of the building elements to reduce in proportion, while the cost of the engineering service portion of building costs is increasing.[5] This has been attributed to a number of causes, the most important of which are related to the growing sophistication in the design of services for fire protection, communications installation, and ventilation and air-conditioning systems. The impact of the cost of the heating, ventilating and air-conditioning elements is of the order of 25% of the total building cost. One quarter of that cost may be accounted for by the cost of the plant alone.

It follows that the cost of the air-conditioning system is relatively high. This presents some justification for the time and effort involved in producing an accurate, sensitive model for so specialised a subsystem.

## 7.2 DESIGN CONDITIONS

Internal Design Conditions.

Jones has produced some practical guidelines for the choice of internal design conditions for the design of air-conditioning systems.[1] These may be summarised:

1. If the temperature of the air is to depart from the optimum it should be to a lower value rather than to a higher one.
2. The design air velocity should relate to the dry bulb temperature as in table 7.1.
3. Relative humidity should lie in the range 30-60% and should never exceed 70%.

| | Winter Heating | | | Summer Cooling | | |
|---|---|---|---|---|---|---|
| Air Temperature In $^{o}$C | 19 | 20 | 21 | 22 | 23 | 24 |
| Air Velocity in Room in m/s | .10-.30 | .1-.15 | .15-.20 | .20-.24 | .25-.30 | .30-.35 |

Table 7.1 (from Jones[1])

4. The mean radiant temperature if it is to depart from the optimum, should be higher rather than lower in winter and vice versa in summer. (In Winter cold surfaces in an otherwise warm room cause complaints of stuffiness, in summer the same set of circumstances may in fact be perceived as "pleasant" by the occupants.

5. The temperature difference between the air at head level and at foot level should be minimised. It should not be greater than 1.5$^{o}$C and should never exceed 3$^{o}$C.

The choice of inside design conditions in multi-storey office buildings depends on both the rate of working of the occupants in the space and also on the outside design conditions. People become used to the climate they live in, in a relatively short period of time so that, for example, in hotter climates the summer cooling termperature of a space would be higher than say the U.K.

In spaces where the occupants are engaged in some form of sedentary work it is usual to choose an inside dry bulb of 4$^{o}$C to 11$^{o}$C less than the o'tside design dry bulb temperature. Temperature needs to be more tightly controlled than humidity as, under normal conditions, people notice changes in temperature more than changes of humidity.

Legislation enacted during the energy crisis[2] dictates that in the U.K. in summer, cooling should not go below 21$^{o}$C.

External Design Conditions.

As indicated at the end of the previous section, the variations in climate (temperature, wind and humidity) have a direct effect on the size of air-conditioning systems. These variations are due to:

(i) Seasonal changes.
(ii) Local geography.

(i) Seasonal Changes

For practical purposes the sun may be assumed to be the sole supplier of energy to the earth (this discussion is concerned only with climate). For a given lattitude the earth receives less solar radiation in winter than it does in summer.

(ii) Local Geography

This determines how much solar energy is absorbed by the earth, how much is stored and the ease with which it is released to the atmosphere. Water masses tend to heat and cool more slowly than land masses. Land surface temperatures tend to be cooler at night than water surface temperatures. Clearly, locations positioned in large land masses tend to experience more extreme annual variations in climatic conditions than will be felt in locations near large bodies of water.

The choice of a set of outside design conditions is usually made in terms of the frequency of occurrence of certain values of dry bulb and wet bulb temperatures.*

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* Dry bulb temperature is the air temperature as indicated by an ordinary thermometer. Wet bulb temperature is measured by a thermometer where the bulb is kept wet by a wick surrounding it. Evaporation of the water takes heat from the mercury and consequently the reading is lower than the dry bulb. The rate of evaporation depends on the air humidity and thus the difference between the two readings may be used as an indicator of humidity.

## 7.4 AIR-CONDITIONING SYSTEM DESIGN

Mechanical Components of the System.

Full conditioning of the atmospheric environment requires control over the purity, movement, temperature and humidity of the air within the limits imposed by the design specification. It follows from the intervening sections that the system must also be able to cope with the daily and annual variations in outdoor temperature humidity and solar radiation. There will also be internal load variations due to the operation of lights and machinery and the movement of people. As well as satisfying the maximum heating and cooling loads the system must be able to operate under partial load conditions.

In order to achieve this a mechanical system will need the following features:

- A method of heating, a boiler.
- A method of cooling, a refrigeration system.
- A method of purifying or cleaning air, filters.
- A method of transporting air throughout the building, fans and ductwork.
- A method of controlling all of the above.

Design Variables.

From the above outline of the technical problem it is possible to identify the main design variables which are of concern to the designer of the building and of the heating and air-conditioning system. These may be summarised as follows, in the separate categories of the building, the internal environment and the external environment.

DESIGN VARIABLES

(i) Building.

Geographical location.

Altitude.

Orientation.

Shape.

Size and height.

Ratio of internal to external zones.

Materials and thicknesses of envelope.

Thermal and vapour transmittance co-efficients.

Areas and types of glazing.

Colour of exterior finishes (affects insolation).

Shading devices.

Building Mass (affects thermal capacity).

Number and activity of occupants.

(ii) Internal Environment.

| | |
|---|---|
| Temperature | Air Purity. |
| Humidity | Ventilation air quantity. |
| Mean radiant temperature | Interaction with lighting. |
| Air motion | |

(iii) External Environment.

Design levels for temperature
humidity.

These variables, their relative influence and their functional relationship with the cost of the air-conditioning system are discussed in the sections which follow.

## 7.4 SYSTEM ECONOMICS

There are a wide range of solutions to the problem of providing a fully air-conditioned environment. The model to be built in the context of the research hypothesis was to be a detailed design optimisation model. To build a model to deal with all of the possible design solutions discussed would have taken many man-years of work, this time was not available. Clearly some reduction of the problem area was required. In order to achieve this a variation of the 'Delphi-peer-group' method was used.

Consultations were held with experts from three of the largest firms of consultants in the U.K. involved in giving economic advice on modern air-conditioning systems.

From the beginning the project had been constrained to dealing with models relevant to multi-storey office buildings. The results of the discussions were unambiguous, the type of system most often installed in new buildings of this type was the variable air volume (VAV) system. The problem definition then became more clearly focussed and took the form; "provide a detailed economic model for the design optimisation of VAV air-conditioning systems in multi-storey office buildings."

Having chosen a type of system many factors remain to influence the eventual cost of the air-conditioning installation. These include the building, shape, orientation, fabric, glazing and structure, and pertaining to the system itself, the degree of personal control, the location of the ductwork, the size of the plant and the extent of standby facilities provided.

Operating costs are influenced by choice of fuel and fuel costs, normal hours of operation per week of the air-conditioning plant and the level of relative humidity to be maintained. By far the largest portion of the operating costs are due to the fuel and electricity charges which, on average, account for 86% of the total operating cost per annum of air conditioning systems in London office buildings.[3] These costs however are extremely difficult to forecast with any acceptable degree of accuracy. Actual energy usage depends greatly on the climatic conditions experienced, the meteorological office data is not of sufficient quantity or quality to enable accurate predictions of this sort to be carried out.

Further complications are caused by the systems of differential tariffs related to load factors which are operated by the gas and electricity companies. The inaccuracy of energy calculations has been noted in a detailed study by Millbank et al.[4] The model discussed below will be constrained to dealing with initial costs only.

Initial costs, as shown above, are influenced by a complex set of variables. It is possible however, if not to organise these in approximate order of priority, at least, to identify the groups of variables with major and minor impacts. Watson,[5] in developing the work of Mitchell and Leary,[6] noted that treated floor area, building shape and glazed area had a major impact on system costs whereas such items as sound attenuation, automatic controls and standby facilities were relatively minor. Watson, drawing on the techniques and general approach of quantity surveying proposed a sub-elemental approach to cost prediction for services. The services system is transformed into an itemised list of groups of components. In fact, a shopping list, the cost of each item is entered, the result being the cost of the system. This is useful from the point of view of a technical accountant but is not much help to the designer, it does little to establish causality between his design decisions and the end result.

A more useful approach is that suggested by Jaros[7] who recommended that the first approach should be to determine the total quantities of cooling, heating, air-delivery and plant sizes as affected by the main design variables, fenestration solar gains, occupant and equipment gains, etc. This approach offers a route by which links may be made between the design decisions and the end result in terms of actual resource implications.

## 7.5 MODEL FORMULATION I

The general problem then for this model is to relate the design decisions (or design variables) both within and outside of the designers control to some measure of economic performance. This may be expressed,

$$E = f\left[\sum_{i=1}^{j} (Vi)\right] \qquad \text{.....[7.1]}$$

The measure of economic performance E may be expressed as the sum of the costs of the various resources incurred as a result of the design decisions $V_j$, or,

$$E = (R_1+R_2+R_3 \;.....n) \qquad .....[7.2]$$

For purposes of design optimisation with respect to economic performance, there is no necessity for $R_n$ to represent the absolute cost of the resources to the building owner. In this case the modeller is merely interested in those aspects of the resource costs which change as a result of changes in design decisions. This is discussed more fully in chapter 4.

Equations [7.1] and [7.2] hold true for the entire building. Equation [7.2] is relatively easy to calculate for an entire building including all of its various subsystems. However, the function f in [7.1] is at present intractable for an entire building, even for one building subsystem it is highly complex being at a minimum, several pages long as is shown below. Any given building design D consists of various subsystems, not in themselves mutually exclusive as follows.

$$D = S_1+S_2+S_3+....S_t \qquad .....[7.3]$$

The building design subsystems may be referred to as 'elements'. There is no one universally accepted set of building elements, the two most common sets in the U.K. being the Building Cost Information Service elements and the more international SfB system [8,9].

The model under discussion here is formulated for one design subsystem. The formulation of the model consists of the resolution of [7.1] and [7.2]. Three tasks need to be undertaken.

1) The identification of the design variables $V_i$.

2) The identification of the resources incurred as a result of the design decisions.

3) The identification of the functional relationship between the design decisions and the resource implications.

The above tasks constitute a detailed exploration of the problem. The technique of inference diagrams (commonly used in systems design and operations research) was utilised to achieve this end.

1) The Identification of the Design Variables.

The technique of inference diagrams was used to gain an understanding of the structure of the problem. The first attempts used very broad categories of design variables in an effort to establish the main groups of variables which could then be examined in detail to identify each individual variable. The design variables were assembled into eight useful groups. These groups are not mutually exclusive and are a matter of one's perception of the problem, the most important factor being to ensure that no group is left out. The main groups of design variables were:

- Building geometry.
- Orientation.
- Fabric (nature of).
- Occupation density.
- Activity of occupants.
- Lighting design.
- Designer's perception of 'Comfort conditions'.
- Designer's assumptions for external climate.

2) Identify the Incurred Resources.

Clearly this refers to the bottom lines of the diagram. This relatively straightforward task is carried out in detail whenever the services subsystem is measured and the subject of a bill of quantities. It is also carried out at a more useful level of detail by the subcontractor as he prepares his bid for the project. This model deals with the VAV air-conditioning system, and the resources listed are those which would be utilized in such a system. The availability of detailed and reliable economic information for those resource groups is discussed in 7.7.

3) Identification of Functional Relationships.

This is the most complex part of the problem. The model builder needs to identify where a relationship exists. The quantification of the relationships and its description mathematically are discussed under "Computation' below.

Problem Hierarchy.

The problem was perceived as having a hierarchical structure. This is illustrated schematically in figure 7.4. The most detailed level is expanded on in 7.5.

The transition between deductive and

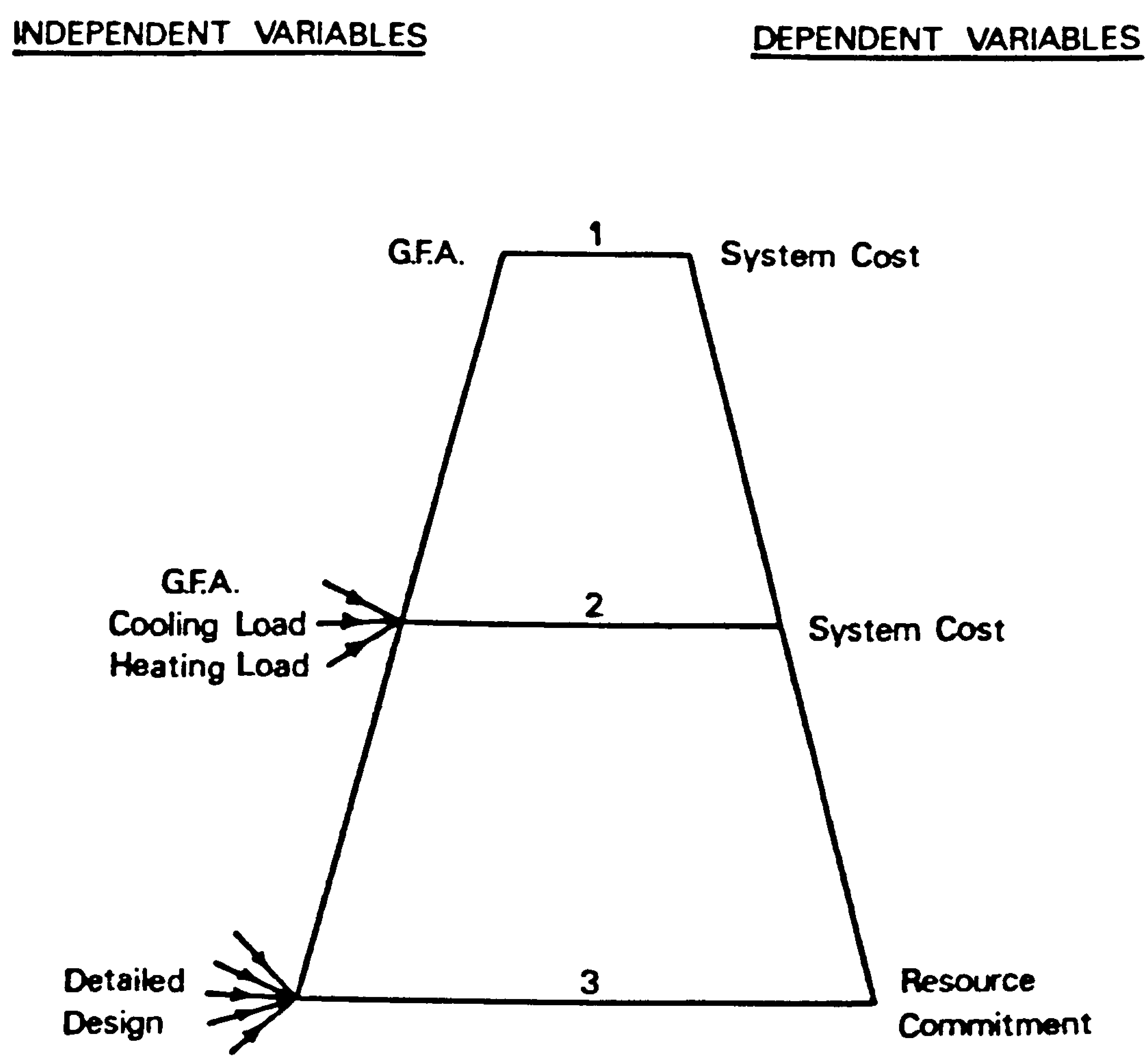


Fig. 7.4 MACE : MODEL HIERARCHY

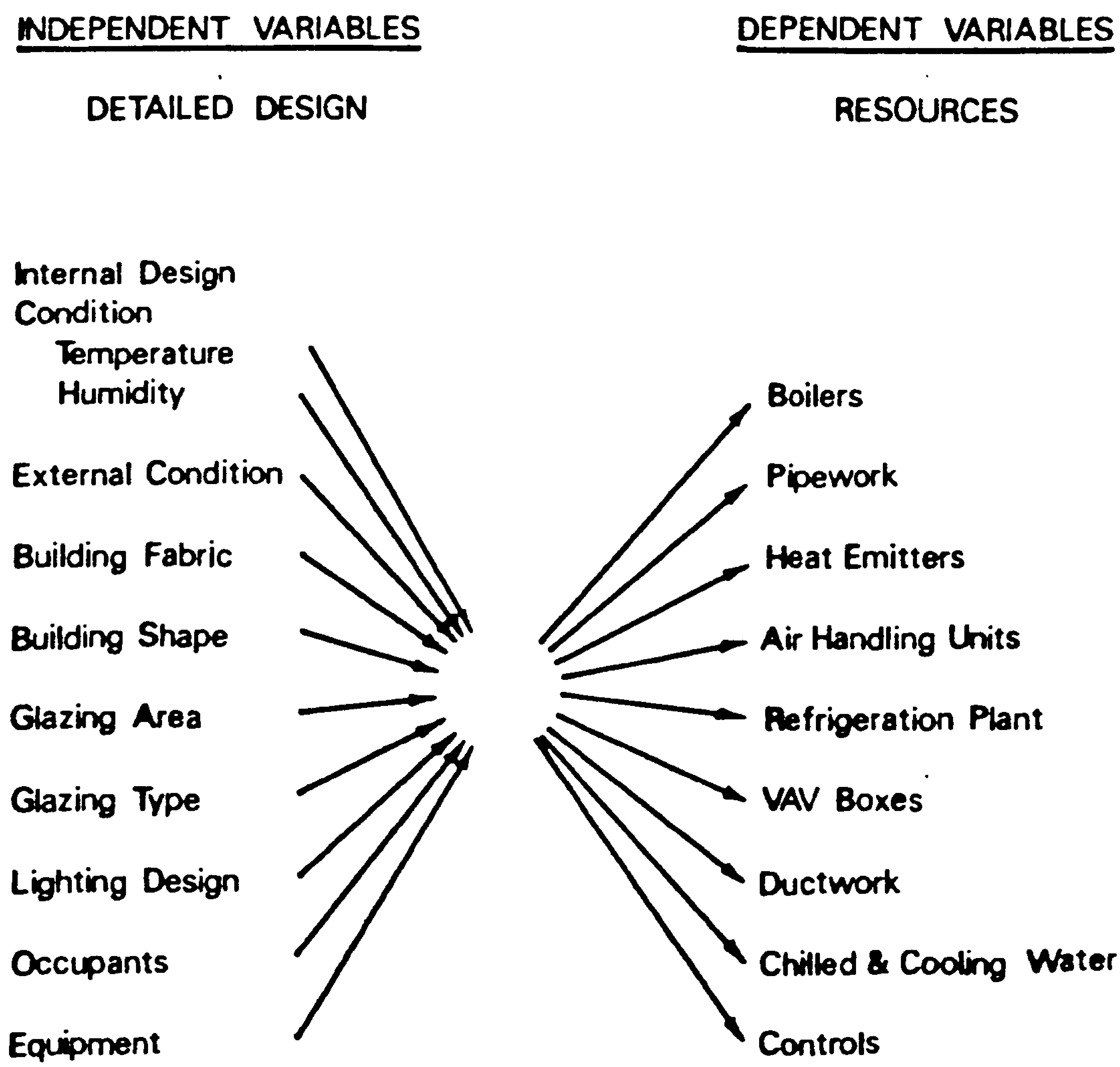


Fig. 7.5 MACE: RELATIONSHIP BETWEEN DESIGN VARIABLES AND RESOURCE COMMITMENT

inductive models (as discussed in chapter 4, see figure 4.7) is appropriate to this hierarchy. Deductive models are pertinent at level 1 and level 2. For design optimisation the model needs to be at the third, most detailed level, at which deductive models are cumbersome and inappropriate. It would be impossible to collect the amount of data needed to build a deductive model at this level and to deduce some degree of causality between the many independent variables and the dependent variable. Hence the model for air-conditioning evaluation (MACE) is an inductive model.

## Independent Variables.

The design variables shown in 7.5 have a disadvantage from the point of view of the model in that some of them (for example, glazing type, lighting design or the amount of equipment and machinery contained in the building) may not be known with an acceptable degree of certainty until relatively late in the design process, by which time even if the model is a sensitive one, it may be too late to iterate back through the design to carry out informal optimisation.

However, this difficulty may be overcome if the model is formulated in such a way that the independent variables can be entered as performance specifications. This gives the advantage that detailed functional relationships may be modelled relatively early in the design, and thus the relevance of the optimisation model to the designer is increased greatly. For example, instead of detailing the building envelope with descriptions of the material cavity and insulation type, the designer may set a performance specification such as 'the envelope shall be lightweight with a U value not exceeding X $w/m^2$'. Similarly for glazing area and type, lighting design may be dealt with by specifying the maximum heat gain tolerable in each zone and so on.

Formulation.

The independent variables and their units, used in the model are;

| | |
|---|---|
| Internal Design Temperature (Summer) | $^oC$ dry bulb. |
| Internal Humidity (Summer) | % saturation. |
| Internal Design Temperature (Winter) | $^oC$ dry bulb. |
| Internal Humidity (Winter) | % saturation. |
| External Design Temperature (Summer) | $^oC$ dry bulb. |
| External Design Temperature (Summer) | $^oC$ wet bulb. |
| Specific enthalpy external | $K_j/K_g$. |
| Amount of outside air per occupant | $m^3/s$ |
| No. of air-conditioning zones | No. |

For each conditioned zone.

| | |
|---|---|
| Dimensions | $m^2$. |
| Volume | $m^3$. |
| External boundaries | $m^2$. |
| Internal boundaries | $m^2$. |
| Orientation | Compass point. |
| Glazing area | $m^2$. |
| Glazing type | U value. |
| Infiltration rate | Air changes/hour. |
| No. of occupants | No. |
| Lighting heat gain | KW. |
| Sun shading devices | Choice of types. |
| Structure type | Heavy/light weight. |

The model also contains certain default values, for example, the permissable temperature rise of air travelling through the ductwork to its distribution point. These may be changed if necessary as the model is highly dynamic, but for the sake of simplification in description these will at present be dealt with as constraints and are discussed in more detail later.

The above list contains 21 independent variables, but as the model is dynamic with facilities for constraints to be altered or incorporated as active design variables, the notation for the model formulation will deal with the general case.

This gives:

$$E = \sum_{t=1}^{T} at. \prod_{j=1}^{N} V_j^{bjt} \qquad .....[7.4]$$

where

$V_j$ are the independent variables

$A_t$ are the constants for each $V_j$ these are usually complex numeric expressions in their own light.

The operation of the model is perhaps more clearly explained by the systems diagram illustrated in figure 7.12, this was drawn for the computer program which was written to evaluate the model. The program code is given in appendix IV.

## 7.6 OBJECTIVE COST FUNCTION

### 7.6.1 Introduction

The algorithms used in the model are described here. The approach taken is to present the output of the model (the measure of economic performance) to describe the computer program written to produce the output, and then define in detail the objective cost function.

The measure of economic performance in the model was taken to be the material cost of the main items of plant in the system. The requirement in design optimisation models is for a very sensitive measure, one which reflects accurately any changes in design decisions. An analysis was carried out (the full analysis is presented in Appendix IV) on a sample of multi-storey office buildings in central London, all having VAV air-conditioning systems. The dependent variable was system cost and three independent variables were gross floor area, size of heating plant and size of cooling plant. Very high correlations were found between the independent variables and the system cost. Assuming that plant cost is linearly related to output it was felt that the plant output sizes were a reasonable measure of economic performance. This assumption is less than perfect, a more accurate assumption would be that the relationship is of a stepwise nature. However, the almost complete lack of data (discussed in Section 7.7) upon which to build up a picture of this relationship made an assumption of linearity here, the only possible course of action given the time and financial constraints on the research project.

The computer program MACE (Model for Air-Conditioning Evaluation) was written on a North Star Horizon microcomputer to evaluate the model. A systems diagram of the program is illustrated in figure 7.6. Once the design variables have been entered, the program performs the

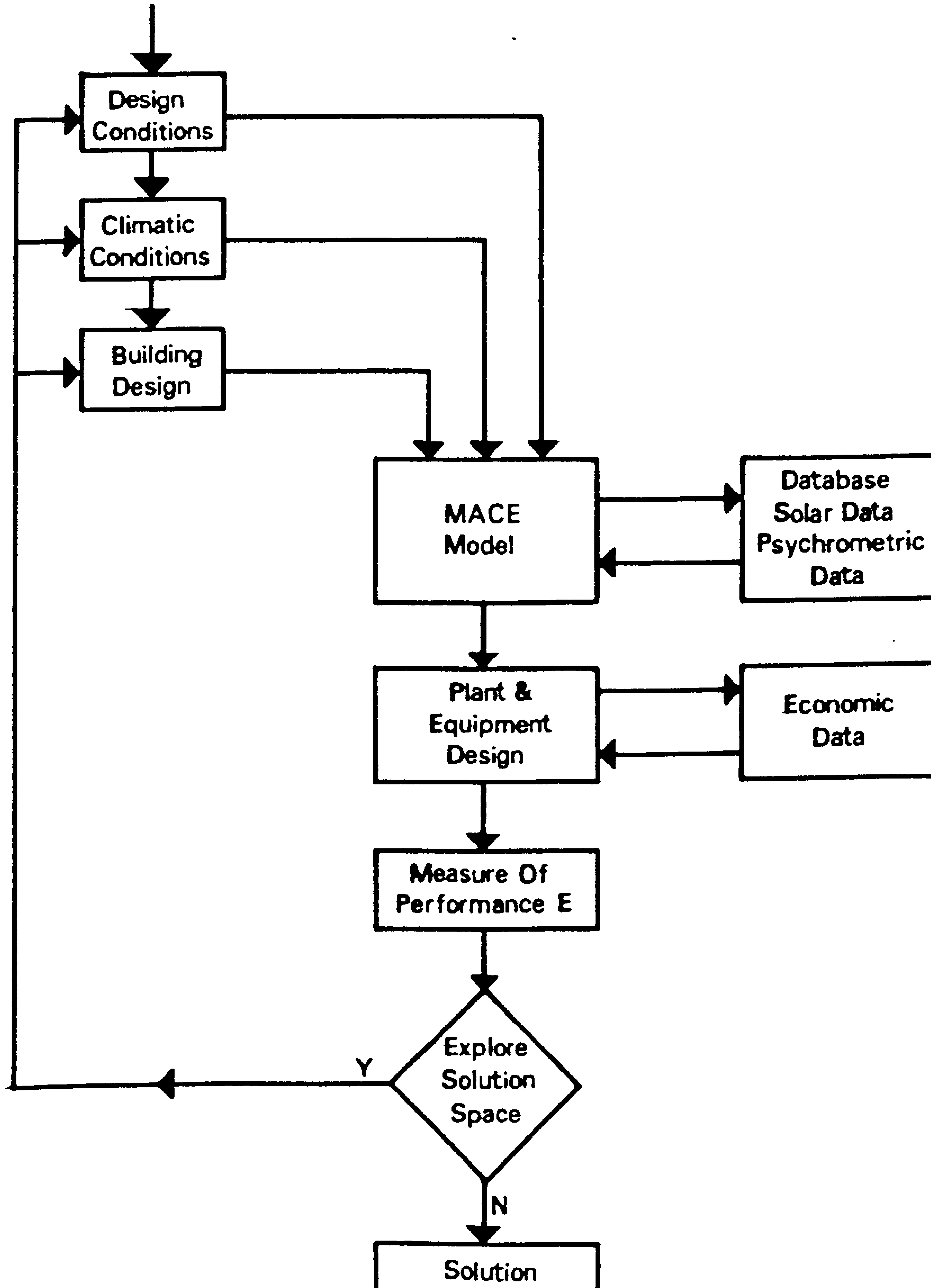


Fig. 7.6 MACE : SYSTEMS FLOWCHART

design calculations for the air-conditioning and heating systems. Modern office buildings tend to be used mostly during the day and for five or six days of the week. Steady state thermal calculations are therefore considered inappropriate and the program takes account of intermittent plant operation and utilizes the "admittance" approach to heat loss calculations as outlined by Harrington-Lynn and in the CIBS guide.[10,11] For the air-conditioning design the hourly heat gains throughout the cooling season are calculated. This includes both sensible and latent gains from insolation (through fabric and glazing) infiltration and internal gains from occupants and equipment. The mass air flow and refrigeration loads are calculated for the hour of maximum heat gain. The program takes account of air-conditioning zones of differing orientation and thus of situations where certain zones require heating only, and others require cooling. The designer has complete freedom with choice of building shape and arrangement of zones.

7.6.2 Computation.

Recapitulating we have:

$$E = (Cm + Bm) \qquad \ldots[7.5]$$

where Cm is the cost of the central air-conditioning plant and Bm the cost of the boilers for the heating system. Introducing this to [7.4] gives

$$(Cm + Bm) = \sum_{t=1}^{T} At.\prod_{j=1}^{N} V_j^{bjt} \qquad \text{...[7.6]}$$

In the model this is resolved into two components

$$(Cm) = \sum_{y=1}^{Y} Ay.\prod_{r=1}^{R} V_r^{bry} \qquad \text{...[7.7]}$$

and

$$(Bm) = \sum_{x=1}^{X} Ax.\prod_{s=1}^{S} Vs^{bsx} \qquad \text{...[7.8]}$$

subject to

$$T = (Y + X) \qquad \text{...[7.9]}$$

and

$$N + (R + S) \qquad \text{...[7.10]}$$

The total number of design variables (Vj) is N and the total number of constants relevant to these in the objective function is T. When the model is resolved into its two components, only a certain number (R) of the design variables and Y of the constants are relevant to the Cm component. The remainder (S) of the independent variables and (X) of the constants are applicable to the second component Bm.

The Cm component (air-conditioning plant) is by far the more complex of the two components, accordingly this will be dealt with first. Equation [7.7] may be expressed as

$$Cm = f_1(V_1 + V_2 + V_3 \ldots V_R) \qquad \ldots[7.11]$$

The function $f_1$ is very complex and may be resolved as follows

$$Cm = M_1(H_1 - H_2) + P_g \text{ (KW)} \qquad \ldots[7.12]$$

When $M_1$ is the mass flow of air through the plant, $H_1$ is the specific enthalpy (total heat) of the mixture (fresh and recirculated) and $H_2$ is the total heat at dew-point. Pg is the heat gain from the plant itself.

$$M_1 = \frac{Sg}{K.S_a} \qquad \ldots[7.13]$$

where Sg is the total sensible heat gain, K is the permissable temperature rise between room inlet and outlet and Sa is the specific heat capacity of air.

$$Sg = (S_1 + S_2 + S_3 + S_4 + S_5) \qquad \ldots[7.14]$$

where $S_1$ the peak solar gain through glazing is

$$S_1 = \left\{ \left[ \sum_{o=1}^{8} (G_o . I_{go}) + r \right] . S_F \right\} + (Au. \sum_{o=1}^{8} G_o . t_d) \quad ...[7.15]$$

where o represents the glazing orientation (N,NE,S,W etc.) $G_o$ is the area of glazing at that particular orientation. $I_{go}$ is the insolation level of that form of glazing g (single, double, blind inside or outside etc.) at that particular orientation. r is the solar radiation at ground floor level reflected from the pavement. $S_F$ is the shade factor. Au is the air to air u-value through the glazing and td is the temperature difference outside to inside.

$S_2$ is the total peak sensible heat gain through the building fabric

$$S_2 = \sum_{0=1}^{8} \left[ \left( \frac{Af.Uf.f}{1000} \right) . \left( td + Is \right) \right] \quad ...[7.16]$$

where Af is the area of the building fabric, Uf is the appropriate u-value, f is the decrement factor (due to the thermal mass of that particular wall fabric) and Is is the sun heat increment, i.e. the amount of heat which not just falls upon the fabric but actually gets through it to the inside - again this factor takes account of the thermal mass of the structure by allowing an appropriate time lag.

$S_3$ is the sensible heat gain through the roof of the upper storey.

$$S_3 = \left(\frac{Ar.Ur.f}{1000}\right) \cdot \left(td + Is\right) \qquad ...[7.17]$$

where Ar is the roof area, Ur is the roof u-value.

$S_4$ is the sensible gain due to infiltration.

$$S_4 = \left[\left(\frac{N.V}{Sr}\right) \cdot \left(H_4 - H_3\right)\right] / 3600 \qquad ...[7.18]$$

where N is the number of air changes per hour (due to infiltration), V is the cubic volume of the space, SV is the specific volume of dry air at room condition, $H_4$ and $H_3$ are respectively the total heat of dry air externally and internally.

$S_5$ is the sensible internal gain.

$$S_5 = (On.Og) + lg + \sum_{i=1}^{J} (Eg) \qquad ...[7.19]$$

where On is the number of occupants in the space. Og is the sensible gain from the occupants (this is clearly related to the activity being carried out in the space as discussed earlier, lg is the lighting heat gain and Eg is the gain from equipment (typewriters, computers, printing presses, etc.).

Referring back to [7.12] $M_1$ has now been resolved, turning to $H_1$, the total heat of the air mixture,

$$H_1 = \left[ (Hr.Mr) + (Ho.Mo) \right] / M_1 \qquad \ldots [7.20]$$

$M_1$ the mass flow of air to be provided by the plant has been calculated in [7.13] to [7.19]. Hr and Ho are the total heat of the re-circulated and outside air, Mr and Mo are their respective masses.

$$Mr = (M_1 - Vg) \qquad \ldots [7.21]$$

where Vg is the ventilation and infiltration gains (sensible and latent).

$$Vg = S_4 + I_2 + V_s + V_2 \qquad \ldots [7.22]$$

$S_4$ is given at [7.18], $I_1$ is the gain due to moisture by infiltration, $V_s$ and $V_1$ are the sensible and latent gains due to the ventilation air.

$$I_l = \left\{ \frac{N.V}{Sr} \cdot [(H_6 - H_5) - (H_4 - H_3)] \right\} / 3600 \qquad \ldots [7.23]$$

where $H_6$ and $H_5$ are the specific enthalpy of air at external and internal design conditions.

$$V_l = Va \left[ (H_6 - H_5) - (H_4 - H_3) \right] \qquad \ldots [7.24]$$

where Va is the volume of air introduced for ventilation, and

$$V_s = Va(H_4 - H_3) \qquad ...[7.25]$$

The final part of [7.12] to examine is $H_2$, the specific enthalpy of the air mixture at dew point. This is directly related to the moisture content of the air as it leaves the central plant. Air-conditioning system designers usually calculate the latter and then refer to tables contained in the CIBS guide C[12] which contains tables for this relevant specific enthalpy. However there is a direct relationship between the two figures given by the straight-line equation

$$H_2 = Ma .(2527.03) + 14.08 \qquad ...[7.26]$$

where Ma is the moisture content of air at plant exit condition.

In order to economise on data storage in the computer program for the model, equation [7.25] was used in lieu of the tables of values in CIBS guide C. Ma is calculated as follows

$$Ma = Mr - \left( \frac{L_l}{M_1 . LH} \right) \qquad ...[7.27]$$

where $L_l$ is the latent load in KW and is given by a summation of [7.23] and the following expression for the heat gain due to moisture from the building occupants.

$$O_l = On.\ O_{lg} \qquad \ldots[7.28]$$

where O is the total latent gain from the occupants, On is the number of occupants in the space and O is the latent gain from each. This depends on the activity being carried out in the space.

Turning to the second component of the objective cost function, the size of the heating plant, as given in [7.8], dealing initially with the steady state heat requirements, the total is given by the sum of the fabric losses and the ventilation losses less any fortuitous heat gains. In the model the fabric losses are divided into groups, each representing a particular fabric type, this gives the designer a free choice with regard to the number and nature of fabric types for the building envelope. This is facilitated, as mentioned above, by giving the performance specifications for each fabric type. Thus

$$Q_F = \sum_{i=1}^{n} U_i A_i (t_{ai} - t_{ao}) \qquad \ldots[7.29]$$

where n is the number of fabric types, $U_i$ and $A_i$ are the u-value and area respectively, $t_{ai}$ and $t_{ao}$ are the inside and outside temperatures.

The ventilation loss Qv is given by

$$Qv = 0.33NV\,(t_{ai} - t_{ao}) \qquad \ldots[7.30]$$

The relationships between air, dry resultant and environmental temperatures depend on the proportion of convective and radiant energy entering the room, the room dimensions and the proportions of fabric and ventilation losses. These relationships are defined using energy balance equations. CIBS guide A[17] however tabulates two factors $F_1$ and $F_2$ such that

$$F_1, F_2 = f(NV/3\Sigma A,\ \Sigma(A.U)/\Sigma(A)) \qquad \ldots[7.31]$$

where N is the ventilation allowance, V is the volume of the space, (A) is the sum of the surface areas and (A.U) is the fabric loss for 1°C temperature difference. The use of these factors gives the total steady state heat requirement as

$$Qp = (F_1 \sum_{i=1}^{n} (A_iU_i) + 0.33.F_2.N.V).(t_c - t_{ao}) - Hg \qquad \ldots[7.32]$$

where Hg represents the fortuitous heat gains and $t_c$ the dry resultant temperature.

Allowances for intermittent heating must take account of the thermal response of the plant and the building, the duration of heating and pre-heating and the relative capital and running costs. The first two elements may be analysed in general terms and have been combined to produce a factor $F_3$ 13 such that the peak heat requirement allowing for intermittent heating may be given by

$$Qp.b = F_3.Qp \qquad ...[7.33]$$

Thus, both components of equation [7.5] have been resolved.

## 7.7 DATA

### 7.7.1 Relationship between Model and Data

This is a complex relationship which needs to be balanced carefully. The model cannot function without the data, the nature of the data has major implications for the form of the model, while at the same time a well-formulated model may expose weaknesses and gaps in the data. These latter may in turn cause the model itself to require modification. An examination of the existing data may indicate the order of importance of the relationships which are to be contained within the model.

Examples of all of the above were found during the formulation and validation of the model. Problems were also encountered due to the inapplicability of existing terminology, which when used was sometimes found to be misleading.

### 7.7.2 Nature of Available Data

The universal set of cost data relevant to the installation of equipment for heating and air-conditioning is diverse and includes the following; manufacturers price lists and quotations for plant* and materials costs, nationally agreed wage rates, Building Services Research and Information Association (BSRIA) published manhour times for specific HEVAC tasks, rates for measured work** from published price books, unit rates from measured bills of quantities or negotiated schedules of rates.

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* In the HEVAC environment 'plant' is taken to mean large pieces of equipment such as air handling units, boilers, etc. and 'materials' the smaller items such as pipes and valves, etc.

** 'Measured work' means the total cost per unit installed, e.g. £X/M run of pipe, £Y/$m^2$ of insulation, £Z/KW of installed boiler capacity - the rates include labour, material and overheads and sometimes profit also.

Clearly the set of information is diverse and in general unco-ordinated. It is worth noticing also that it contains a mixture of information based on costs and prices. As discussed in chapter 4, this latter is an important distinction which has to be carefully made when structuring any model or modelling hierarchy. It is possible to draw many patterns through such a set of data and to argue the 'correctness' of each. There is no one correct answer, rather what we are concened with is the 'usefulness' of any ordering of the data.

Three levels of data have been identified as being of some use when considering the relationship between the level of detail of the model and the state of development of the design. These are certainly not the only three and depending where certain arbitrary lines are drawn more or less could be uncovered. The three levels discussed below were chosen merely because they seemed to constitute a useful ordering of the data. The differences between levels may be seen in terms of the 'aggregation' of the items. The concept of aggregation and its associated problems is discussed in chapter 4.

Level 1 is the overall price for the installation and is never fully known until the job is complete and all of the bills have been paid by the building owner, only then is it possible to calculate the price that has been paid for the system.

Level 2 is commonly called a cost analysis. An analysis is made of the successful contractor's bid for the project, it is broken down into various subheadings based on the physical parts of the system. Clearly this is in fact an analysis of the price and not the cost. The third level is that of the costs of the resources (as defined in chapter 4). It is this level which is used to calculate level 1, the system price. The level in between is largely contrived and is often merely an arbitrary breakdown of the overall bid.

A causal, inductive model of this nature clearly needs data at level 3, the resource level. At the resource level the available data is as follows.

| | |
|---|---|
| Labour Rates | - in various trade journals for example 'Building'. |
| Labour Times | - the only published data is a 1976 document from the BSRIA[14]. |
| Material and Plant Costs | - Spons Mechanical & Electrical Price Book[15]. |

Each of these generally available sources of information is intended for use by estimators when, for some reason, a gap is discovered in the estimator's own in-house data. This is then supplemented with the additional external information. This research project did not have access to comprehensive, detailed in-house data of this type. The only data available for use in the model is that which is publicly available. This situation presented a number of problems for the model. Table 7.2 lists the sources of data and summarises the contents of each with respect to the model outputs, i.e. the main plant and items for the conditioning and heating processes. Clearly a comprehensive set of resource cost data does not exist from one source. Given this, two options remain, namely:

(i) Combine the various sources of information to produce the full spectrum of resource costs.

(ii) Select particular resources where the economic data exists in one source, for detailed consideration.

The first option would not produce meaningful results in this instance. Even if the sources were put together and allowances made for the fact that one is not comparing like with like, that the data was gathered by different people at different times under different sets of assumptions and possibly for different purposes, and that the sources were never meant to be combined anyway, the resultant would still not be the complete set of resource costs. Still missing would be the data concerning the material costs of the central air-conditioning plant. Attempts were made by the author to collect this data from a number of manufacturing firms, but it proved impossible to obtain for research purposes. The absence of the latter data also rendered the second option unsuitable. Clearly it was not

| | Conditioning Installation Central Plant | | | Heating Installation Central Plant | | |
|---|---|---|---|---|---|---|
| | Materials | Lab. Time | Lab. Cost | Materials | Lab. Time | Lab. Cost |
| BSRIA[14] | | ✓ | | | ✓ | |
| SPONS[15] | ✓ | ✓ | ✓ | | | |
| Trade Magazines | | | ✓ | | | ✓ |
| Consultants Data | aggregated | | | aggregated | | |

Table 7.2 AVAILABLE DATA FOR A/C INSTALLATIONS

feasible to formulate the model if the costs attached to the central conditioning plant could not be pinpointed. The solution adopted was to carry out a simplification of the measure of economic performance and to reformulate the model temporarily, in order to generate some results, while at the same time retaining the original formulation for use when the data becomes available.

## 7.8 FORMULATION II

The measure of economic performance adopted in the model is the cost (of materials and labour and without any profit or tactical and market considerations) of the heating boilers and of the central air-conditioning and cooling plant. The relationships of these items with cost are indicated as the solid lines in figures 7.7 and 7.8. The relationship is a 'stepwise' one, as the capacity of the plant (in tons of refrigeration for the cooling plant and in KW of heat for the heating plant) increases, so does the cost of the installation but plant capacity as manufactured is discrete and so the cost relationship will necessarily consist of plateaux and steps.

If a complete set of resource data is to hand then the steps themselves may be plotted, however the general trend of the cost relationship may be approximated by a

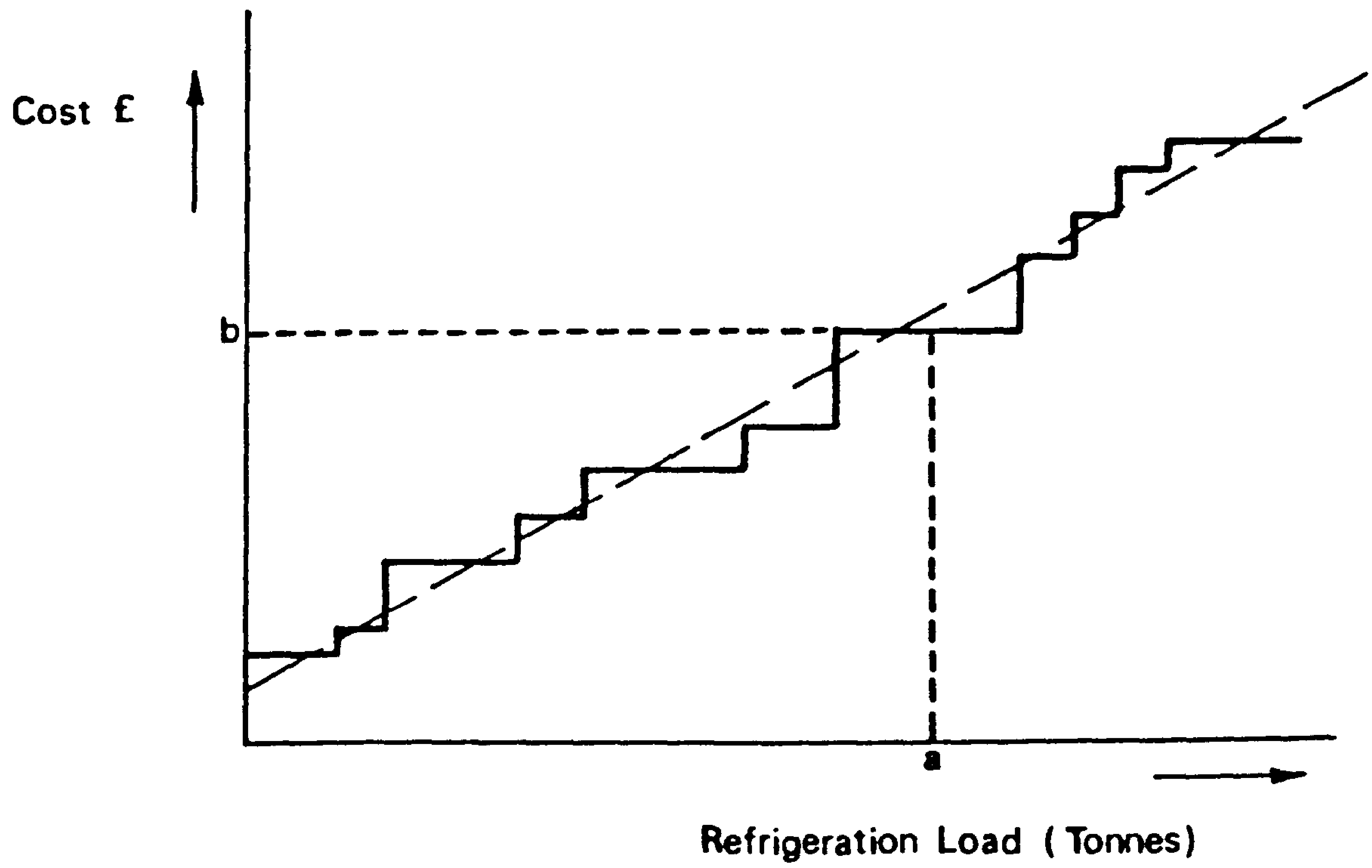


Fig. 7.7 COST RELATIONSHIP OF A/C PLANT

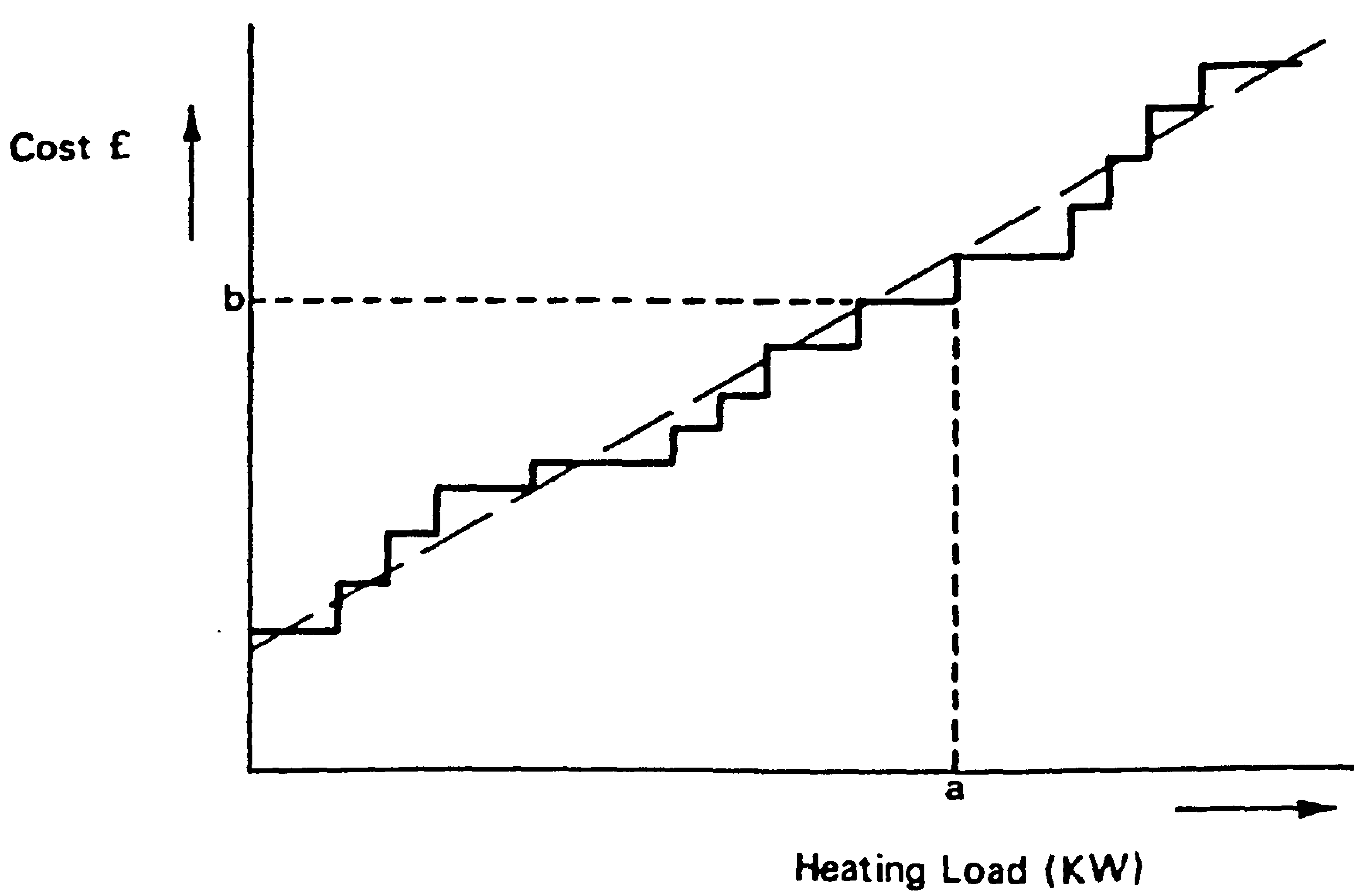


Fig. 7.8 COST RELATIONSHIP OF HEATING PLANT

simplification of linearity. Without access to such data it is impossible to fully test the consequences of such an assumption, this problem is discussed more fully in chapter 8. It follows that equation 7.5 showing the measure of economic performance may be rewritten as

$$E = (C_s + B_s) \qquad \ldots[7.34]$$

where $C_s$ is the size of the cooling and conditioning plant and $B_s$ is the capacity of the boilers. This does not affect the computation as $C_s$ may be substituted for $C_m$ in [7.7] and $B_s$ for $B_m$ in [7.8]. The model now presents as output the capacities of the main plant items with respect to the particular building design. The designer may iterate through the model at will in order to minimise these if required.

## 7.9 CONSTRAINTS

The main constraints have been mentioned in passing already, they are; the model deals only with multi-storey office buildings which use VAV air-conditioning with some form of perimeter heating. Other constraints are as follows: the design humidity level expressed as percentage saturation is restricted to three discrete values 40%, 50% or 60%; building location is constrained to lattitude

51.7°N. This restriction is caused by the data for the cooling load due to solar gain, other data files could be incorporated if necessary.

## 7.10 VALIDATION

The model was validated by comparing its performance to that of manual calculations. Hypothetical buildings were proposed and the results computed both manually and by the computer program of the model. Due to the very time consuming nature of the manual calculations this model was validated only for a well defined range of buildings. At the bottom of the scale a simple one storey one zone was tested and at the other end a more complex two storey four zone building was tested. All of the results used for testing the criteria of suitability were run on buildings from within this range.

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# CHAPTER 8

# THE RESULTS

## 8.1 Introduction

## 8.2 Data Evaluations

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### 8.2.2 Model 1

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### 8.2.4 Model 3

## 8.3 Data/Model Interface Evaluations

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## 8.1 INTRODUCTION

It is worth recapitulating briefly on the central objectives of the thesis and, in that context, this chapter before presenting the results. The research is addressed to the problems of making some form of consistent measurement or evaluation of the performance of economic models in building design. More specifically it seeks to carry out tests and generate some quantitative results based on the criteria which were derived in the theoretical analysis presented in chapter 4.

The criteria will each be dealt with in turn. Each criterion will be examined in relation to all three models. In some cases it will be possible to interrogate or manipulate the model experimentally. Unfortunately this is not feasible in all cases due to the complex nature of the subject.

Thus, the models presented in chapters 5, 6 and 7 are used as vehicles to evaluate the criteria for performance which were proposed earlier. These models are taken to represent the 'leading edge' of such models today. Given the constraints on this project they are assumed to be the best of their type that could have been built in the time allowed. They have all been validated, in some cases for a constrained set of buildings, but validated nevertheless.

During the construction of the models certain decisions were taken with respect to problem constraints and default values. These pragmatic considerations will be taken as 'givens' and thus for granted. Evaluation of these particular constraints would in wider terms be of limited value as these are a function of the particular human and machine environment in which the model is developed. Therefore it would not be possible to make any findings of wider significance to models generally, as such assumptions and constraints are generally unique to each case. However, in some cases the technique of modelling employed will imply various assumptions and these will, where relevant, be examined.

We may state the general form of a cost model in building design as in equation [7.4].

$$E = \sum_{t=1}^{T} A_t \cdot \prod_{j=1}^{N} V_j^{bjt}$$

where

$E$ = the measure of economic performance.

$V_j$ = the independent variables.

$A_t$ = the constants, for each $V_j$ these are usually complex expressions themselves.

All model users are concerned with the sensitivity with which E responds to changes in the variables $V_j$. In general terms this could be measured by the derivative of $E = \frac{de}{dv}$

These results are concerned with examining wherever possible the linkage between $\Delta V_j$ and $\Delta E$. In cost models for complex design problems these relationships are often difficult to relate but will, where possible, be pursued here.

## 8.2 Data Evaluation

### 8.2.1 Introduction.

The fundamental question which needs to be answered is, how does the quality of the data affect the performance of the model? Aspects of the quality of data were examined in some detail in the theoretical analysis of chapter 4. Four areas of importance were presented, two of these are sufficiently quantitative as to be capable of some sort of objective evaluation. Potential methods for evaluating the influence of these sub-criteria are presented below.

(i) Data Transformations.

The latter refer to the phenomenon where distortion creeps into the data. This is dependent on how far distant the data is removed from its original source. The original resource data is first transformed into rates on bills of quantity and later into elemental rates used for traditional 'cost planning'.

The effects of this on particular models are very difficult to evaluate. The central problem may be characterised as the fact that 'rates for measured work' (bills of quantity rates) and 'elemental rates' do not actually represent that which they purport to represent. Furthermore, there is a propensity for this to increase as the distance from the original data increases. A very large experiment would be required to fully evaluate this. Firstly, the relative performance of at least two teams of estimators would have to be measured. This would entail the two groups simultaneously pricing a number of projects in order to establish if one team prices consistently higher than the other. The second round of the experiment would consist of both teams producing some form of 'cost plan' or tender estimate for a new set of projects, one team using transformed data (rates from bills of quantities or elemental rates), the other using raw resource data. The third stage would be to compare the relative performances of the teams in the first and second rounds and identify any change.

However, even a large experiment such as this would be inconclusive, if sufficient detail were available to make the use of resource data possible. Transformed elemental data would not be used in practice. The fact remains that this type of data is used early in the design stage, it is inaccurate and the degree of its inaccuracy is largely unknown. In the context of this research, model 1, the superficial floor area model, relies as we have seen on transformed elemental data. The model will not function with raw resource data, therefore it is not possible to evaluate this factor here. Model 2 uses unit rates for measured work but would function with resource data were it available. The problems encountered in building model 3, the air-conditioning model, epitomise the difficulty of evaluating the effects of using or not using transformed data. Model 3 was designed to utilise raw resource data in the evaluations of design alternative, however it was not possible to obtain a comprehensive set of such data. The chief problem was in obtaining reliable data for the usage of the resource labour. This type of data is not generally available.

(ii) Variability of the data.

There are at least two levels of variability in the data. Firstly, the fact that different sources of data present different values for identical items. The second level is the existence of some uncertainty around any particular data point. The evaluation of this second level of variability is considered later in the section which considers the interpretation of model output. The sensitivity of models to the variability among data sources may be examined quantitatively below.

Before proceeding to the detailed examination of the criteria with respect to each model. Some of the more general questions raised in chapter 4 are summarised in table 8.1. Throughout this work a traditional experimental approach has been adopted. Modelling is however undoubtedly a "soft science" and this approach is not always possible or appropriate. There are many questions for which there are no accepted scales of measurement for the answer. This does not mean that the questions should not be raised. Table 8.1 summarises some questions of this nature.

| CRITERION | MODEL | | |
| --- | --- | --- | --- |
| | 1 | 2 | 3 |
| Assumptions explicit ? | Yes | Yes | Yes |
| Is it described statistically ? | No | No | No |
| Can it take account of uncertainty ? | No | No | Yes |
| Aggregation | Very High | High | None |

Table 8.1 QUALITY OF DATA

8.2.2 Model 1.

An examination from first principles of the superficial area model shows that the results it produces may be almost entirely dependent on the data source used. Consider the model as stated in equation [5.2].

$$C = \sum_{E=1}^{32} (t.q.qu.R)_E$$

where

E = the element number, there are 32 in all.

t = the time adjustment.

q = the quality adjustment.

qu = the quantity adjustment.

R = the element unit rate.

The element unit rate R is selected from a cost analysis of a project considered to be comparable. Hence the value which R takes depends on the analysis chosen. However, conventional wisdom would have it, that the result C would not be influenced unduly, as the adjustmetns to t, q and qu would compensate accordingly. Consider the adjustments, t is a relatively straightforward arithmetical adjustment produced by the application of some sort of index. Similarly qu is a quantity adjustment which compensates for the difference in floor area. The quality adjustment q is very different in nature however. The value of q is subjectively chosen by the user. For example if the specification of the building which is being used as a comparison is considered to be of a quality inferior to the project in hand, an upwards adjustment will be applied. There is no agreed scale of measurement for these adjustments, users tend naturally to think in terms of round figures as the model is usually applied relatively early in the design process. Thus a user would be more likely to choose an adjustment of ± 5% or 10% than say 7.25% or 3.5%. The figure R is itself a blunt instrument as has been shown in chapter 4, it has been subjected to two transformations of unknown magnitude.

Hence, two of the four factors in each of the thirty-two terms of the model are crude figures with no agreed scales of measurements. An experiment suitable to generate empirical results of the influence of the choice of data source R would be a large and cumbersome affair of the type described earlier and thus not possible in this research. Thus the argument that the model is sensitive to the choice of data source must rest on this analysis from first principles.

### 8.2.3 Model 2.

Model 2, the staircase evaluation model, was specifically designed so that the model would be distinct from the database. The database used consisted of rates from published 'price books'. There are many such price books available, however, not all of them presented items identical to the specifications assumed by the model. It would be possible to make subjective adjustments to various rates and thus to incorporate many alternative data sources. It was decided not to do this however, as it would incorporate and even hide, personal evaluation within the data, this was not considered desirable if the model were to be used experimentally. Taking this into account, two sources of data were found to each contain all the items necessary with only very minor adjustments. Hence it is possible in this case to carry out some experiments to evaluate the sensitivity of the model to the data.

The results of the sensitivity tests are presented in figures 8.1 and 8.2, the procedure adopted was as follows. The model was run for a given set of regulations and in this case, for a range of occupation densities. The building chosen for analysis is situated in central London, the details of which are presented in the caption to figure 8.1. The model was used to present an analysis of the relationship between the number of people on each floor and the capital cost of the staircases necessary to comply with the regulations for egress in case of fire. The first run of the model which gave the results for the line $D_1$ in figure 8.1 used as data rates drawn from the 1983 edition of Spons building price book.[1] The second run which gave the results for line $D_2$ used as data, rates drawn from

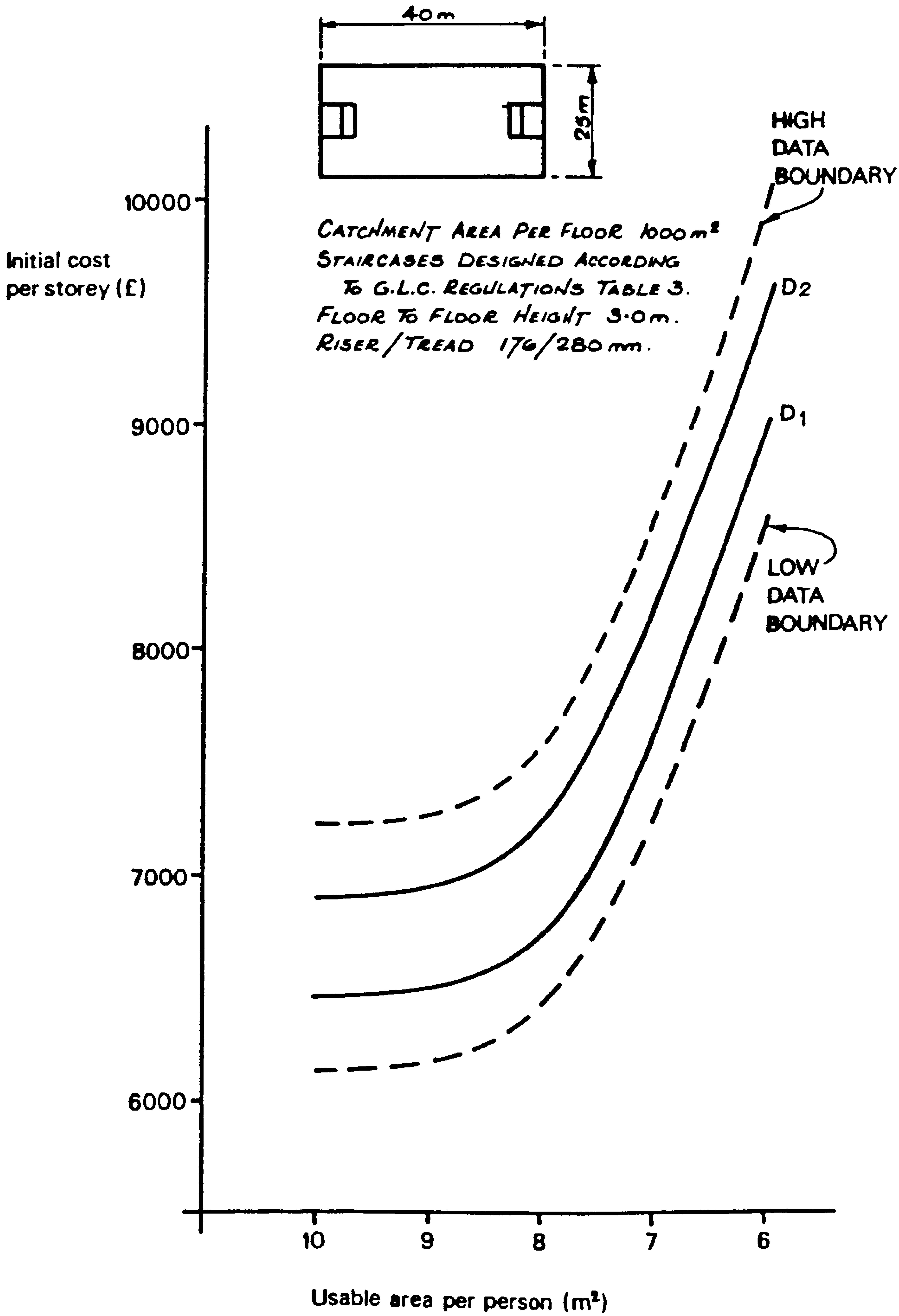


Fig 8.1 MODEL 2 : SENSITIVITY TO DATA SOURCE

Laxtons Building Price Book.[2]

Clearly there is a significant difference between the output obtained using the two sources of data. In fact data source two produces output which is consistently higher than data source one by a factor of 7 1/4% of the data one output. Effectively the experiment so far consists of purchasing a 'shopping basket' of items first from one source and then from another. On the particular selection of items chosen here one source has cost more than another and we have seen the quantitative effect on the model output.

However, this does not fully explore the variability of the data. Within the set of data items considered there will be positive and negative variations and some items may even be the same. A further experiment is necessary to establish the boundaries of the most extreme cases of variability. A best-case and worst-case analysis was carried out by repeating the earlier analysis except that the model is required to search both databases to evaluate each solution. In the first case the model is required to compare the value of each item in question and select the highest value irrespective of which data-source it is from. This produces the worst-case analysis shown by the high data line in figure 8.1. Similarly on the next run the model was required to search both databases for each item as it was required, and to pick the best case or lowest value. This produced the low data boundary as shown in figure 8.1.

Neither of the two data sources analysed above provide any sort of statistical description of the information which they contain. It has been shown that there is a considerable variation in the results obtained but without a standard deviation or a distribution shape for the data it is not possible to know which is the more 'correct'. It is possible to run the model and take this into account, this should in fact produce output which more clearly resembles the state of our knowledge of reality. Figure 8.2 presents the results of four such runs. The same analysis was carried out as before but this time the choice of data source is left as random for each item. There are five points on each line, each point represents the evaluation of one design solution. The evaluation of a solution in terms of initial cost is carried out by measuring 23 items of construction work. In selecting values for each of these items the model consulted either database 1 or 2 according to the value of a random number generator. Thus some points may have been produced by a majority of the items being selected from database 1 and others by a majority from database 2 and so on. The erratic nature of the results represents the erratic nature of the data used.

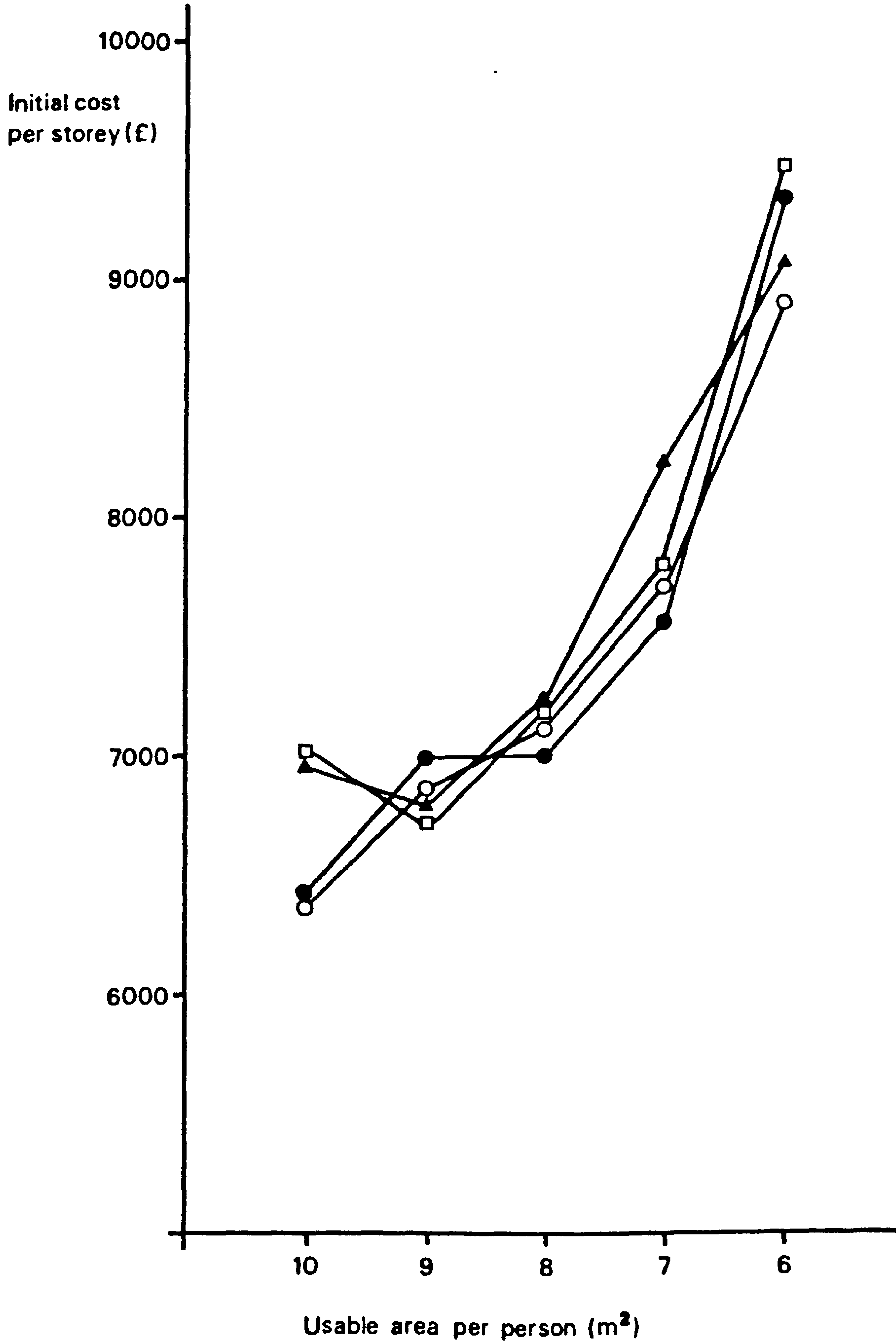


Fig 8.2 MODEL 2 : VARIABILITY CAUSED BY DATA

### 8.2.4 Model 3.

A second formulation of model 3, the air-conditioning model, was required to taken into account the fact that a comprehensive set of data for the costs of the resources did not exist. A linear approximation of the stepwise plant cost function was used as the economic measure, this has been illustrated in figures 7.8 and 7.9. Therefore a quantitative evaluation of sensitivity to data is not appropriate in this case.

## 8.3 Data/Model Interface

### 8.3.1 Introduction.

This section considers the relationship between the model and its data. There is no known way of evaluating numerically the strength or usefulness of this relationship for it is difficult to isolate from other factors. However, we can at least ask some pertinent questions from first principles, the answers to which will help to evaluate the importance of this factor and give some indication of potential weaknesses in models. The two fundamental issues are firstly, is there an available set of data which is at a level of detail appropriate to that of the model? The answer to this will involve a thorough examination to establish exactly what level of detail will enable the maximum benefit to be derived from the model. Secondly, if the model and the data are not well matched, it is necessary to establish whether the data is at a greater level of detail than the model. If this is the case then effort should be directed towards refining the technique of modelling in order to maximise the gain from the extant data. If on the other hand, the data is at a coarser level of detail than the model, then the relatively larger problems of improving the recorded data need to be addressed.

In practical terms the model builder needs to work from the data which is available and to 'tune' the model technique accordingly. This implies an acceptance of current conditions. Research addressed to the problems of cost models in this application should not accept current conditions as being the best available.

### 8.3.2 Model 1.

Is there in existence a set of data which is at a level of detail appropriate to this model? It was suggested earlier (section 8.2.2) that the data used in this model could be characterised as a 'blunt instrument'. The derivation of the data has been considered in detail in chapter 4, section 4.2.1. The model technique, that of comparison and adjustment, is itself relatively blunt, in that of the three adjustments which are applied to the original data, one has no scale of measurement, the user selects a figure based on his 'experience and professional judgement'. Insofar as this is the case we may say that the model and the data are well matched. It would seem unlikely that any significant improvement in results would be gained from an increase in the level of detail of the data, as this would rapidly expose the weaknesses of the model technique and vice versa.

### 8.3.3 Model 2.

The STEPS model retains a very detailed mathematical representation of the staircase, stairwell smoke lobbies, etc. This detailed model is used to compute measurements of all dimensions necessary to physically construct the structure. Therefore the model could support detailed resource data were it available. In fact this data is not generally available. Therefore in this case the best data that was available was not detailed enough to maximise the benefit to be gained from the model technique. Hence, due to an incompatibility at the data/model interface, the technique of modelling is under-utilised.

### 8.3.4 Model 3.

The technique of this model is similar to that of model 2 and the problems at the data/model interace are also similar although on a larger scale. Based on the designer's performance requirements and the details of the orientation and performance specification of the building, the model builds up a detailed picture of the air-conditioning and heating plant required. This type of model can support highly detailed resource cost data. Again this was not available. A detailed account of the data which is available is given in chapter 7, section 7.7.2. Suffice it to say here that the full potential of the model is not realised due to the dearth of data at an equivalent level of detail. The model overcomes this adequately enough as referred to in section 8.2.4 but the problem of the recording and availability of data needs further attention.

## 8.4 Model Technique

### 8.4.1 Introduction.

The analysis of model techniques presented in chapter 4 section 4.2.4 was in three parts.

Deductive Methods.

Inductive Methods.

Stochastic Methods.

The three are not mutually exclusive, models may be predominantly of one type but with some elements of others also. For example, inductive models may contain some stochastic process for dealing with uncertainty. There is no stochastic model as such among the three presented in this work. Although a tool for evaluating uncertainty was in fact developed during the reserach, it is presented in the next section, Interpretation of output.

### 8.4.2 Model 1.

The superficial area model is used in the quantity surveying technique of 'cost planning'. This has been explained in chapter 5. As a model type it is unique and difficult to categorise, its limitations arise, it is suggested from three features.

(i) Comparative nature of the model.
(ii) Assumption of linearity.
(iii) Subjectivity.

(i) Comparative nature of the model.

Clearly no two buildings are the same, the reasons for this were outlined in chapter 1 section 1.2. The superficial area model as used in elemental cost planning requires that the element unit rate for a previous project be 'adjusted' for time, quality and quantity in order to act as the rates for the project in hand. This was shown in equation [5.1]. Any two people using a cost model purely mechanistically should get the same answer, if the model is consistent. This is unlikely to be the case with the superficial area model. Each of the three adjustments has limitations. The adjustment for time, (updating the previous project to today's prices) is carried out by the application of an index. An experiment to evaluate the inaccuracy of indices over time is outlined in section 8.5.3. The adjustment for quality is very subjective, this was described earlier in section 8.2.2. The adjustment for quantity will be examined below, it rests on an assumption of linearity.

Finally it should be mentioned that the users of this model do not generally perceive it in the model form as presented here. Rather it is viewed as a set of procedures to be followed. The mathematical form of the model exposes the technique much more clearly.

(ii) Linearity.

Consider a user preparing a cost plan for a high quality office building in London providing say 13,000m$^2$ of accommodation. The procedure is that a building analysis is selected which is considered comparable. This is the first limitation, choosing just one building is of course unsound, statistically. After updating the analysis by means of a tender price index and before making any adjustments for the quality of the specification, the element totals are adjusted for the difference in floor area. Consider just one element, the heating and air-conditioning services. The following is a real example, the office building was built in London in 1982.

| Gross Floor Area M$^2$ | Element Cost per M$^2$ of GFA | Total Cost of Element £ |
|---|---|---|
| 20,671 | 93.34 | 1,929,364 |
| 13,000 | 93.34 | 1,213,420 |

This straight adjustment would of course be followed by a consideration of the element cost per m$^2$ of GFA, as indicated earlier there is no accepted scale of qualitative differences. The initial assumption in the simple adjustment presented above is that the cost of the element is linearly related to the gross floor area of the building. To ascertain whether in fact this is the case we need to consider a sample of buildings. Such a sample is presented in figure 8.3.

The sample consists of nine office buildings erected in London in the period 1980-83. The elements considered in the graph are the heating and air-conditioning services. The sample is homogenous in that all buildings used the same air-conditioning system, a variable air volume system with perimeter heating. The relationship appears to be broadly linear although there are some wide variations particularly in the region of the building area 15,000 $m^2$. The potential for error due to this variation may be indicated quantitatively in this case. The adjustment for quantity which was made above having a floor area of 20,671 $m^2$ as a comparison, assumed that the relationship between gross floor area and the cost of the services installation was represented by the line $L_1$ in figure (8.3). Suppose we had considered the building of area 9727 $m^2$ instead of the one chosen earlier. This would assume that the relationship is represented by the line $L_2$. The element total for a 1,300 $m^2$ building in this case would be £1,500,460, a difference of nearly £0.5 million. Clearly, experienced users of the model would not make a naive judgement such as that. The graph and the example do show however the importance quantitatively of such experience. It is unfortunate that our scales of measurement are not such that we could externalise clearly the 'professional judgement' needed to use the superficial area model.

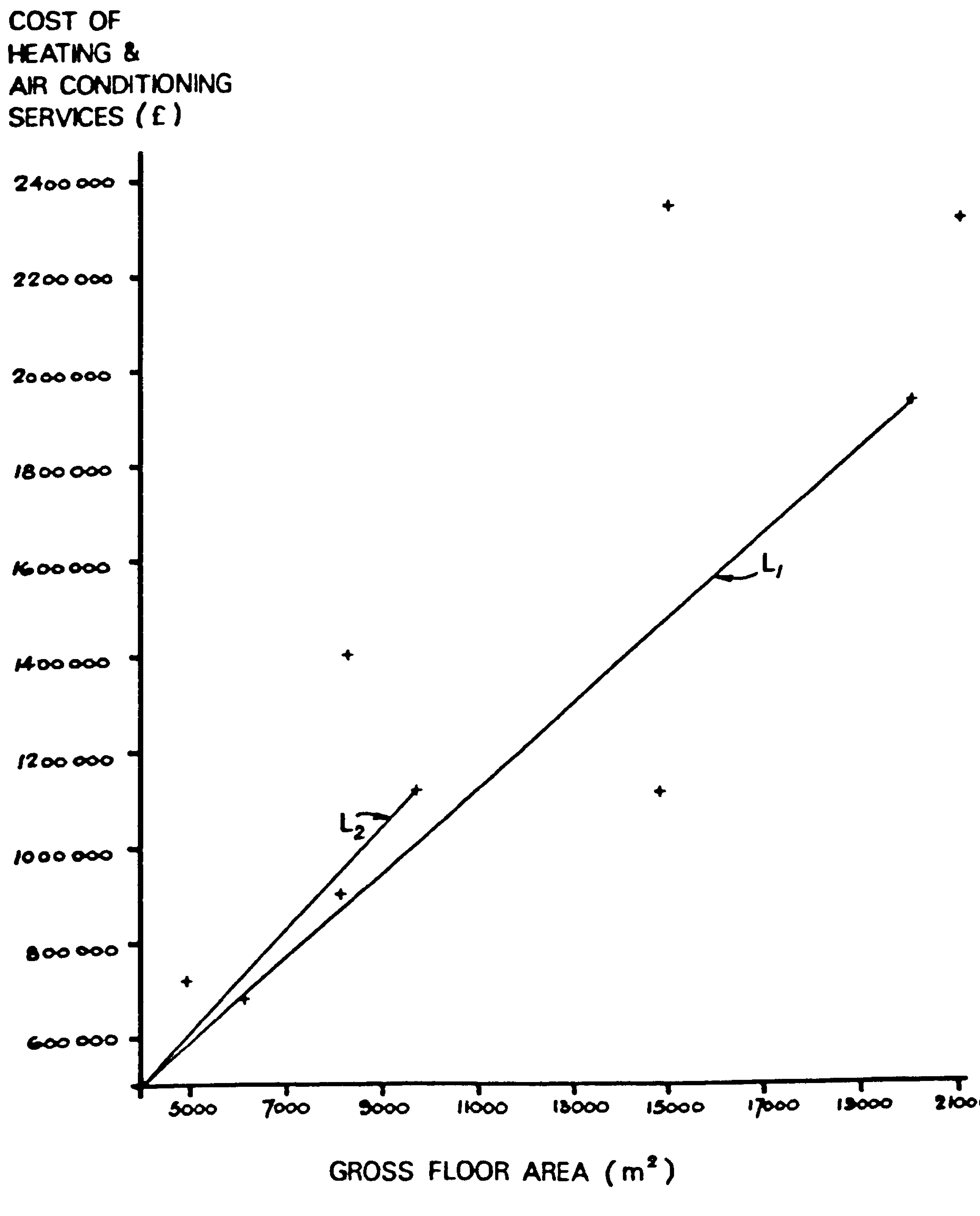


Fig. 8.3 RELATIONSHIP BETWEEN SERVICES COST & GROSS FLOOR AREA

(iii) Subjectivity.

This has been discussed in the preceding paragraphs and in section 8.2.2. However, a further example will be considered here which shows that it is possible to quantify some aspects of the subjectivity of the model technique. Let us consider mathematically what happens when a building is chosen for comparison and the simple quantitative adjustment for the difference in floor area is made. Figure 8.4 plots the cost of the services installation against the floor area for six office buildings. It was demonstrated above that, depending on which building was chosen for comparison, the services cost function could be represented by any of the lines $L_1$ to $L_6$. However, an adroit user of the model may decide to survey the cost of the element for each of the six buildings and use the average rate. Mathematically this user is taking the slope of each line and computing the average slope. The slope is illustrated in figure 8.5. A more meticulous user may decide to analyse the data and fit a line mathematically to it. Such a best fit line is shown in figure 8.5.

The point at issue here is that for these six buildings we now have eight possible linear relationships. There is no doubt that the least squares lines in figure 8.5 is the most correct mathematically. However in normal practice one of the seven others would be used. Consider a building with a G.F.A. of 140,000 sq. ft., let us assume that the

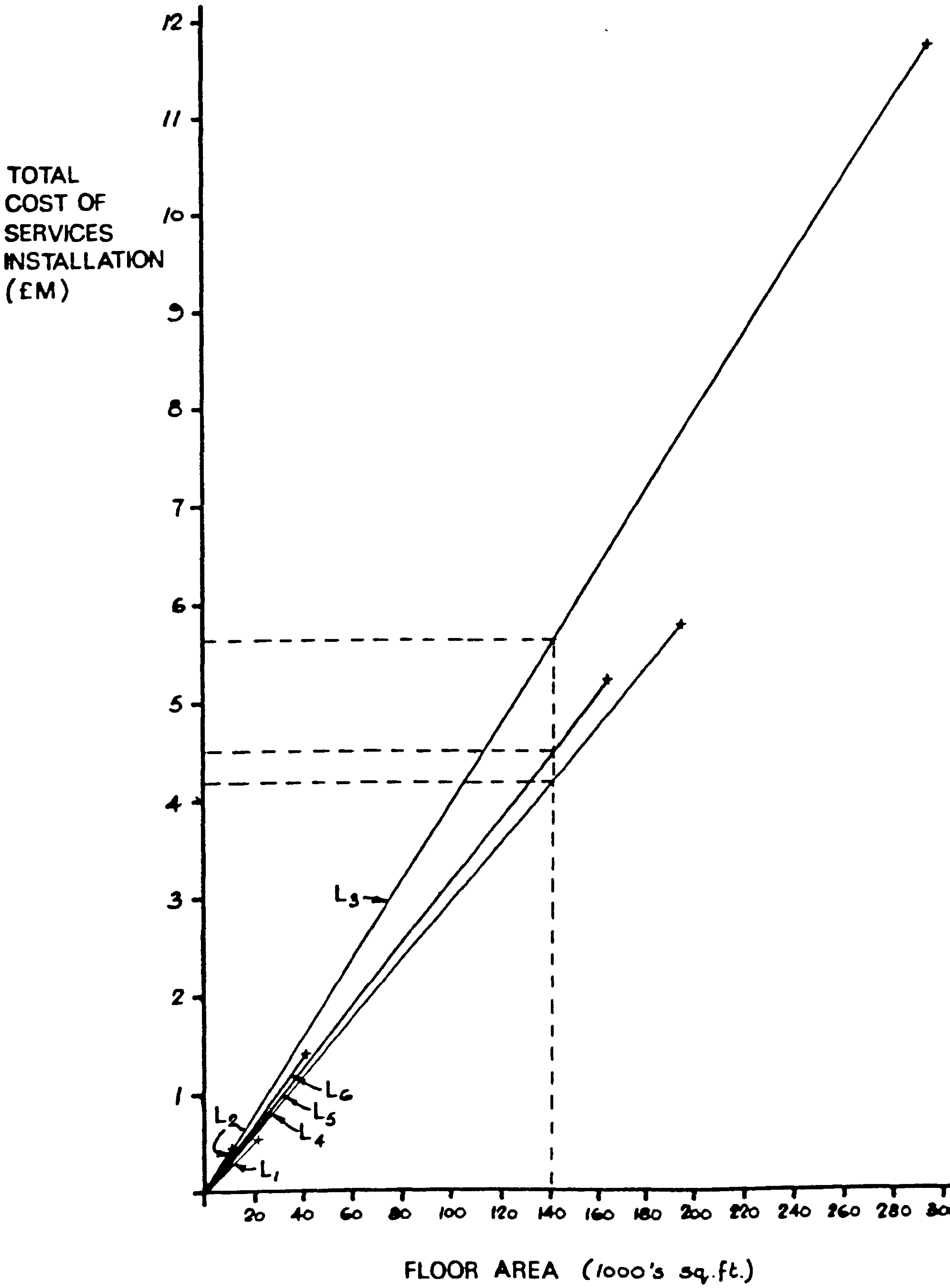


Fig 8.4 SUPERFICIAL AREA MODEL: ASSUMPTIONS OF LINEARITY

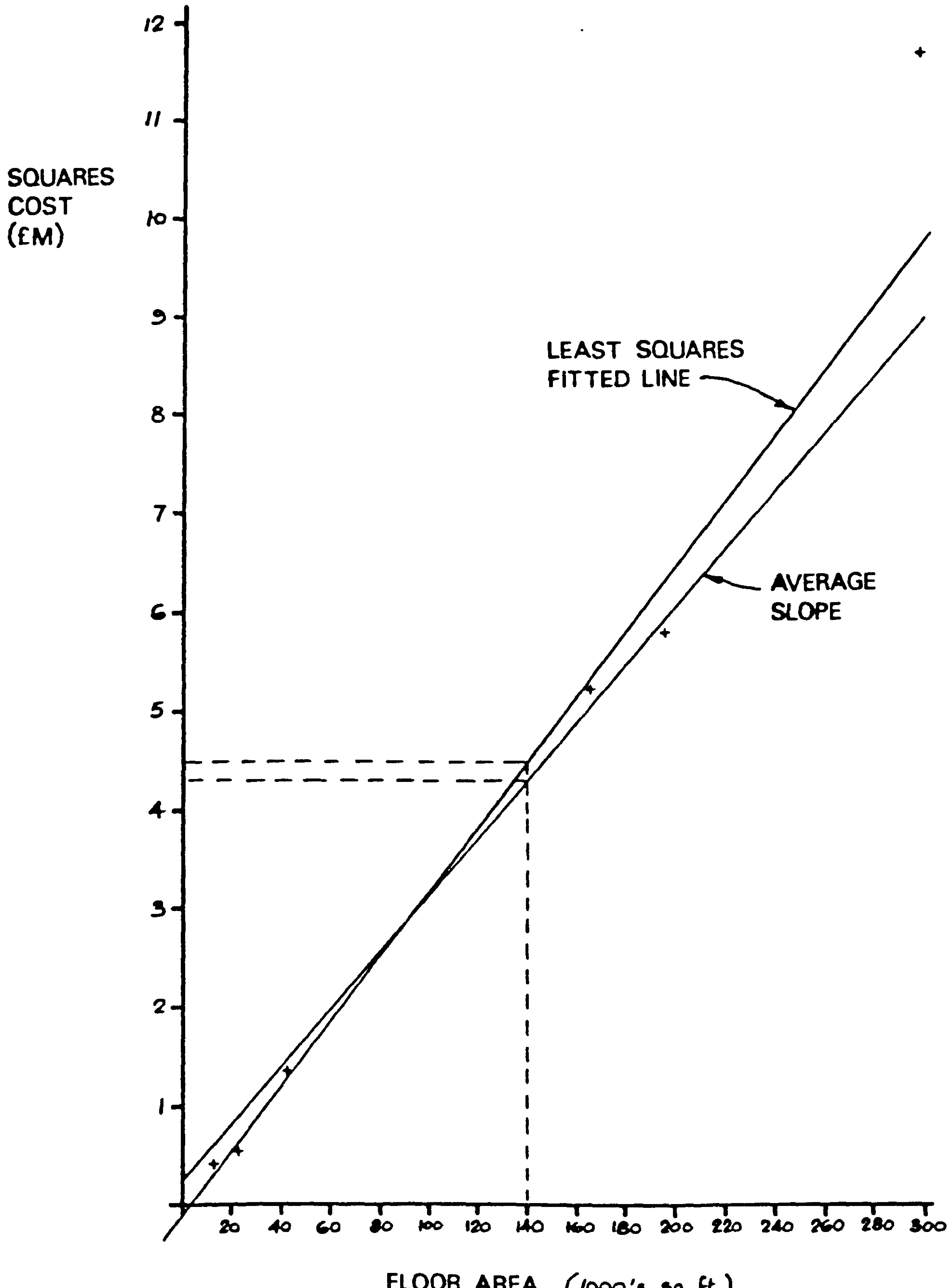


Fig 8.5 SUPERFICIAL AREA MODEL: FITTED LINES

regression lines give the best approximation of the relationship. This gives a result of just over £4.5m. If the average slope is used, the figure £4.3m may be read off diagram 8.5. The lines which apply on figure 8.4 give answers of between £4.2m and £5.6m.

Thus the range around the figure we have assumed to be the most correct is £300,000 to £1.1m. For this particular case that is the size of the adjustment which is supposed to be accounted for by professional judgement. The range accounts for about 25% of the total cost of the element.

The regression technique is itself less than perfect as is well known. It may be seen on figure 8.5 that the least squares line has been heavily influenced by the large building which, in terms of the scatter diagram, is an outlier. Outliers have a disproportionate effect due to the fact that the technique fits the line by minimising the squares of the distances.

It is generally known that one should not extrapolate regression based trends beyond the limits of the original sample. From figure 8.5 it is clear also that although there is a reasonable similarity between the average slope and the least squares relationships in the middle one third of the sample range, this reduces considerably as the lines move towards the limits of the sample.

Finally, the whole basis of the superficial area model is such that the cost of the building and of each element is expressed per unit of floor area. Clearly no two units of floor area cost the same. Consider as an extreme example, a sports hall. The real cost of any given unit of floor area in the middle of the hall will be entirely different to a unit taken near the perimeter of the building which will include substructure components, the external walls, roof supports and a considerable amount of services. This basis for representing cost bears little relation to reality and the way that costs are incurred.

### 8.4.2 Model 2.

Model 2 is a computer-based simulation or inductive model. There is no theoretical limit to the number of variables which may be incorporated or the complexity of the design problems which may be simulated. There are of course practical limits. In this case the model was limited to run on a microcomputer. This, coupled with the relatively short-time available for its design and development gave rise to the following limitations. The model is designed to assist the designer in evaluating and designing staircases to comply with the building regulations for egress in case of fire in multi-storey office buildings. The model accomplishes this, but is limited at present to only one type of staircase and stairwell construction. The model deals adequately with the relationship between size of catchment area and density of occupation and the cost of the solution. The shape of the catchment area is not considered, this was due to the very limited graphics capability of the computer which supported the model originally.

As with most models of this type, the limitations are particular to the case in point. The model is at present being developed further by a researcher interested, particularly in fire regulations and the limitations above are being resolved. Detailed models such as this are very intensive users of analysis and programming time. These barriers are not insurmountable and given sufficient resources this type of model has few limitations not already presented in manual calculations and, many advantages.

### 8.4.4 Model 3.

The model for air-conditioning evaluation is an inductive model similar in nature to model 2 above but rather more complex. The comments in the preceding section regarding the constraints and limitations of inductive models apply here also. A further assumption made in this model will be examined here. Due to the lack of available data at a detailed resource level, the model was reformulated using as the economic measure a linear approximation of the theoretical stepwise plant cost function. It was stated in chapter 7 section 7.8 that without access to a comprehensive set of data it was impossible to fully test the consequences of this assumption. A small sample of data was subsequently located which enabled a partial evaluation of the assumption. This is outlined below.

The assumption made in model 3 is explained in chapter 7 section 7.8 and illustrated in figures 7.8 and 7.9. The sample obtained was unfortunately not resource data. Two quantity surveying practices provided between them the detailed contract figures and specifications for the heating and air-conditioning installations of nine high quality office buildings erected in London in 1982 and 1983. The criterion for the sample was that the buildings should be as comparable as possible, thus the sample is small but homogenous. All the buildings in the sample had VAV air-conditioning systems with perimeter heating. Two buildings were eventually dropped because on a closer examination of the services' specification it was discovered that they used heat pump technology for energy conservation, this reduced the installed capacity of the boilers and thus rendered them incomparable to the other systems. It is difficult to place a concrete figure on the heating capacity of certain heat-pumps, and thus it was not possible to adjust the boiler capacity accordingly for the

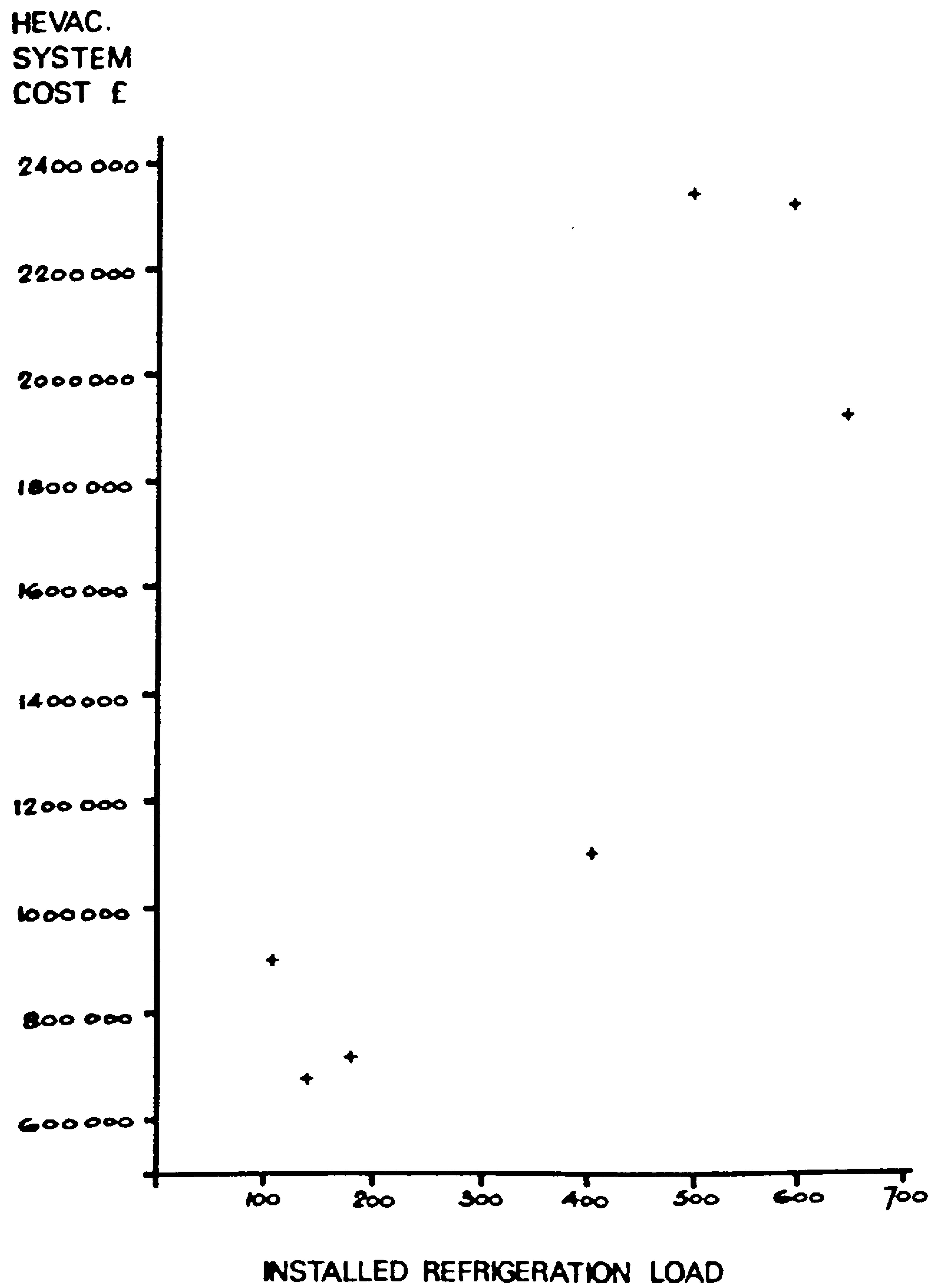


Fig. 8.6 RELATIONSHIP BETWEEN INSTALLED REFRIGERATION LOAD & HEVAC SYSTEM COST

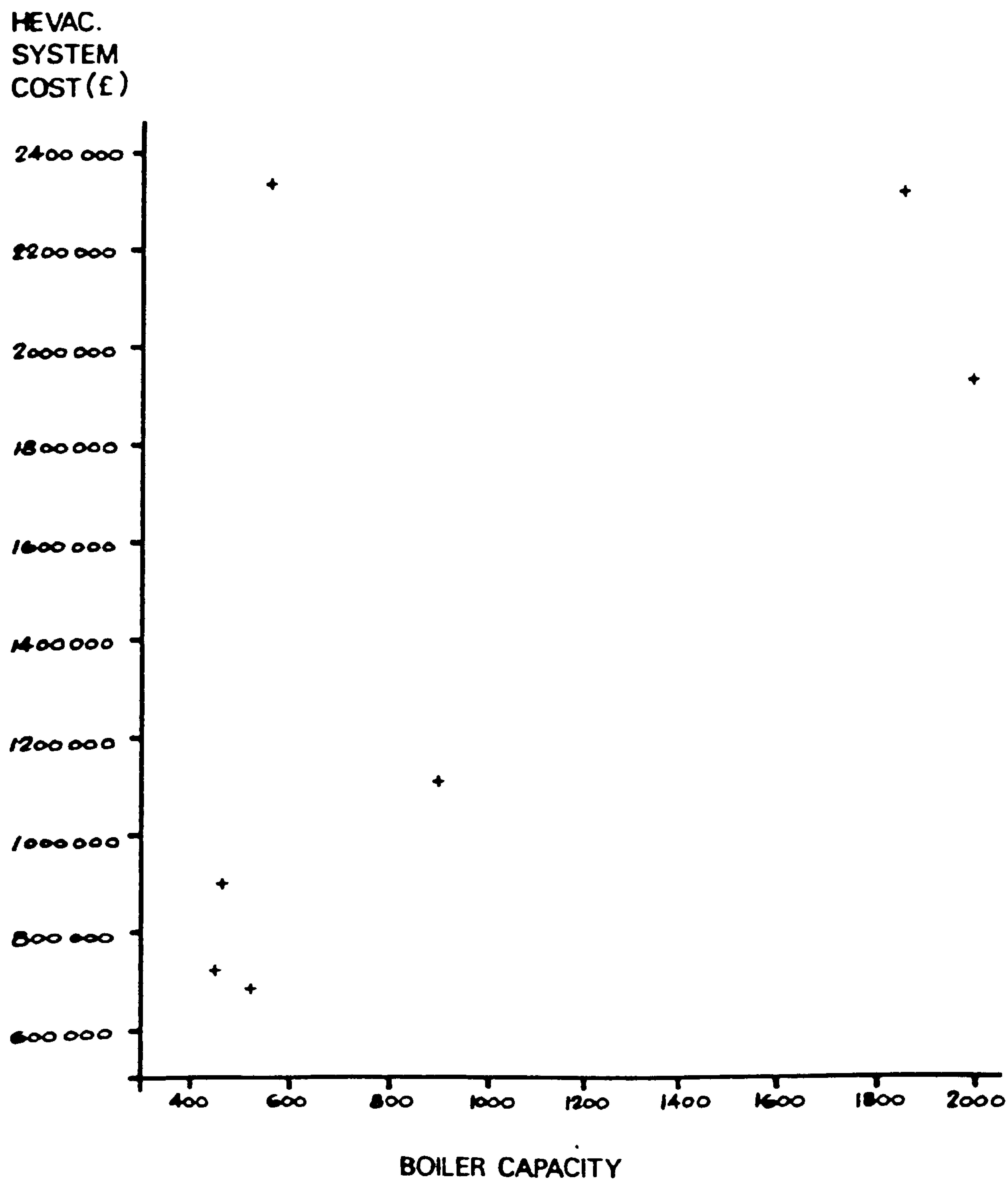


Fig 8.7 RELATIONSHIP BETWEEN INSTALLED BOILER CAPACITY & HEVAC. SYSTEM COST

analysis. Hence the sample was reduced to seven from nine. The results are presented in figures 8.6 and 8.7.

Clearly there is not enough data to indicate whether or not the relationship is a stepwise one as proposed in chapter 7. There does appear to be sufficient evidence though of linearity not to render the assumption invalid. An analysis produced a correlation co-efficient of 0.8 for cooling load to cost, and 0.62 for heating load to system cost. The correlation co-efficient for GFA to system cost was 0.84. A multiple regression analysis produced a multiple correlation co-efficient* of 0.92.

## 8.5 Interpretation of Output

### 8.5.1 Introduction.

In the theoretical analysis of chapter 4 two major areas were identified for investigation in the interpretation of output. These were the interpretation of the model output with respect to firstly the age of the model and secondly the uncertainty in the model data and output.

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* The extent of the relationship between the independent variables as a group and the dependent variable, (heating load, refrigeration load, gross floor area, VS System cost).

8.5.1.1 Age of Model.

As models age there are three ways in which they may be updated. They may be entirely reformulated with new relationships and new data. The model may be left as it stands but the data files updated. The model and data may both be left as they are and the outut may be adjusted by the application of an index. The latter two are the more common in practice and they will be compared quantitatively below.

8.5.1.2 The Measurement of Uncertainty.

The nature of the imprecisions in building cost data was described in chapter 4 section 4.2. We are concerned here with the evaluation of the uncertainty in model outputs and thus the risk involved in any decision based on such an output. The subject of risk analysis in building design is vast and complex and can only be touched on briefly here. [3,4,5,6] The concern of this section is to examine the methods of evaluating uncertainty and to present an aid for such evaluations which was developed during this research.

Two theoretical approaches are relevant here, it is suggested, possibility (fuzzy set) theory and probability theory. It was shown in chapter 4 section 4.2 that possibilistic and probabilistic imprecision appear to be parallel phenomena. The fuzzy-set approach has many attractions, one of which is the 'membership function'. The membership function is a numerical representation of the degree to which an element belongs to a set. The function takes values between 0 and 1, higher values indicating increasing "belongingness" to the set. However, the computational techniques of the theory are not well developed and the success of applications has not been fully established.[7] The theory has potential applications in architectural design one of which has been shown recently, but the applications are still highly constrained and simplistic and therefore of little use in this work.[8]

A powerful technique for the probabilistic handling of imprecision which currently has no analog in fuzzy-set theory is the sampling technique of Monte-Carlo simulation. This was used as a basis for the program MODELLE which was written to facilitate the probabilistic evaluation of cost models. Any inductive model of up to twenty terms may be stored and simulated any number of times. Thus the function could represent the entire cost of the building where the estimator could carry out a risk analysis of his proposed tender. Alternatively a function could represent just one item of work, for example a suspended slab, where the uncertainty surrounding the various plant, labour and material items may simulated and the additive effect computed. Currently the program makes use of any combination of triangular and uniform distributions defined by the user. The output of the evaluation is in the form of graphs showing the frequency of occurences of values and the median and quartiles and also a cumulative probability histogram from which the risk attaching to particular values may be identified.

### 8.5.2 Model 1.

(i) Age of Model.

It was shown earlier that in normal use the data for the superficial area model is updated by means of a price index. The nature of the model makes it impossible to assess the influence or the efficacy of such indices. The evaluation of this criterion is easier on model 2 and the results of such a study are presented later.

(ii) Uncertainty.

To carry out this evaluation a set of eight cost analyses for London office buildings was used. The data is summarised in table 8.2. The source of the sample a firm of London quantity surveyors used their own set of nine elements. The analyses showed the cost of each element per square foot of building area. The analyses are in imperial units to meet the needs of the London property market. Table 8.2 shows for each of the nine elements the highest vlaue found in the sample, the lowest value and the average. The buildings are broadly comparable.

A user producing a cost plan by means of the superficial area model could quite reasonably choose the "overage" element rates. Let us assume a building of 20,000 square feet on this basis the model produces a building cost of £1.53 million. If on the other hand in a Bayesian approach, we make use of all of the information we may evaluate, the risk attached to the figure of £1.53 million.

Using triangular distributions defined by the lowest average and highest costs for each element, the cost of erecting the 20,000 square foot building was simulated one hundred times in MODELLE. The results are presented in figures 8.8 and 8.9. From figure 8.8 it can be seen that the median figure is just under £1.5m. Figure 8.9 shows there is a 60% chance that the figure of £1.53m will be exceeded.

### 8.5.3 Model 2.

(i) Age of the Model.

The following experiment compares two methods of updating the model. Updating by index and updating by inserting new data. The model was set up to run with a data file

| ELEMENT NUMBER | LOWEST | AVERAGE | HIGHEST |
|---|---|---|---|
| 1 | 4·29 | 5·36 | 7·47 |
| 2 | 4·36 | 8·65 | 10·97 |
| 3 | 0·32 | 1·02 | 2·66 |
| 4 | 7·23 | 13·46 | 22·57 |
| 5 | 0·47 | 1·39 | 4·03 |
| 6 | 0·47 | 1·36 | 4·03 |
| 7 | 5·85 | 7·33 | 9·52 |
| 8 | 19·67 | 29·02 | 38·29 |
| 9 | 4·09 | 9·15 | 12·60 |

COST PER SQ.FT. OF G.F.A.

Table 8.2 DATA FOR EVALUATION OF UNCERTAINTY

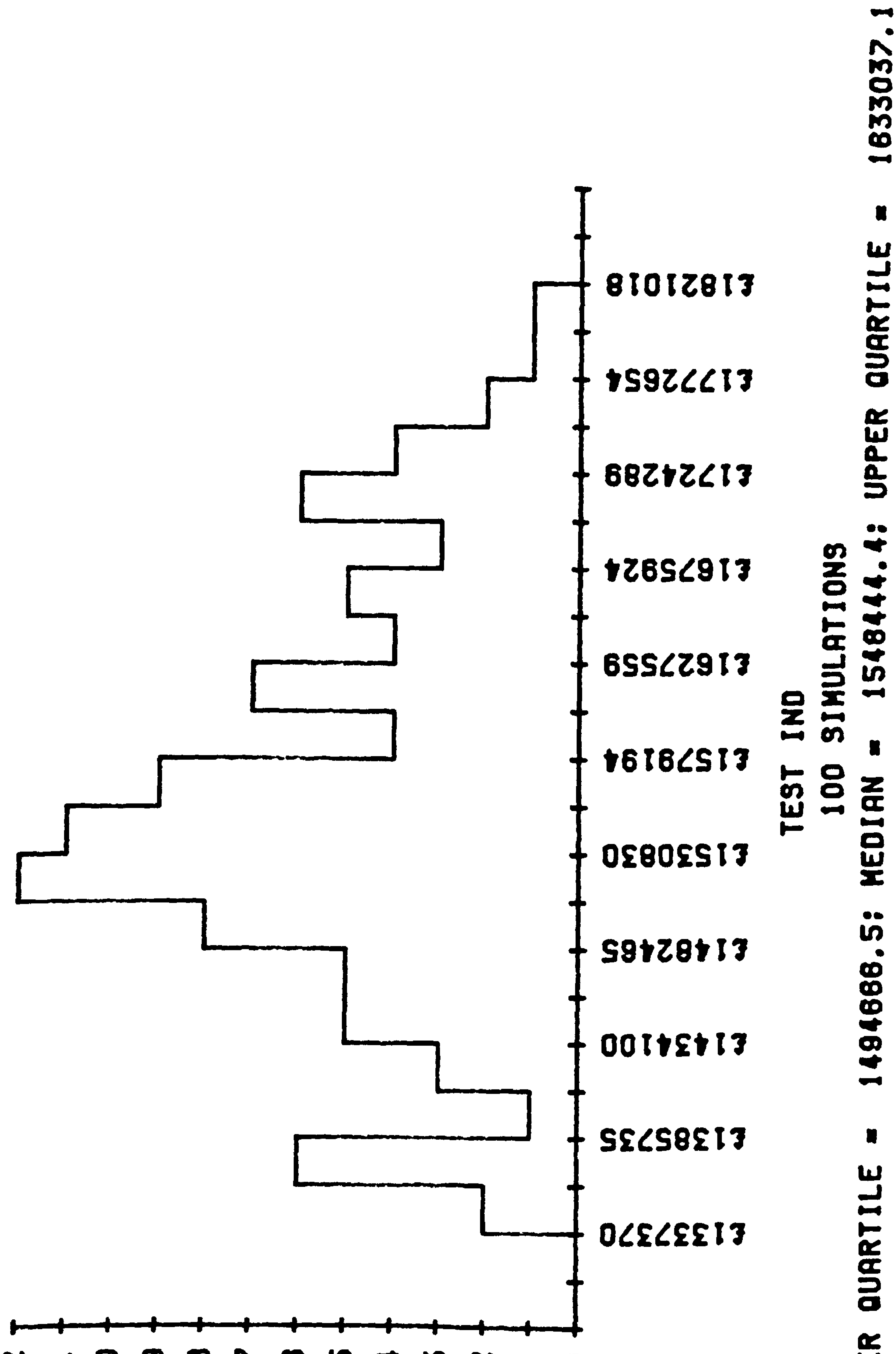


Fig. 8.8 MODELLE RESULTS

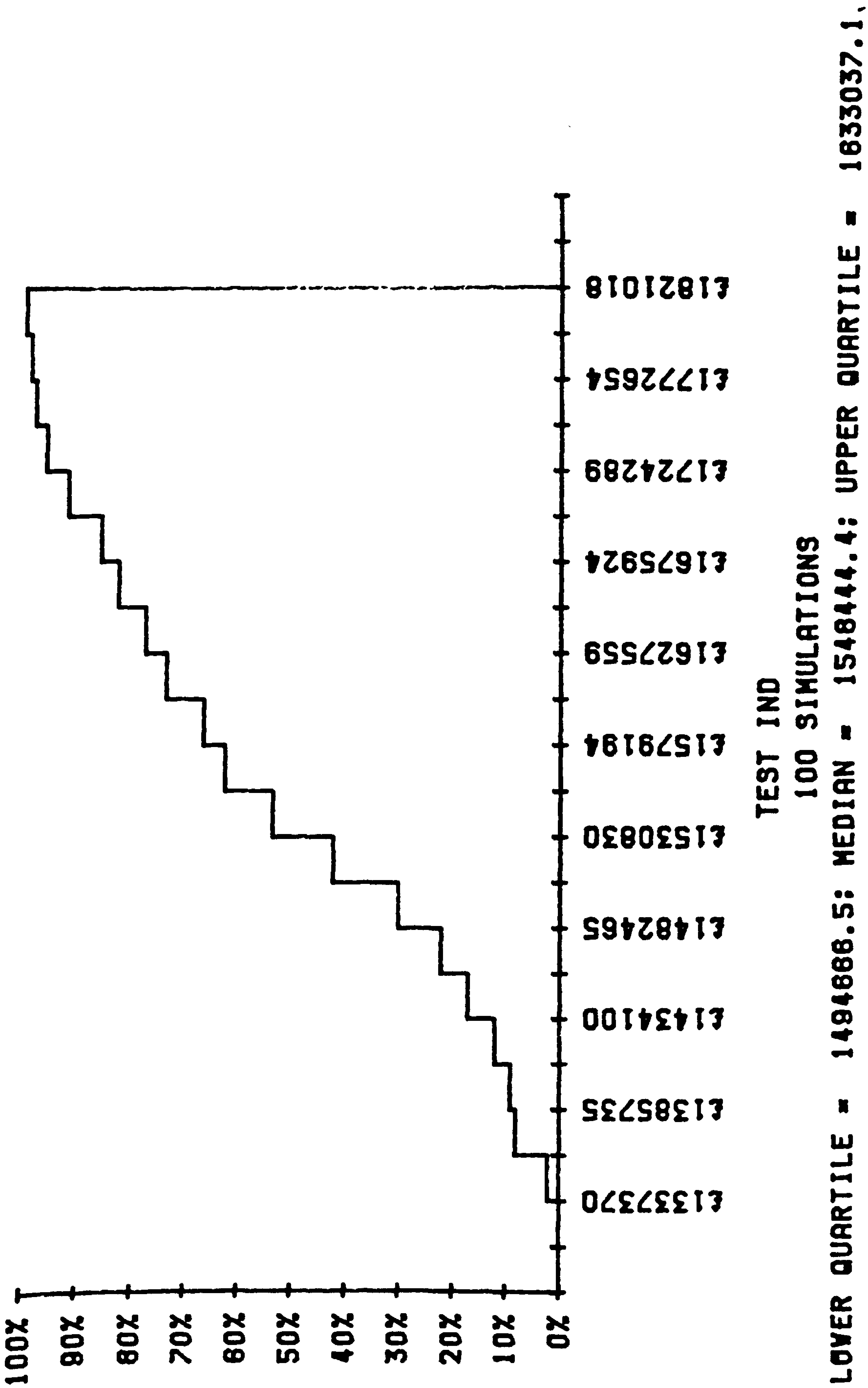


Fig. 8.9 MODELLE RESULTS

containing old data from a building price book current in 1975. The results of this run were then updated to 1983 levels by means of a popular building cost index. The index used was the General Building Cost (excluding mechanical and electrical work) Index No. 4, published quarterly by the BCIS. The model was then run again for the same building (the details of the building are not relevant to this discussion), but using data current at the first quarter 1983. Figure 8.10 presents a graph of the results.

From the graph it is clear that in the intervening eight years the index has become out of step with current data. In fact by updating via the index the old model output using 1975 data, the results are just under 30% higher than by using a new set of data. This is undoubtedly a major discrepancy.

However, the use of such an overall index obscures much of the minutiae of movements within sectors of the industry. There is a relatively wide variation in the rate at which building costs grow. Naturally this reflects short and long term changes in commodity prices and supplies of trained skilled operatives, in relation to the economy generally. This has important consequences for highly specialised inductive models such as model 1 and model 2 here. Figure 8. 11 shows a selection of four NEDO work sections compared with a general building cost index. All

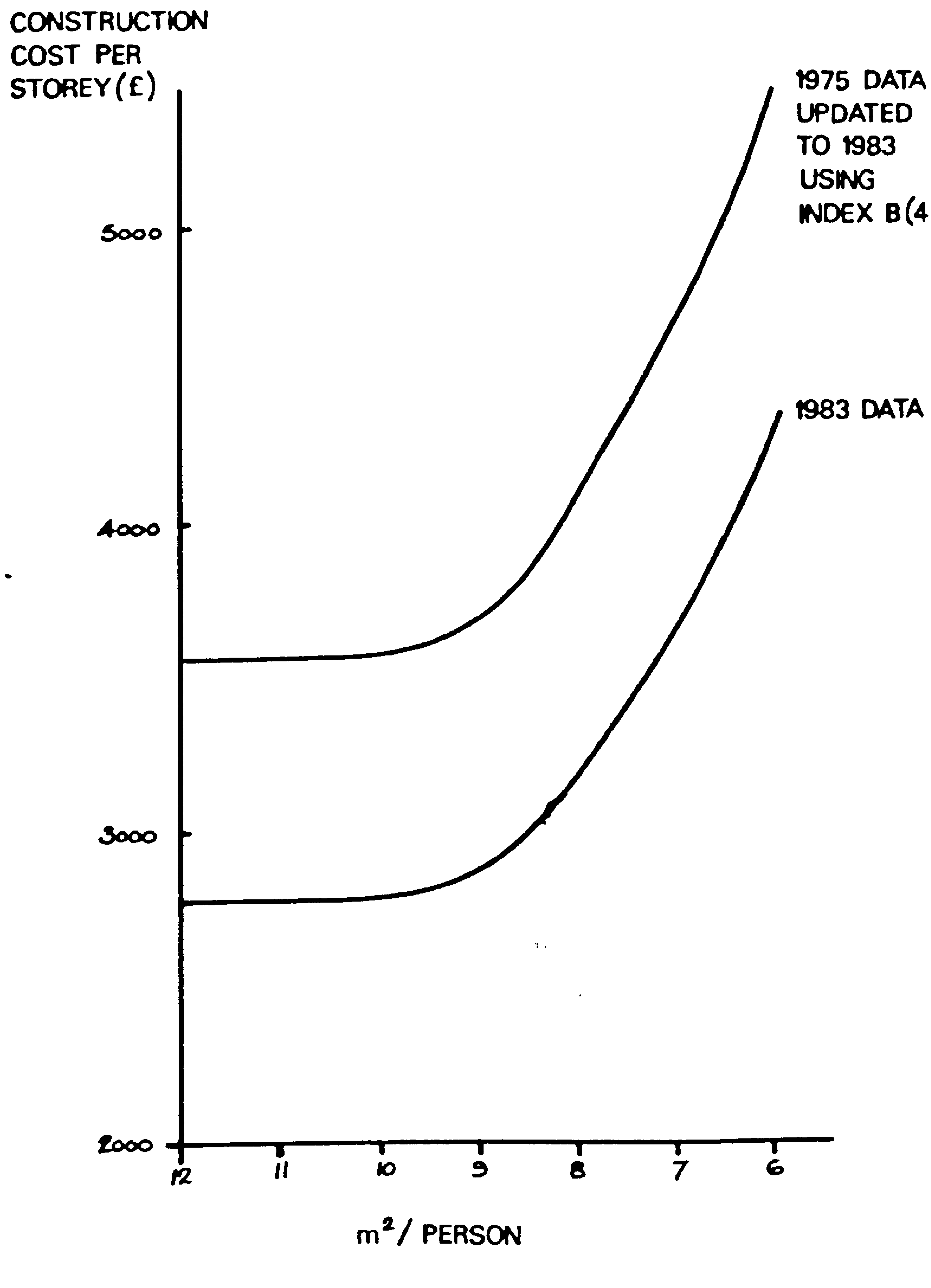


Fig. 8.10 INACCURACY OF UPDATING BY INDEX

indices have been transformed to box 100 at June 1976. An interesting comparison may be made between concrete work and steel work. From a common base of 100 at June 1976, in June 1983 concrete work stood at 240 and steel work at 184.

(ii) Uncertainty.

The evaluation of uncertainty in this context requires some statistical description of the variability of the input data. This was available in the data for model 1, but as indicated in table 8.1 at the outset, such information is not presented with price-book data such as is used in model 2.

8.5.4 Model 3.

Model 3 was reformulated without a formal data structure as discussed in section 8.3.4, therefore its output does not lend itself to the evaluations which were possible on models 1 and 2 above.

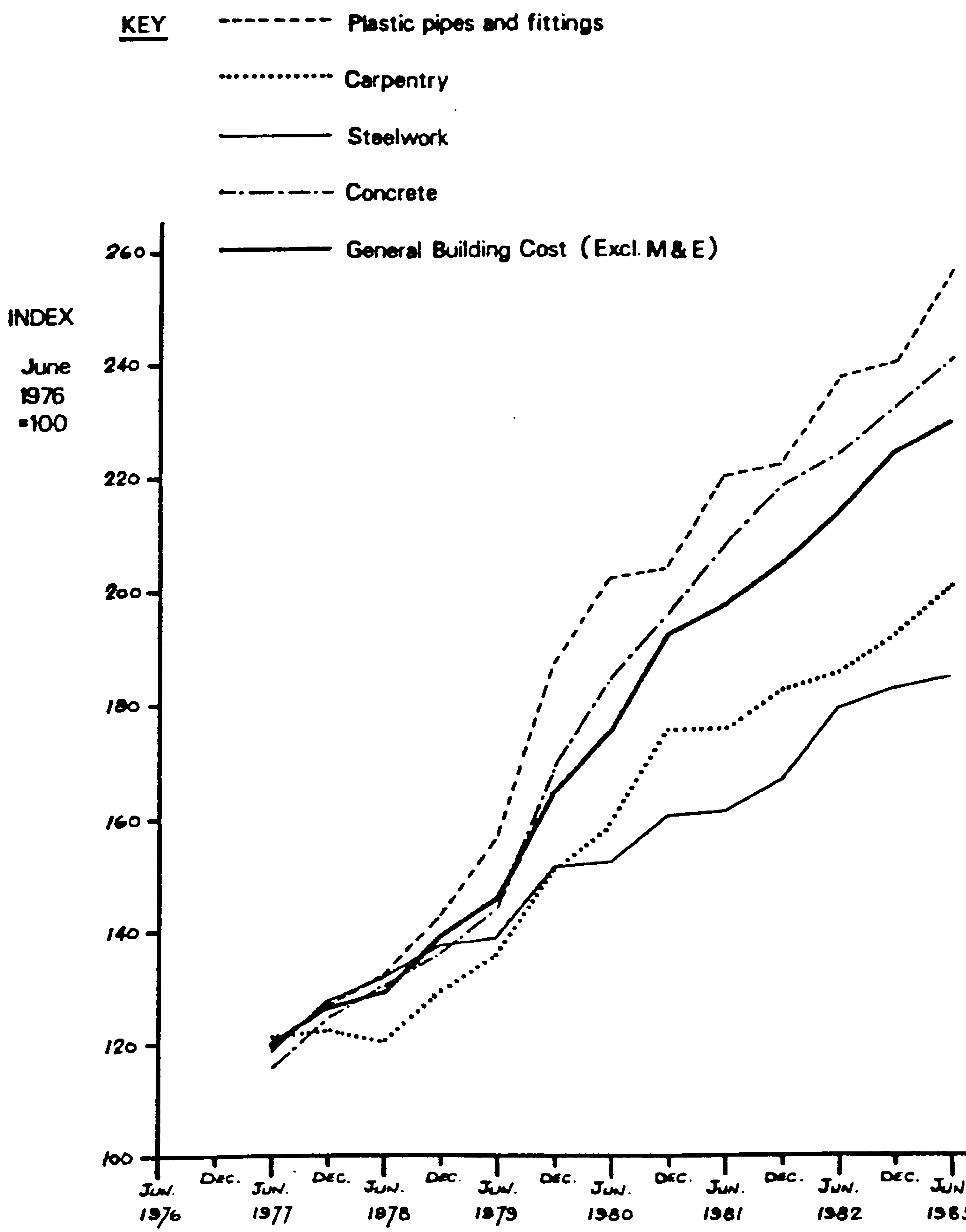


Fig 8.11 DIFFERENTIAL MOVEMENT OF INDICES

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# CHAPTER 9

# CONCLUSIONS AND RECOMMENDATIONS FOR FURTHER WORK

## 9.1 Introduction

## 9.2 Conclusions

### 9.2.1 Data

### 9.2.2 Data/Model Interface

### 9.2.3 Model Technique

### 9.2.4 Interpretation of Output

### 9.2.5 Relevance of the Criteria

### 9.2.6 Some general conclusions

## 9.3 Limitations of this Research

## 9.4 Recommendations for Further Work

## Conclusions and Recommendations for Further Work

> "The endless cycle of idea and action,
> Endless invention endless experiment,
> Brings knowledge of motion but not of stillness;
> Knowledge of speech but not of silence;
> Knowledge of words and ignorance of the Word
> All our knowledge brings us nearer to our ignorance."
>
> T. S. Elliot,
> Choruses from "The Rock"[1]

### 9.1 INTRODUCTION

This work has attempted to be experimental as far as possible. One of the points arising from the quotation which begins these conclusions is that it is not always possible or indeed appropriate to adopt such an approach. It is held here that in the search for solutions to difficult problems, a wide range of approaches is appropriate. These will include the 'scientific', where one is dealing with measurable phenomena. More verbose methods are appropriate where the best that can be done is to proceed with a rational method of enquiry, exerting every possible effort to avoid error, which is more or less how the scientific method has been defined by Medawar.[2] Finally as anyone who works in CAD will know, the use of imaginative faculties is often paramount in problem solving. At the same time however, one has had to guard against shallow eclecticism.

How far have the objectives of the work been realised? It was proposed in chapter 1 that although the use of models in building economics has increased, little attention had been devoted to the evaluation of the strengths and weaknesses of the modelling techniques currently being employed. Accordingly the research was addressed to the problem of obtaining some quantitative results based on criteria derived from a theoretical analysis and a critical study of existing work.

Hence, the nature of the building design process was examined (chapter 2) and the literature of cost modelling in building design was reviewed. Chapter 4 presented a theoretical analysis of the features of models in this context and a set of performance criteria were identified. Chapters 5, 6 and 7 presented three models developed during the research and chapter 8 presented, largely without comment, the results of assessments of the models with respect to each of the criteria. The conclusions from these results and from the research generally are presented below. Each criterion is considered separately then they are discussed as a group, this is followed by some more general conclusions. The limitations of the research and recommendations for further work are also discussed.

## 9.2 CONCLUSIONS

### 9.2.1 Data.

Throughout the research the protean nature of the problems raised by data become more and more obvious. Four major issues emerged which have a bearing on how data is collected and used in models in building economics. It is important to ascertain the degree of aggregation of building cost data. It was shown that data which is highly aggregated, such as rates from bills of quantities and element costs per unit floor area taken from cost analyses, has also been subjected to transformations, the nature of which is known while the magnitude of the effect is not.

The central paradigm of traditional 'cost planning' was found to be questionable on the basis that cost planning may be a self-fulfilling prophecy. That the data used in building economics is not compatible with the way costs are generated (i.e. by the use of resources) was not unknown before this work was undertaken. Similarly for the fact that there is a wide variability of values among data sources. However this work was able to obtain some quantitative results of the effect of this variability on models, something which had not been done previously in this context.

Model 1 was found to be sensitive to the data source used.

The nature of the model defied any attempt at quantifying the degree of sensitivity. Model 2 was used in a pair of experiments which demonstrated its sensitivity to data. The output was affected by a factor of around 7% when a different data source was used. When a Bayesian approach was taken, by describing to the model the full extent of the variability of the data, the results became very erratic indeed. Model 3 had to be reformulated because of the absence of appropriate data.

Turning from the particular models of this work to the general case it is concluded that models are sensitive to data and that this sensitivity can in certain cases by quantified. It should also be pointed out, (if the reader will pardon a little didacticism) that any model user should where possible familiarise himself with the sensitivity of the model to its data and thus also chose the data with an amount of circumspection.

### 9.2.2 Data/Model Interface.

The relationship between data and model is a very complex one. It is important because it is often this relationship which dictates whether or not it is possible to refine the output of a model and increase its accuracy without having to start afresh and build a new model. The state of the relationship indicates whether one should concentrate on improving the model or, a relatively more difficult problem, improving the data used.

Model 1 was found to be well matched with its data and it was concluded that little improvement could be made in the output. For example, if the data was improved by finding better data the weaknesses of the technique would become more apparent and vice versa.

Model 2 was not well matched with its data. The potential of much more detailed data could have been exploited fully by the model were such data available. While the model produced a very detailed output of the design solution with the capability of breaking it down into resource units, materials and labour, the only data available was aggregated into 'rates for measured work'. Also there was no accompanying statistical description of the rates so that it was not possible to evaluate the uncertainty by producing probabilistic output. This was the fault of a weakness in the existing data, not in the model itself.

Similar problems were found in model 3. The model technique used outstripped the available data such that the full potential of the model was not realised.

A general conclusion may be drawn from the evaluation of this criterion with respect to the three models. The new generations of sophisticated simulation or inductive models which are computer based, highly detailed and dynamic, are exposing weaknesses and inadequacies in the economic data which is available for use in such models. In particular, these new models enable the designer to go into more detail at an earlier stage in the design process, however, it has been shown here that equivalently detailed building cost/price data does not exist at this time in the process. One reason for this is of course that the procedures and documentation we use today in the industry have evolved over the years to meet the requirements of the older, less powerful manual modelling methods. Hence it would seem reasonable to suggest that the sometimes unfulfilled potential of these mdelling techniques could be used as the driving force to push the industry into giving careful consideration to the type of economic data which should be recorded and promulgated. There would appear to be a valid analogy with how, in the computer industry, the hardware developed in the 1970s at a much quicker rate than software.

### 9.2.3 Model Techniques.

Two dominant types of model technique were distinguished, deductive techniques and inductive or simulation. Deductive models are statistically derived often using some form of correlation or regression analysis. Inductive models simulate the design process by building up the solution based on the designer's decisions and often producing as output the resource requirements of the solution.

Model 1 was found to rely on making comparisons with existing buildings. The building industry has, in economic terms, many unique features which were indicated as early as chapter 1. These features render comparisons between buildings very difficult. The model also assumes implicitly that the relationship between floor area and cost of building is linear. The model contains three simple arithmetic adjustments, one of which, the adjustment for quality,, is highly subjective. This subjectivity is usually characterised as 'professional judgement', but the fact is that there is no consistent scale of measurement and the accuracy of the adjustment is therefore non-quantifiable.

Model 2 is one of the current generation of highly detailed inductive models specifically designed to be computer-based. As has been mentioned earlier, there is no theoretical limit to the number of variables which may be considered. There are limitations to this type of model although they are usually situation specific. For example model 2 at present is configured for only one construction type. Model 3 uses a similar technique although in a different application and contains a number of technical assumptions and default values. A more interesting limitation though is the problem of finding appropriate cost data for models of this type. Model 3 was reformulated using a linear approximation of what was perceived theoretically as a stepwise cost function. When compared with an admittedly small sample of data obtained later, the assumption was found to have been reasonable. The real problem is not fundamental - one can only assume that as time passes the quality of data will be improved to make full use of the model technique.

Deductive techniques have relatively more limitations. The rely on samples of historical data, unlike the more dynamic inductive techniques it is not possible to generate original solutions. Discrete and stepwise functions cannot be dealt with accurately. Least squares approximations tend to give a disproportionately large effect to wild data.

### 9.2.4 Interpretation of Output.

The two central areas investigated were the interpretation of model output with respect to the age of the model and the uncertainty of the results. It was demonstrated quantitatively that indices do get out of date. An experiment which was run on model 2 showed that after a period of eight years the index had become out of step with the current data by a factor of 30% of the model output.

It was shown the general indices of cost escalation obscure the details of movement within particular types of building work.

A tool was developed which made possible the probabilistic analysis of inductive cost models. This form of analysis was applied to model 1 producing the result that a typical output of the model had a 60% chance of being exceeded. There are some limitations to the mathematical simulation technique employed, these are discussed in a separate section below.

On a more general note,, indices are widely used in building economics, the results presented earlier lend support to the argument that it is far better, where possible, to use up to date information. Secondly it is concluded that it is possible to produce a numeric evaluation of the uncertainty in model outputs and, that based on the analysis in chapter 4, the importance of uncertainty is such that every attempt should be made to incorporate it into models of any nature.

### 9.2.5 Relevance of the Criteria.

How have the criteria themselves fared in the light of the results obtained? In an ideal world there would be an agreed scale of measurement for every criterion, this is not the case of course and who would want it to be? The criteria of performance identified here have been difficult to apply consistent measures to, however, they do seem to cover the spectrum of potential problems that may arise in applying economic models in building design. The field is young and, as far as the author is aware, this work has been a first attempt at assessing model performance in this way. Hence some researchers may disagree with the criteria chosen, that in itself would be beneficial as one route to new knowledge is of course through the dialectic.

Therefore we may conclude that if one can accept the fact that not all things can be 'measured' on some agreed scale, then the criteria chosen are sufficient for their purpose. If not, then one may feel the need to change them.

### 9.2.6 Some General Conclusions.

While the details of the criteria chosen may be questioned, it is suggested that the rigorous questioning and even sceptical approach taken in this work has been useful. Furthermore, it is likely to become more useful as the climate of CAD changes. More and more models in CAD are being presented by systems purveyors as the market for CAD software in the building industry and education is being exploited. The user or potential buyer is often left with a bewildering choice as it is frequently difficult to compare models with each other. In areas such as that, a set of criteria such as outlined here would be of assistance in forming an organised body of thought as to the strengths and weaknesses of particular models.

Finally, it is hoped that this work has helped to correct a misconception which seems common in quantity surveying circles at least, and that is that "cost model" is synonomous with regression theory and least squares fitted curves. This is of course not the case at all and such models form a small and particularly weak subset of models.

## 9.3 LIMITATIONS OF THE RESEARCH

At a general level a more judicious choice of models might have been made with the benefit of hindsight. In particular, the two inductive models, model 2 and model 3, were for highly detailed and specialised application. Such models were, in the event, highly satisfying to design and build, but their specialised nature rendered them less than perfect as vehicles for experiment in this context, insofar as it was sometimes difficult to generalise the results of perturbations or experiments.

The technique of mathematical simulation used to produce the probabilistic analysis of the output of model 1 has some limtiations also, Monte-Carlo simulation assumes that the events simulated are independent. This is not the case in building economics. For example the model simulated in chapter 8 was broken down into nine elements. If one element in the building costs more than was expected, say because of bad weather or low productivity, there is an increased likelihood that other elements will be affected similarly. Although much experimental work was undertaken to find a way of considering events which are not independent a satisfactory approach was not identified.

## 9.4 RECOMMENDATIONS FOR FURTHER WORK

Typically, this research has raised more questions than answers. From the outset it has been clear that the true nature of the effect of CAD on design solutions whether from design models or economic models has not yet been investigated. Eastman found that the type of solution produced to design problems is to some extent dependent on the means used to represent the problem.[3] CAD was not among the factors tested, it would seem important to do so.

A startling number of issues raised in the research were traced back to problems of the quality and availability of data reflecting resource costs in the building industry. The experimental approach to the evaluation of model performance seems useful but the older models (like the superficial area model) are difficult to assess in this way, they contain many subjective and hidden factors. We need to find ways of evaluating their usefulness.

There seems to be no excuse for not incorporating probabilistic evaluations in all cost models, the techniques do exist and can be successfully applied. New techniques are emerging and these should be tested. The data problem is relevant again here as there is a dearth of information regarding the actual distribution shape of various types of data in particular the shapes for productivity rates and materials usage.

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# APPENDIX 1

## BUILDING COST DATA

A1. Sources of Data.

A2. Analysis of Data.

## A1. Sources of Data

This discussion is concerned only with data sources relevant to capital cost estimation. A survey carried out in 1980 gave support to the view commonly held in the profession, that quantity surveyors have a clear preference for using in-house data.[1] Further, in a particular office, individuals have a strong preference for using data generated from projects with which they have been personally involved. Only when this source fails to provide the necessary data does the surveyor begin to consider information generated in other parts of the organisation, and published information is the last resort. This is not a startling discovery, it shows that quantity surveyors are using data with which they are most familiar, so that they know exactly what the figures represent and can take this into account when adjusting them. In other words, this is an implicit recognition of the nature of the data as discussed above. This in-house data normally relates cost to units of finished work, this is also the case with most of the data sources discussed below. The significance of this will be discussed below in the section on the quality of data. This in-house historic data is stored in either elemental or work-section format. Most offices will normally also have a file of current resource costs, i.e. materials, labour, plant, etc. In-house cost information is generally stored as:

(i) Priced bills of quantities, these are usually in work section format according to the rules of the Standard Method of Measurement. (An example of priced work section unit rates is shown in table 4.2.)

(ii) Cost analyses, normally in some type of elemental format, i.e. SfB or BCIS, or an elemental system especially tailored to the needs of the particular firm. (See Appendix II for example.)

## Information Published Annually

These are published in December or January and are, therefore, regarded as 'coarse' information as they can take into account only such information regarding wages and material increases as are known at October or November of the previous year.

"Laxton's Building Price Book"[2] is the longest running of this type of reference work, now in its 152nd edition. The information is intended to apply to a job of value approximately £300,000 in the London area. It contains the market prices for materials, wages and dayworks rates and professional fees. It should be pointed out, however, that in the author's own experience, if information regarding a material price is required for a particular project by the consultant quantity surveyor, it is normal for the latter to ascertain the price directly from the supplier where the purchase would most likely be made for that particular project.

"Griffiths Building Price Book"[3] and "Spon's Architects and Builders Price Book"[4] contain broadly similar information to that described above. "Hutchins Priced Schedules"[5] carries the above information with the addition of the number of manhours it assumes for the build-up of each additional rate. This introduces the possibility of making adjustments to unit rates from the productivity levels expected on a particular project, if these are known with any degree of certainty. Whether it is possible to have this knowledge with an acceptable degree of uncertainty has been called into question with some justification.[6]

The remainder of the annually published information is broken into specialist areas. The publications are, "Spon's Mechanical and Electrical Services Price Book", "Spon's Landscape Price Book" and "The Schedule of Rates for Building Works", this latter is published in seven specialist sections.[7,8,9]

## Monthly Cost Information

Several periodicals publish regularly updated information and these are listed in references 10,11,12,13. The most comprehensive cost information service in this country is the Building Cost Information Service (BCIS).[14] The information here is not presented in the form of unit rates, but rather as cost analyses and cost studies of particular buildings with monthly briefings covering cost indices, and market trends. Table 4.2 shows the quantity of information contained in the monthly publications (BCIS by virtue of its format of cost analyses and indices does not lend itself to tabulation in this way).

| Publication | No. of Items |
|---|---|
| Cost Index | 322 |
| Cost File | 318 |
| Estimating Supplement | 318 |
| Q.S. Data File | 459 |

## A2. Quality of Data

It is useful to present the building cost in mathematical form to assist in (i) identifying the individual units of information which are needed and which must be appraised as to quality, (ii) comparing the nature of the components of each item of data with the way in which it is presented in the sources of data outlined above.

For a project containing n sub-tasks the total cost is

$$TC = \sum_{j=1}^{N} K(MC_j + LC_j + PC_j)$$

The cost of one sub-task j (one unit rate) may be expressed as:

$$C_j = K(MC_j + LC_j + PC_j)$$

or

$$C_j = K(MC_j + PC_j + W_j/P_j) \qquad \text{...[A.1]}$$

where

- TC = Total project cost (initial).
- K = Factor for overheads and profit.
- MC = Materials costs.
- LC = Labour costs.
- PC = Plant costs.
- W = All-in wage rate per hour of the gang required for the operation.
- P = The number of gang hours required to perform one unit of the operation.

It would be possible in theory for a firm to make a record, after the event, of the cost incurred under each term. (In fact there is a slim chance of achieving this ideal state due to imperfections in the system of recording and feedback of cost information from the site to the estimators.)

On the other hand, if the rate is being prepared for a mythical project in London (as is the case for most published cost data) or even for an actual project at some future date by a contractor, each term becomes subject to increased uncertainty as it becomes the most likely, predicted, cost for each term of a particular sub-task. Equation [A.1] can then be written as follows:

$$AC_j = K(AMC_j + APC_j + AW_j/AP_j) \qquad \text{...[A.2]}$$

where

A = Prefix signifying anticipated cost of each term.

However, this does not fully represent how the cost is incurred to the contractor. Much of modern building work is sub-contracted, particularly such tasks as demolition, structural frame, windows, mechanical and electrical services, partitions and suspended ceilings. In any given project the responsibility for analysis of the resources required in sub-contracted tasks is that of the sub-contractor. Therefore the contractor's view of the way costs are incurred may be expressed as:

$$AC = \sum_{j=1}^{N} K(AMC_j + APC_j + AW_j/AP_j) + \sum_{i=1}^{M} S_i \quad \ldots[A.3]$$

where

M is the number of sub-contracts
$S_i$ is the tender cost of the ith sub-contract
A prefix indicating that each term is an anticipated value.

In the situation of a contractor having only one current project, then the term K is relatively easy to calculate with a high degree of precision.

How are building costs generated? In economic terms costs are generated by the use of resources. The level of cost is directly proportional to the amount of resource usage. Equation [A.3] represents how the building estimator calculates the cost of the building before it is constructed, it represents the real-world practical measurement of cost. However, in economic terms this expression is highly simplified and ignores many real costs, this has been discussed in detail in Chapter 4, section 4.1.2. With this constraint in mind it will be useful to consider each term.

The overhead element of K should remain constant unless a major change is anticipated in the organisation of the firm, the profit element will be set for each tender according to the firm's reaction to current market conditions.

$AMC_j$, the cost of material is again relatively easy to calculate. In addition to measurement taken from the architects drawings, allowances have to be made for breakages, waste, theft, etc. Large items of plant such as cement silos and tower cranes are not usually costed in relation to each task performed, rather they incur cost in relation to the time they spend on the site. Even contractors with their own large plant "hire it out" to each project at its economic cost, which takes into account maintenance, depreciation and replacement. The cost of small plant items such as power saws and drills, nail guns, etc. is incurred in a more amorphous way over the entire project and is difficult to calculate accurately. Labour costs are incurred in direct proportion to the time taken to complete the tasks. $AW_i$ is relatively easy to calculate as it is subject to national wage agreements, local working rule agreements and government controlled increases. Of notorious difficulty is $AP_i$, the amount of time in man-hours taken to perform the various tasks. Identical tasks rarely occur in construction, even if they do there are also variable weather conditions and human idiosyncracies to be taken into account. Each sub-contractor has to go through the above process to produce his own tender figure $S_i$, which is given as a firm price to the main contractor.

APPENDIX 1

## REFERENCES


| | | |
|---|---|---|
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| 6. | Fine, B. | Seminar "Research In Cost Modelling and Management in Construction", Reading University, 13th July 1981. |
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| | | |
|---|---|---|
| 9. | H.M.S.O. | Schedules of Rates for Building Works. |
| 10. | Cost Index | Published in "Building Specification". |
| 11. | Cost File | Published in "Building". |
| 12. | Q.S. Datafile | Published in "Q.S. Weekly". |
| 13. | Estimating Supplement | Published in "Building Trades Journal". |
| 14. | Royal Institution of Chartered Surveyors | Building Cost Information Service (BCIS). |

## APPENDIX II

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BCIS Code: 8-4-8800

## DETAILED COST ANALYSIS

| | |
|---|---|
| Job title: [illegible] | Client: Milton Keynes Development Corporation |
| Location: Central Milton Keynes, Bucks. | Tender date: 1) 7th June 1982 2) Base month: May 1982 |

### INFORMATION ON TOTAL PROJECT

#### Project and contract information

Project details and site conditions: 4 storey reinforced concrete framed office block on piled foundations, clad externally with glazed aluminium frame curtain walling. The roofs generally are reinforced concrete construction covered with asphalt.
Circulation areas and lettable areas on 2nd, 3rd and 4th floors fully serviced and finished with the exception of floor finishes to lettable areas. Ground floor lettable area left as shell for fitting out under separate contract.
Access to the site is good.

Contract: JCT Standard Form of Contract, Local Authorities Edition with Quantities. Fluctuating price, selected tenders with fluctuations based on NEDO Formula. 6 tenders issued, 6 received, all national contractors. Second lowest tender approx. 2.35% above lowest. Contract period stipulated by client 13 months, offered by builder 18 months.

Market conditions:

Very keen tendering

**Contract particulars:**

Type of contract: JCT Standard Form of Contract, LA Edition with Quantities

Basis of tender:

| | | | |
|---|---|---|---|
| Bill of quantities | [X] | Open/Selected competition | [X] |
| | | Negotiated | [ ] |
| Bill of approx. quantities | [ ] | Serial | [ ] |
| Schedule of rates | [ ] | Continuation | [ ] |

Contract period stipulated by client: 16 months.
Contract period offered by builder: 18 months.
Number of tenders issued: 6
Number of tenders received: 6

| | | |
|---|---|---|
| Cost fluctuation | YES [X] | NO [ ] |
| | LABOUR [ ] | |
| | MATERIALS [ ] | |
| Adjustments based on formula | YES [X] | NO [ ] |
| Provisional sums | £ 142,000 | |
| Prime Cost sums | £ - | |
| Preliminaries | £ 229,635 | |
| Contingencies | £ 126,375* | |
| Contract sum | £ 3,924,484 | |

* Includes £30,000 for fitting out Ground floor shell Units.

**Competitive tender list**

| £ | N/L |
|---|---|
| 3,924,484 | N |
| 4,016,633 | N |
| 4,026,084 | N |
| 4,228,154 | N |
| 4,247,257 | N |
| 4,299,759 | N |

### ANALYSIS OF SINGLE BUILDING

#### Design / shape information

Accommodation and design features:

The building is rectangular in shape, 141.0 x 16.5 on plan x 15.82m high (from ground floor level to roof level). On the ground floor the building is recessed along one 141.0m front to produce a 4.6m wide covered walkway and is divided into 3 No. blocks by 2 No. 6.0m passageways between them. There are 2 No. plantrooms on the roof, each 30.0m x 7.5m on plan x approx. 4.0m high (from main roof level to parapet wall coping level).

**Areas:**

| | | |
|---|---|---|
| Basement floors | - | $m^2$ |
| Ground floor | 1506 | $m^2$ |
| Upper floors | 7294 | $m^2$ |
| Gross floor area | 8800 | $m^2$ |
| Usable area | 6966 | $m^2$ |
| Circulation area } | | $m^2$ |
| Ancillary area } | 1834 | $m^2$ |
| Internal division } | | $m^2$ |
| Gross floor area | 8800 | $m^2$ |
| Floor spaces not enclosed | - | $m^2$ |
| Roof area | 2287 | $m^2$ |

Functional unit: 6966 $m^2$ usable area

$\frac{\text{External wall area}}{\text{Gross floor area}} = \frac{5855\ m^2}{8800\ m^2} = 0.665$

Internal cube = 31680 $m^3$

**Storey heights:**

| | | |
|---|---|---|
| Average below ground floor | - | m |
| at ground floor | 3.60 | m |
| above ground floor | 3.60 | m |

**Design/Shape:**

Percentage of gross floor area:

| | | |
|---|---|---|
| (a) below ground floor | - | % |
| (b) Single-storey construction | 4.90 | % |
| (c) Two-storey construction | - | % |
| (d) 4 -storey construction | 95.10 | % |
| (e) -storey construction | | % |

#### Brief Cost Information

| | | |
|---|---|---|
| Contract sum | £ 3,924,484 | |
| Provisional sums | £ 142,000 | |
| Prime Cost sums | £ - | |
| Preliminaries | £ 229,635 | being 6.44 % } of remainder of contract sum. |
| Contingencies | £ 126,375 | being 3.54 % } |
| Contract sum less contingencies | £ 3,798,109 | |

Functional unit cost excluding external works ( Tender £512.02 per $m^2$ usable area ( Base date £551.86 per $m^2$ usable area (1st Qtr.1980 UK mean)

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## SUMMARY OF ELEMENT COSTS

Gross internal floor area: 8800 m²

Tender date: 1) 7th June 1982
2) Base month: May 1982

| Element | Preliminaries shown separately: Total cost of element £ | Preliminaries shown separately: Cost per $m^2$ gross floor area £ | Preliminaries shown separately: Element unit quantity | Preliminaries shown separately: Element unit rate £ | Preliminaries apportioned amongst elements: Total cost of element £ | Preliminaries apportioned amongst elements: Cost per $m^2$ gross floor area £ | Preliminaries apportioned amongst elements: Cost per $m^2$ gross floor area at 1st Qtr 1980 UK mean £ |
|---|---|---|---|---|---|---|---|
| 1. Substructure | 224,259 | 25.48 | 1506 m² | 148.91 | 238,690 | 27.12 | 29.23 |
| 2. Superstructure | | | | | | | |
| 2.A. Frame | 261,938 | 29.76 | - | - | 278,794 | 31.68 | |
| 2.B. Upper floors | 136,905 | 15.56 | 7294 m² | 18.77 | 145,715 | 16.56 | |
| 2.C. Roof | 130,856 | 14.87 | 2287 m² | 57.22 | 139,277 | 15.83 | |
| 2.D. Stairs | 35,059 | 3.98 | - | - | 37,315 | 4.24 | |
| 2.E. External walls } 2.F. Windows & external doors } | 1,439,248 | 163.55 | 5855 m² | 245.81 | 1,531,865 | 174.08 | |
| 2.G. Internal walls & partitions | 74,679 | 8.49 | 4129 m² | 18.09 | 79,485 | 9.03 | |
| 2.H. Internal doors | 45,242 | 5.14 | 183 No. | 247.22 | 48,153 | 5.47 | |
| Group element total | £2,123,927 | £241.35 | | | £2,260,604 | £256.89 | £276.88 |
| 3. Internal finishes | | | | | | | |
| 3.A. Wall finishes | 44,515 | 5.06 | 4197 m² | 10.61 | 47,380 | 5.38 | |
| 3.B. Floor finishes | 98,543 | 11.20 | 7155 m² | 13.77 | 104,884 | 11.92 | |
| 3.C. Ceiling finishes | 126,702 | 14.40 | 6840 m² | 18.52 | 134,855 | 15.32 | |
| Group element total | £ 269,760 | £ 30.66 | | | £ 287,119 | £ 32.62 | £ 35.16 |
| 4. Fittings and furnishings | £ 106,568 | £ 12.11 | | | £ 113,426 | £ 12.89 | £ 13.89 |
| 5. Services | | | | | | | |
| 5.A. Sanitary appliances } 5.B. Services equipment } | Included with | Elements 50 - 50 | | | | | |
| 5.C. Disposal installations | 7,019 | 0.80 | | | 7,471 | 0.86 | |
| 5.D. Water installations } 5.E. Heat source } 5.F. Space heating & air treatment } 5.G. Ventilating system } | 221,240 | 25.14 | | | 235,477 | 26.76 | |
| 5.H. Electrical installations | 241,630 | 27.46 | | | 257,179 | 29.22 | |
| 5.I. Gas installations | Included with | Elements 50 - 50 | | | | | |
| 5.J. Lift & conveyor installations | 93,882 | 10.67 | | | 99,923 | 11.35 | |
| 5.K. Protective installations | - | | | | - | - | |
| 5.L. Communication installations | 36,397 | 4.14 | | - | 38,739 | 4.40 | |
| 5.M. Special installations | 9,299 | 1.05 | | | 9,898 | 1.13 | |
| 5.N. Builder's work in connection with services | 17,137 | 1.95 | | | 18,240 | 2.07 | |
| 5.O. Builder's profit and attendance on services | - | | | | | | |
| Group element total | £ 626,604 | £ 71.21 | | | £ 666,927 | £ 75.79 | £ 81.69 |
| Sub-total excluding External works, Preliminaries and Contingencies | £3,351,118 | £380.81 | | | £3,566,766 | £405.31 | £436.85 |
| 6. External works | | | | | | | |
| 6.A. Site work | 126,651 | 14.39 | | | 134,801 | 15.32 | |
| 6.B. Drainage | 32,791 | 3.73 | | | 34,901 | 3.97 | |
| 6.C. External services | 52,216 | 5.93 | | | 55,576 | 6.31 | |
| 6.D. Minor building works | 5,698 | 0.65 | | | 6,065 | 0.69 | |
| Group element total | £ 217,356 | £ 24.70 | | | 231,343 | £ 26.29 | £ 28.34 |
| Preliminaries | £ 229,635 | £ 26.09 | | | - | - | - |
| TOTALS (less Contingencies) | £3,798,109 | £431.60 | | | £3,798,109 | £431.60 | £465.19 |

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## SPECIFICATION AND DESIGN NOTES

| | |
|---|---|
| 1. SUBSTRUCTURE | Excavation, driven piling, reinforced concrete pile caps, ground beams, foundations, ground floor slab + lift well pits + slabs. |
| 2. SUPERSTRUCTURE | |
| 2.A Frame | Reinforced concrete including columns and beams; steel frame to roof level plant room |
| 2.B Upper floors | Reinforced concrete including associated beams |
| 2.C Roof | Reinforced concrete roof structure including associated beams, parapet walls + plant bases. 20mm mastic asphalt, 50mm Roofmatic insulation, precast concrete paving. Trocal covering to plant room. Glynwed Timesaver cast iron pipes and fittings. |
| 2.D Stairs | 5 No. Reinforced concrete stairs including associated walls and landing. Terrazzo treads and risers; plaster walls and soffits. Painted mild steel balusters. |
| 2.E External walls<br>2.F Windows and external doors | Aluminium painted glazed curtain walling to all elevations |
| 2.G Internal walls and partitions | Reinforced concrete lift walls, 100, 140 + 200mm Thermalite block partitions generally 140mm Hemelite to stair walls, WC partitions. |
| 2.H Internal doors | Ply faced solid core flush doors (76 No.) fire resistant doors (110 No.) |
| 3. INTERNAL FINISHES | |
| 3.A Wall finishes | Plaster generally, ceramic tiles to WCs. Travertine finish to reception area. |
| 3.B Floor finishes | Granolithic to plant/service areas, terrazzo to WCs, reception and stairs area, vinyl sheet to tea and cleaners rooms; screed only to lettable areas (carpet in Direct Works) |
| 3.C Ceiling finishes | Plaster to tea and cleaners rooms and other small areas. Expamet and Treated Glacier suspended ceilings to main areas. |
| 4 FITTINGS AND FURNISHINGS | Vanitory units to toilets, kitchen units to tea rooms, mild steel matwell frames, and floor grilles, column cladding, security screens and ladders, mirrors. Provisional sum for other fittings. |
| 5. SERVICES | |
| 5.A Sanitary appliances<br>5.B Services equipment<br>5.C Disposal installations<br>5.D Water installations<br>5.E Heat source<br>5.F Space heating and air treatment<br>5.G Ventilating systems | Specialist installing mechanical services installation - hot and cold water services, low temperature hot water heating systems to upper 3 floors, all toilet areas and both main entrance lobbies (generated centrally in roof plant rooms). The ground floor, apart from above exceptions, will not be heated at this stage - varied services provided as necessary. External ventilation to toilets directed to roof extract units. Toilet lobbies have fresh air inlet ventilation directed from roof. External ventilation to kitchen on upper 3 floors directed to roof extract units. Gas supply to boilers (in roof plant room). Hose reels on each floor served from booster fire main. Sanitary fittings and disposal service. |
| 5.H Electrical installations | Specialist installing electrical services installation - incoming supplies, earthing, Landlord's power distribution, tenants' power distribution, tenants' lighting, underfloor trunking, landlord's lighting, external lighting, emergency lighting, fire alarms, telephone, television and lifts. |
| 5.R Special installations | Specialist installing maintenance cradle installation - cradle, track and supports, trolley, and all fixings. |
| 6. EXTERNAL WORKS | |
| 6.A Site works | Excavation and filling to paved areas, excavation of tree pits, topsoiling of landscaped areas and tree pits. Concrete beds, foundations and ground beams to kerbs and walls. Kerbs and cladding (granite and reconstituted granite) to dwarf walls. Mild steel tree pit retaining frames;concrete block and flag paving. |
| 6.B Drainage | 150mm clay drainpipes (227m) + 225mm clay drainpipes (178m). 50mm plastic tree pit drain pipes. (101m ), 100mm cast iron drainpipes (69m), 150mm cast iron drainpipes (68m). Concrete gullies (23 No.), precast concrete manholes (25 No.) and catchpits (2 No.). Ducts and pipes for service connections. |
| 6.C External services | Street lighting. |
| 6.D Minor building work | Porte cochere. |
| PRELIMINARIES | 6.44% of remainder of contract sum (excluding contingencies) |

**CREDITS:**

| | |
|---|---|
| CLIENT:<br>ARCHITECT:<br>QUANTITY SURVEYOR:<br>CONSULTING ENGINEERS: | Milton Keynes Development Corporation |
| GENERAL CONTRACTOR: | John Laing Construction Ltd. |

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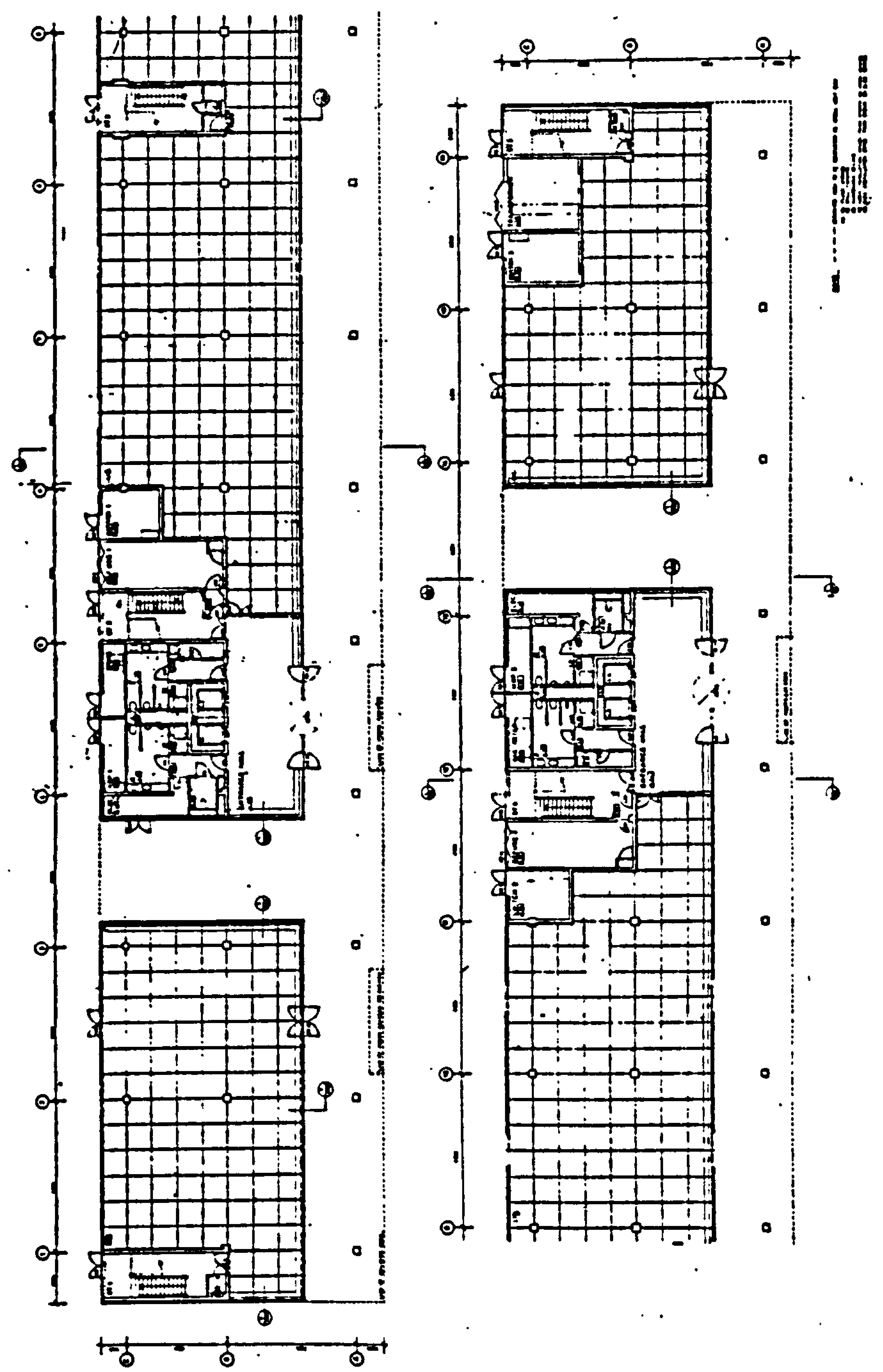

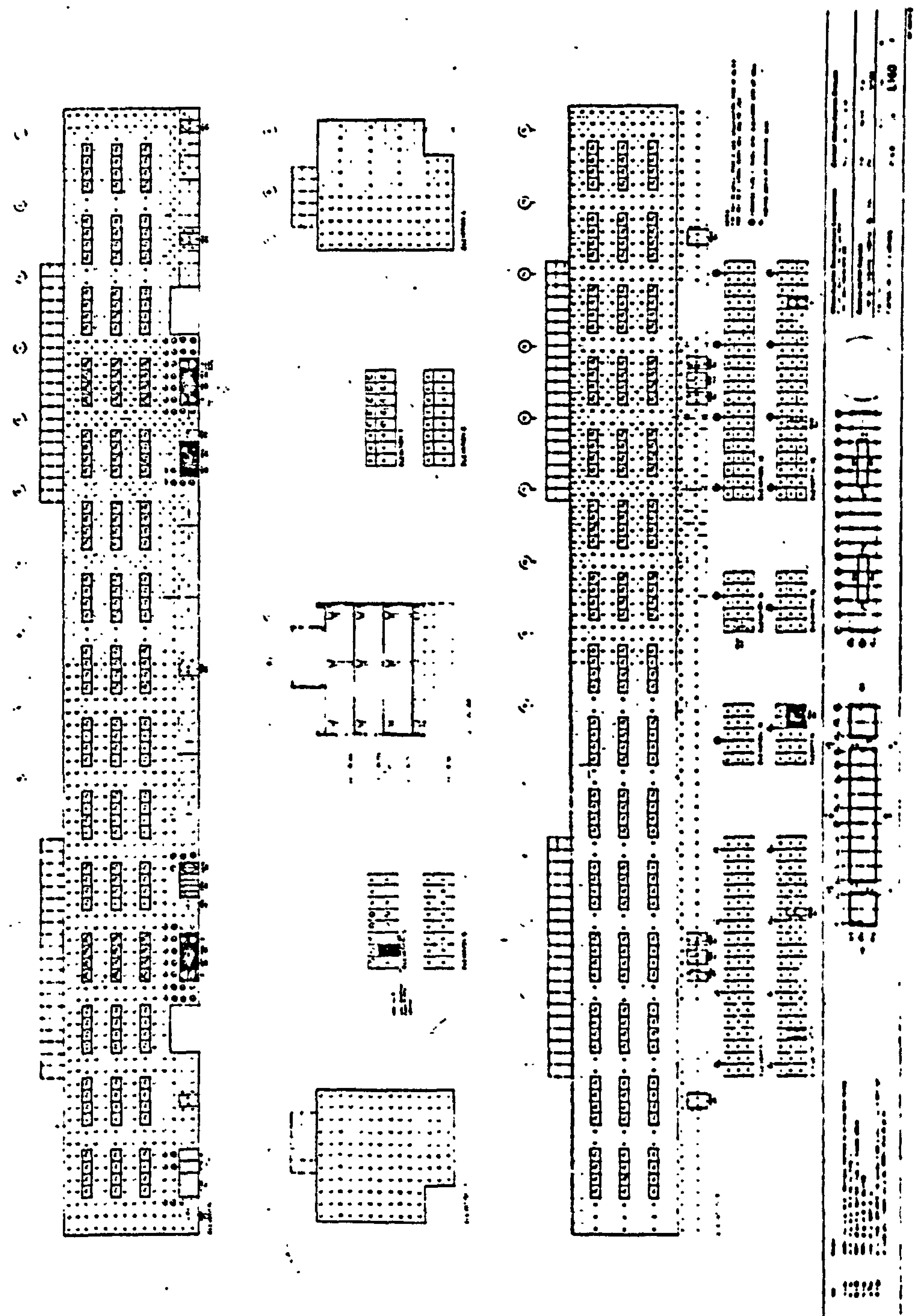

## APPENDIX III

```
5 REM PROGRAM NAME          ****************************
10 REM STAIRCASE COST MODEL ********************************
20 REM JOHN RAFTERY****************************** 1982*********
30 REM VERSION FOR TESTING ***********************************
100 DIM Y1$(50),Y2$(50),R(30),  ,R$(40),   W$(40),H9$(20),R1(30)
105 DIM R2(30)
110 G9 =1\S7$="NO"\REMNO MORE   UNLESS   ADJUSTED
165T9 = 0\R7 = R9 *L*B
200 !CHR$(12)
210 !TAB(25)," COST MODEL FOR STAIRCASE DESIGN "
220 !TAB(25)," === == === === ========= ====== "
260 !\!\!TAB(25),"DESCRIPTION OF MODEL "
270 !    TAB(25),"=========== == ===== "
275 !\!\!
280 !"THIS MODEL RELATES THE D   PARAMETERS OF THE STAIRCASE TO ITS TOTAL"
290 !"DISCOUNTED LIFE COST,ASSESSING THE CONSEQUENCES OF LOSS OR GAIN OF "
300 !"USABLE SPACE DUE TO THE STAIRCASE DESIGN"
305 !
380 !\!\!TAB(25),"ADJUST DATABASE
385 !\!TAB(2 ),"PROCEED TO MODEL                 "\INPUT M9
390 GOSUB 6500
394 IF M9 =1 THEN 4000 ELSE 396
395 !  PROJECT REF  \ INPUT Y2$
396 !\!\        STAIR REF    \INPUT Y  \  "ENTER TODAYS DATE"\INPUT D8$
400 !CHR$(12)\!\!TAB(25)          BUILD             VARIABLES"
410 !\!\! FLOOR TO FLOOR HEIGHT (IN METRES)  \INPUT S
420 !\!\!"OCCUPANT LOAD  (             )  TO METRES)"\INPUT O
430!\!\!"CATCHMENT AREA FOR THIS STAIRCASE(SQ METRES  \INPUT C
440 !CHR$(12)\!"CHOOSE TH       SIZE"
441 !\!
450 !"     SLOPE(DEGREES) MAX         INTREAD         R
```

```
[illegible]
540 INPUT M9\ [illegible]
550 IF M9=1 THEN 620
560 IF M9 =2 THEN 630
570 IF M9 =3 THEN 640
580 IF M9 =4 THEN 650
590 IF M9 =5 THEN 660
600 IF M9 =6 THEN 670
610 IF M9 =7 THEN 680
615 !CHR$(12)\ "YOU TYPED IN A [illegible] TRY AGAIN"\GOTO450
620 R=.1?5\T=.330\GOTO690
630 R=.178\T=.279\GOTO690
640 R=.180\T=.2??\GOTO 690
650 R=.180\T=.250\GOTO 690
660 R=.191\T=.254\GOTO 690
670 R=.190\T=.2?0\GOTO 690
680 !\!\!"ENTER RISER & TREAD(R,T) IN MM",\INPUT R,T
685 R=R/1000
686 T=T/1000
690 !CHR$(12)
700 !"CHOOSE METHOD OF CALCULATING STAIR WIDTH"
710 !\!\!"GLC REGS TABLE 2",TAB(30),"1"
715 !"GLC REGS TABLE 3",TAB(30),"2"
```

```
720 !"PAULS APPROACH",TAB(30),"3"
730 !"CP 3 APPROACH",TAB(30),"4"
735 INPUT M9\GOSUB 5100
740 IF M9 = 1 THEN 5200
745 IF M9 = 2 THEN 770
750 IF M9 = 3 THEN 840
755 IF M9 = 4 THEN 5600
760 GOTO 700
770  REM CLC WIDTH
780 N=C/D
790 W=((10*N)-100)/1000\S6 [illegible] MIN TWO [illegible] [illegible]IRED
800 IF W(1.1 THEN 820 ELSE 825
820 W =1.1\GOTO900
825 IF W )1.83 THEN 826 ELSE900
826 !CHR$(12)\!"MORE THAN TWO STAIRCASES REQ[illegible]"
827 !\!"MODEL NOT READY FOR THIS SITUATION YET "
828 GOTO1210
840 REM PAULS MODELLE
850 N=C/D\S6 = 2 \REM MIN TW[illegible] [illegible] NEEDED
860 W=((6.8*N)+300)/1000
870 IF W (1.4 THEN 890
880 GOTO900
890 W=1.4
900REM CALC STAIRWELL WIDTH
910 B=2*W+.100
920 !CHR$(12)\!"LANDING WIDTH IS ",%5F3,B
925 !"LANDING LENGTH IS ",%5F3,W
930 !\!"THE MODEL WILL NOW ADD AN INCREMENT FOR ACCESS"
935 !"THE ADDITIONAL AREA FOR ACCESS IS",%5F[illegible] [illegible] %5F3,W
940 !\!"IS THIS OK (Y/N)",\INPUT M9$\IF M9$ = "Y" THEN 950 ELSE 960
950 W1 = W + W\GOTO 980
960 !\!"ENTER INCREMENT FOR ACCESS",\INPUT I \W1 = W + I
980 !CHR$(12)\!"ADDITIONAL [illegible] [illegible] LOBBY",TAB(30),"1"
982 !"FIRE FIGHTING LOBBY",TAB(30),"2"\!"NEITHER OF THE ABOVE",TAB(30),"3"
983 !"IF USING G L C REGS TAB[illegible] SMOKE LOBB[illegible] [illegible]IRED"
984  INPUT M9\IF M9 = 1 THEN 4200
986 IF M9 = 2 THEN 4300 ELSE [illegible]
990 !"ENTER ADDITIONAL LENGT[illegible] [illegible])",\INPUT I\W1 = W+I
1000 REM CALC NR OF RISERS & [illegible] OF RISER
1010 R1 = S/R\IF R1 =INT(R1) THEN 1030
```

```
1020 R2 = INT(R1+1)\GOTO 1040
1030 R2 = R1
1040 R3 =S/R2\IF R2/2 = INT(R2/2) THEN 1060 ELSE 1045
1045 F1 = INT(R2/2)\F2=INT((R2/2)+0.5)\GOTO1080
1050 REM R2 IS NO OF RISERS\R3 IS H OF RISER
1060 F1 = R2/2\F2 = R2/2\IF F2 >14 THEN 1070 ELSE1080
1070 !CHR$(12)\!"THIS MODEL IS CONSTRAINED TO HANDLE ONLY TWO-FLIGHT "
1072 !"DOG-LEG STAIRS. THE ONE WHICH MEETS YOUR REQUIREMENTS DOES NOT "
1074 !"FALL WITHIN THIS RANGE. SORRY !!"\GOTO 1210
1080 D = (F2-1)*T
1090 LET L = D+ W :W1
1100 REM OUTPUT STAIR DESCRPTN
1110 !CHR$(12)
1120 !TAB(25),"THE STAIRCASE REQUIRED IS AS FOLLOWS "
1130 !TAB(25),"===== ===== ======== == == ======= "
1142 !"PROJECT       ",Y1$
1143 !"STAIR REF     ",Y2$
1150 !"STAIRWELL LENGTH (INTNL)   ",TAB(30),%9F3,L
1160 !"STAIRWELL WIDTH(INTNL)     ",TAB(30),%9F3,W
1170 !"RISER HEIGHT (MM)          ",TAB(35),INT(R3*1000)
1180 !"ACCESS LANDING LENGTH      ",TAB(30),%9F3,A
1190 !"ACCESS LANDING WIDTH       ",TAB(30),%9F3,B
1195 !"NR OF RISERS IN FIRST FLIGHT",TAB(33),F1
1196 !"NR OF RISERS IN SECOND FLIGHT",TAB(33),F2
1200!\!\!TAB(25), DO YOU WISH TO"
1210 !\!\!"GO BACK TO ALTER DESIGN VARIABLES- ---------- ---------  1"
1220    !\!"PROCEED WITH EVALUATION OF THIS SET-   -- ---------- -----  2"
1225 !\!"EXIT FROM MODEL  ---- ------------- -- -------- ------------ 3"
```

```
1230 INPUT M9
1235 IF M9 =1 THEN 400
1237 IF M9 =3 THEN 5000
1240 REM EVALUATE THIS SET
1242 IF H9$= "HILO DATA TEST" THEN GOSUB 7000 ELSE 1250
1244 GOTO1300
1250 OPEN£1,F$
1260 FOR I = 1 TO 21
1270 READ£1%(I-1)*65,X,R$,R(I),U$
1280 NEXT I
1290 CLOSE£1\REM RATES IN RARRAY
1300 REM CONC VOL
1310 V1 = B*W*0.2\REM HALF LANDING
1320 V2 =B * W1     *0.2\REM ACCESS LNDG
1330 V3 = (R2-2)*(0.5*T*R3*W)\REM IN STEPS
1340 V4 = 2*(SQRT((R4*T)^2 + (S/2)^2) * W * 0.2)\REM STRING VOL
1350 V5 = 2*(0.25 *0.25 * W)
1360 C(1) = R(1)*(V1+V2+V3+V4+V5)\REM COST OF CONCRETE
1370 C(2) =R(2) * 2 * (SQRT((R4*T)^2+(S/2)^2) * W)\REM SLOPING FORMWORK
1380 C(3) = R(3) * ((W*B +(W1*B1)) -(2*W*0.25))\REM HORIZ FORMWORK
1390 C(4) = R(4) * (2*B)
1400 C(5) = R(5) * (R2*W)
1410 C(6) = R(6) * 2 * SQRT((R4 * T)^2+(S/2)^2)
1420 C(7) = R(7) * (3*B + 2*W1+2*W)\REM FWK TO LANDING EDGE
1430 C(8) = R(8) * ((D*B*10)/1000)
1440  C(9) = R(9) * ((W1*B)+(B*W))
1450 C(10) = (R(10)*(1000*T+1000*R3))*(R2 *W)
1460 C(11) = R(11) * (R2*W)
1470 C(12) = R(12) * (R2* 2)
1480 C(13) = R(13) * (2*W+2*B+2*W1)
1490 C(14) = R(14) * 2*(SQRT((R4*T)^2+(S/2)^2))
1500 C(15) = R(15) * 2*(SQRT((R4*T)^2+(S/2)^2))
1505 LET S9 = SQRT((R4*T)^2+(S/2)^2)
```

```
1510 C(16) = R(16) * 2 *S9
1520 C(17) = R(17) * (2*L*S + [illegible] + 2*S9*W [illegible] + B*W1)
1530 C(18) =R(18) * (L*B)
1540 C(19) = R(19) * (2*L*S+2*B*S+2*S9*(W+B[illegible]L*B)
1545 D9=0
1550 C(20) = R(20)* ((2*L)+(3*B)*0.200)
1560 C(21) = R(21)* (G9)\REM G9 IS NO OF DOORS
1599 FOR I = 1 TO 21\C9= C9+ C(I)\NEXT\C9= INT(C9)\C9 = C9*S6\REM S6 NR OF STS
1600 REM DISCOUNTED COST *********************************************
1602 !CHR$(12)
1605           ! ENTER THE FOLLOWING"\!\!\!
1610 !"ANTICIPATED RENTAL",\INPUT R9
1620 !\!\!"DISCOUNT RATE",\INPUT D9
1630 !\!\!"DISCOUNT PERIOD",\INPUT Y9
1640 !CHR$(12)
1650 R7 =S6*( R9 * (L*B))\T9 = R7
1660 FOR I= 1 TO Y9
1670 P = R7 *(1/(1+(D9/100)))^I
1680 T9 = T9 + P
1690 NEXT I
1700 !CHR$(12)
1710 REM OUTPUT RESULTS
1720 ! TAB(35),"S T E P S  M O D E L "
1730 !TAB(35),"                          "
1735 !"PROJECT",TAB(30),Y1$,TAB(50),"STAIR REF",TAB(65),Y2$
1736 !  "WIDTH CALCULATED ACCORDING TO ",W$
1750 !"CATCHMENT AREA',TAB(30),C,TAB(50),"DATA USED:",F$
1760 !"OCCUPANT LOAD",TAB(30),[illegible]
1765 !"FLOOR TO FLOOR HEIGHT",TAB(30),S
1770 !"RISER\TREAD (MM)",TAB(30),[illegible]I(R0*1000 ,"  ",T*1000
1780 !"STAIRWELL LENGTH (INTNL)",TAB(30),%9F2,L
```

```
1790 !"STAIRWELL WIDTH (INTNL)",TAB(30),%9F2,B
1800 !"ACCESS LANDING LENGTH",TAB(30),%9F2,W1
1805 !"NR OF RISERS IN FIRST FLIGHT",TAB(30),F1
1806 !"NR OF RISERS IN SECOND FLIGHT",TAB(30),F2
1810 !"FLOOR AREA OCCUPIED BY"
1820 !"STAIRWELL",TAB(30),L*B
1840 !"RENT",TAB(30),R9
1850 !"INTEREST RATE",TAB(30),D9
1860 !"DISCOUNT PERIOD",TAB(30),Y9
1880 !"CONSTRUCTION COST",TAB(30),%$9F2,C9
1890 !"-------------------"
1900 T9 = T9 +C9
1910 !"TOTAL DISCOUNTED COST",TAB(30),%$9F2,T9
1920 !"-------------------------"
1925 !"TYPE C TO CONTINUE"\INPUT M9$
1930!CHR$(12)\!TAB(25),"PRINT RESULTS",TAB(50),"1"
1940 !TAB(25),"ALTER DESIGN VARIABLES",TAB(50),"2"
1950 !TAB(25),"EXIT",TAB(50),"3"
1960 INPUT M9\IF M9 )3 THEN 1930
1970 IF M9 =1 THEN 1995
1980 IF M9 =2 THEN 1985 ELSE 1990
1985 !CHR$(12)\GOTO380
1990 GOTO 5000
1995 !CHR$(12)\!"SET PAPER TO TOP OF PAGE AND TYPE C TO CONTINUE",\INPUT M9$
2000 !£1TAB(05),CHR$(14),"S T E P S           M O D E L "
2010 !£1TAB(01),"---  ------------------------------"\!£1,CHR$(15)
2015 !£1D8$
2020 !£1\!"PROJECT",Y2$\!£1,"DATE: ",D8$
2022 !£1"          STAIR REF.,  ",TAB(30),Y1$
2024 !£1"WIDTH CALCULATED ACCORDING TO ",W$
2026 !£1"SMOKE LOBBY: ",S7$
```

```
2028!£1"NR. OF STAIRCASES IN THIS ANALYSIS: ",S6
2029 !£1\!£1"FLOOR TO FLOOR HEIGHT",TAB(30),%9F2,E
2030 !£1"CATCHMENT AREA",TAB(30),%9F2,C,TAB(50),"DATA:",F$
2040 !£1"OCCUPANT LOAD",TAB(30),%9F2,O
2050 !£1"RISER\TREAD (MM)",TAB(30),        INT(R3*1000),"\",       T*1000
2055 !£1"SMOKE LOBBY: ",S7$
2060 !£1"STAIRWELL LENGTH (INTNL)",TAB(30),%9F2,L
2070 !£1"STAIRWELL WIDTH (INTNL)",TAB(30),%9F2,B
2075 !£1"NR OF RISERS IN FIRST FLIGHT",TAB(34),F1
2076 !£1"NR OF RISERS IN SECOND FLIGHT",TAB(34),F2
2080 !£1"ACCESS LANDING LENGTH",TAB(30),%9F2,W1
2090 !£1"FLOOR AREA OCCUPIED BY"
2100 !£1"STAIRWELL",TAB(30),%9F2,(L*B)
2120 !£1"RENT",TAB(30),%9F2,R9
2130 !£1"INTEREST RATE",TAB(30),%9F2,D9
2140 !£1"DISCOUNT PERIOD",TAB(30),%9F2,Y9
2150 !£1\!£1\!£1
2160 !£1"CONSTRUCTION COST",TAB(30),%9F2,C9
2170 !£1"-------------------"
2180!£1
2190 !£1"TOTAL DISCOUNTED COST",TAB(30),%9F2,T9
2200 !£1,CHR$(12)\!CHR$(12)\GOTO1930
4000 REM UPDATE ROUTINE FROM 385
4010 ! CHR$(12)\OPEN£1,F$
4020 !TAB(5),"REF",TAB(10),"ITEM DESCRIPTION",TAB(63),"RATE",TAB(70),"UNIT"
4030 FOR I = 1 TO 21
4040 READ£1%(I-1)*65,X,R$,R(I),U$
4050 !TAB(5),X,TAB(10),R$,TAB(60),%$9F2,R(I),TAB(70),U$
4060 NEXT I
4065 CLOSE£1
4070      !"ENTER ITEM TO BE ADJUSTED (0 TO ESCAPE)",\INPUT I\IF I =0 THEN4075
4072 GOTO4080
4075 !CHR$(12)\GOTO 380
4080 !CHR$(12)\OPEN £1,F$
```

```
4090 READ£1%(I-1)*65,X,R$,R(1),U$
4100 !TAB(5),X,TAB(10),R$,TAB(40),R(1),TAB(70),U$
4110 !\!\!"ENTER NEW RATE",\INPUT R8
4120 WRITE£1%(I-1)*65,X,R$,R8,U$
4130 CLOSE£1\!CHR$(12)\GOTO4010
4200 !CHR$(12)\!"SMOKE LOBBY"\G9 =G9 +1\S7$="YES"\REM S L SIZE CALC
4210 !\!"THE MODEL WILL ADD A SMOKE LOBBY SIZE",%9F2,W," * ",%9F2,B
4220 !\!"IS THIS OK (Y/N)",\INPUT M7$\IF M7$ ="N" THEN 4240
4230 W1 = W1 + W\GOTO4290
4240 !\!\!"THE LOBBY WIDTH WILL BE ",%9F2,B
4250 !"ENTER REQUIRED LENGTH (M)",\INPUT I \W1 = W1 + I\GOTO 4290
4290 GOTO 1000
4300 REM F F LOBBY SIZE CALC\G9=G9 +1
4310 IF W1* B <5.5 THEN 4320 ELSE 4350
4320 !"C P 3 DICTATES A MINIMUM LOBBY SIZE OF 5.50 SQ.M"
4330 I = 5.5/ B\W1 = W1 + I
4340 !"TYPE C TO CONTINUE",\INPUT M9$\GOTO 4390
4350 !"W * B IS GREATER THAN 5.50 SQ.M"
4360 !"THE MINIMUM LOBBY REQUIRED IS ",%9F2,W1," * ",%9F2,B
4370 W1 = W1 + W\GOTO4390
4390 GOTO 1000
5000 END
5100 IF M9 = 1 THEN 5131
5110 IF M9 = 2 THEN 5132
5120 IF M9 = 3 THEN 5133
5130 IF M9 = 4 THEN 5134
5131 W$="GLC REGS TABLE 2"\GOTO5140
5132 W$="GLC REGS TABLE 3"\GOTO5140
5133 W$="PAULS METHOD"\GOTO5140
5134W$ ="CP3 APPROACH"\GOTO5140
5140 RETURN
5200 !CHR$(12)\!TAB(20),"G L C. REGULATIONS"
5210 !TAB(20),"TABLE 2"
5220 !TAB(1),"NUMBER"
5230 !TAB(1),"OF STOREYS",TAB(15),"NO. OF PERSONS ONE STAIRCASE CAN",
5235 !" ACCOMODATE"
5240 !TAB(1),"SERVED"
```

```
5250 !"--------------------------------------------------------------------"
5260 !TAB(4),"1",TAB(14),"220",TAB(21),"240",TAB(28),"260",TAB(35),"280",
5265 !TAB(42),"300",TAB(49),"320",TAB(56),"340",TAB(64),"360"
5270 !TAB(4),"2",TAB(14),"260",TAB(21),"285",TAB(28),"310",TAB(35),"335",
5275 !TAB(42),"360",TAB(49),"385",TAB(56),"410",TAB(64),"435"
5280 !TAB(4),"3",TAB(14),"300",TAB(21),"330",TAB(28),"360",TAB(35),"390",
5285 !TAB(42),"420",TAB(49),"450",TAB(56),"480",TAB(64),"510"
5290 !TAB(4),"4",TAB(14),"340",TAB(21),"375",TAB(28),"410",TAB(35),"445",
5295 !TAB(42),"480",TAB(49),"515",TAB(56),"550",TAB(64),"585"
5300 !TAB(4),"5",TAB(14),"380",TAB(21),"420",TAB(28),"460",TAB(35),"500",
5305 !TAB(42),"540",TAB(49),"580",TAB(56),"620",TAB(64),"660"
5310 !TAB(4),"6",TAB(14),"420",TAB(21),"465",TAB(28),"510",TAB(35),"555",
5315 !TAB(42),"600",TAB(49),"645",TAB(56),"690",TAB(64),"735"
5320 !TAB(4),"7",TAB(14),"460",TAB(21),"510",TAB(28),"560",TAB(35),"610",
5325 !TAB(42),"660",TAB(49),"710",TAB(56),"760",TAB(64),"810"
5330 !TAB(4),"8",TAB(14),"500",TAB(21),"555",TAB(28),"610",TAB(35),"665",
5335 !TAB(42),"720",TAB(49),"775",TAB(56),"830",TAB(64),"885"
5340 !TAB(4),"9",TAB(14),"540",TAB(21),"600",TAB(28),"660",TAB(35),"720",
5345 !TAB(42),"780",TAB(49),"840",TAB(56),"900",TAB(64),"960"
5350 !TAB(3),"10",TAB(14),"580",TAB(21),"645",TAB(28),"710",TAB(35),"775",
5355 !TAB(42),"840",TAB(47),"905",TAB(56),"970",TAB(63),"1035"
5360!"WIDTH OF"
5370 !"STAIRCASE",TAB(14),"1.100",TAB(21),"1.200",TAB(28),"1.300",
5380 !TAB([illegible]),"1.400",TAB(42),"1.500",TAB(49),"1.600",TAB(56),"1.700",
5390 !TAB([illegible]),"1.800"
5395 !"--------------------------------------------------------------------"
5400 !\!\!"ENTER [illegible] (M)"\INPUT W(36-2\GOTO 900\REM MIN2 STRS
5600 [illegible]\TAB([illegible]) [illegible] CHAP. IV:PART 3:1968"
5610 !TAB(7);"MIN [illegible] FOR MULTI STAIRCASE BLDGS WITH MORE THAN",
5615 [illegible]
5620 !TAB([illegible]) [illegible] LEVEL"
```

```
5630 [illegible]------------------------------------------------"
5640 !TAB(1),"[illegible] MIN [illegible] WIDTH FOR EACH STAIRCASE"
5650 !TAB(1),"[illegible] STOREY",TAB(27),"2 STAIRCASES",TAB(42),"3 STAIRCASES",
5655 !TAB([illegible]),"[illegible]"
5660 !TAB(14),"[illegible]",TAB([illegible]),[illegible]
5670 !TAB(1[illegible]),"[illegible]
5680 !TAB(13),"115",TAB(32),"1220",TAB(48),"107[illegible]",TAB([illegible]),[illegible]
5690 !TAB(13),"130",TAB(32),"1370",TAB(48),[illegible]
5695 !
5700 !TAB(13),"145",TAB(32),"1525",TAB(48),"1070",TAB(64),"1070"
5710 !TAB(13),"160",TAB(32),"1680",TAB(48),"1070",TAB(64),"1070"
5720 !TAB(13),"175",TAB(32),"1830",TAB(48),"1070",TAB(64),"1070"
5730 !TAB(13),"200",TAB(48),"1070",TAB(64),"1070"
5735 !
5740 !TAB(13),"230",TAB(48),"1220",TAB(64),"1070"
5750 !TAB(13),"260",TAB(48),"1370",TAB(64),"1070"
5760 !TAB(13),"290",TAB(48),"1525",TAB(64),"1070"
5770 !TAB(13),"300",TAB(48),"1525",TAB(64),"1070"
5780!
5790 !"NEXT PAGE (Y/N)",\INPUT M9$\IF M9$ = "N" THEN [illegible]000 ELSE 5800
5800 !CHR$(12)\!TAB(25),"CP 3: CHAP. IV:PART 3:1968"
5810 !TAB(7),"MIN STAIRCASE WIDTH FOR MULTI STAIRCASE BLDGS WITH MORE THAN",
5815 !"TWO"
5820 !TAB(22),"STOREYS ABOVE GROUND LEVEL"
5830!"------------------------------------------------------------"
5840 !TAB(1),"NO. OF PERSONS",TAB(35),"MINIMUM WI[illegible] - FOR EACH STAIRCASE"
5850 !TAB(1),"IN THE STOREY",TAB(27),"2 STAIRCASES",TAB(42),"3 STAIRCASES",
5855 !TAB(59),"4 STAIRCASES"
5860 !TAB(13),"320",TAB(48),"1680mm",TAB(64),"1070mm"
5870 !TAB(13),"3[illegible]",TAB(48),"1680mm",TAB(64),"[illegible]"
5880 !TAB(13),"350",TAB(48),"1830mm",TAB(64),"1220mm"
5885 !
5890 !TAB(13),"390",TAB(64),"1370mm"
5900 !TAB(13),"435",TAB(64),"1525mm"
5910 !TAB(13),"480",TAB(64),"1680mm"
5920 !TAB(13),"525",TAB(64),"1830mm"
```

```
5930!"-------------------------------------------------------------"
5940 GOTO6000
6000 !"ENTER WIDTH (mm),NO.",\INPUT W,S6\W =W/1000\GOTO900
6500!CHR$(12)\"SPONS  DATA",TAB(30),"1"\!"... DATA",TAB(30),"2"
6510!"OLD DATA (1975)",TAB(30),"3"
6515 !"HILO DATA TEST",TAB(30),"4"
6520 INPUT F9\IF F9>4 THEN 6500
6530 ON F9 GOTO 6540,6550,6560,6570
6540 F$="RATES"\GOTO6580
6550 F$="RATES2"\GOTO6580
6560 F$ ="OLDTA"\GOTO6580
6570 H9$ ="HILO DATA TEST"
6580 RETURN
7000 REM SUB FOR HILO DATA TEST
7010 OPEN£1,"RATES"
7020 OPEN£2,"RATES2"
7030 FOR I = 1 TO 21
7040 READ£1%(I-1)*65,X,R$,R1(I),U$
7050 READ£2%(I-1)*65,X,R$,R2(I),U$
7060 IF R1(I) >= R2(I) THEN 7070 ELSE 7080
7070 LET R(I) = R1(I)\GOTO 7100
7080 LET R(I) = R2(I)\GOTO 7100
7100 NEXT I
7110 CLOSE£1\CLOSE£2
7120 Y1$ ="HIGH DATA TEST"
7130 RETURN
```

## APPENDIX IV

```
60REM MACE3/JJR 08.82 ************ ******************* **************
80 DIM A3(20),C1(20),U2(20),A8(20),O9(20),L9(20),S(55),D$(20),T$(8),R1(20)
90 DIM W(8,20),F(10,9),A(8,11),G(11)    ,L(8,11),D(8,11),M(8,20),R(11)
95 DIM L7(20),L8(20),W1(20),M1(20),U3(20)
100 !CHR$(12)\C$=CHR$(12)\DEF FNR(V,Y9) = INT((V*10^Y9)+.5)/10^Y9
110 !"*****************************************************************"
120 !"                              M A C E"
125 !\!"            Model for Air Conditioning Evaluation"\!
130 !\!\!"Cost model for the evaluation of air conditioning designs."\!\!
132 !"The model considers Variable Air Volume systems in multi storey"
134 !"commercial building developments"
140 !"******************************************************************"
150 !\!\!\!
160 !"ADJUST DATABASE",TAB(30),"1"
170 !"PROCEED TO MODEL",TAB(30),"2"
175 !"EXIT",TAB(30),"3"
180 INPUT M9\IF M9 = 1 THEN 7000\IF M9 = 2 THEN 195
190 IF M9 =3 THEN 9999ELSE 110
195 GOTO9600
200 !C$
210 !"                P R O J E C T   D E T A I L S"
215 !\!\!"PROJECT NAME",\INPUT N1$
220 !\!"NO. OF ZONES FOR SEPARATE COOLING LOAD CALCULTION",\INPUT Z9
225 !C$
```

```
230 !"              D E S I G N   C O N D I T I O N S"
240 !"              ---------------------------------"
250 !\!\!
270 !"INTERNAL DESIGN TEMP (SUMMER) C.D.B.",\INPUT T1
280 !"HUMIDITY LEVEL %AGE SATURATION)",\INPUT H1
290 !"EXTERNAL DESIGN TEMP (SUMMER) C.D.B.",\INPUT T3
300 !"EXTERNAL DESIGN TEMP (SUMMER) C.W.B.",\INPUT T4
310 !"TOTAL HEAT EXTERNAL (SPECIFIC ENTHALPY KJ/Kg)",\ INPUT H3
320 !"AMOUNT OF OUTSIDE AIR PER OCCUPANT (M3/S)",\INPUT A1
330 !"PLEASE WAIT"\GOTO8000
340 FOR Z = 1 TO Z9
345 !C$
350 !"           Z O N E   ",Z
360 !"          ---------------"
370 !\!\!
380 !"AREA",\INPUT A3
390 !"AVERAGE HEIGHT",\INPUT H4\LET C1(Z) =A3*H4
410 !"ENTER THE WINDOW AREA FOR EACH ORIENTATION (O IF NOT APPROPRIATE)"
420 !"N ",\INPUT W(1,Z)
430 !"NE",\INPUT W(2,Z)
440 !"E ",\INPUT W(3,Z)
450 !"SE",\INPUT W(4,Z)
460 !"S ",\INPUT W(5,Z)
470 !"SW",\INPUT W(6,Z)
480 !"W ",\INPUT W(7,Z)
490 !"NW",\INPUT W(8,Z)
495 !"WINDOW U-VALUE",\INPUT U2(Z)
500 !"ENTER THE WALL AREA FOR THE FOLLOWING (O IF INAPPROPRIATE)"
510 !"N ",\INPUT M(1,Z)
520 !"NE",\INPUT M(2,Z)
530 !"E ",\INPUT M(3,Z)
540 !"SE",\INPUT M(4,Z)
550 !"S ",\INPUT M(5,Z)
560 !"SW",\INPUT M(6,Z)
570 !"W ",\INPUT M(7,Z)
580 !"NW",\INPUT M(8,Z)
```

```
590 !"WALL U-VALUE",\INPUT U1(Z)
600 !C$\!"ROOF AREA",\INPUT R1(Z)\IF R1(Z) =0 THEN 1000
620 !"ROOF U-VALUE",\INPUT U3(Z)
1000 !CHR$(12)\ !"                    INFILTRATION GAINS"
1010 !\!"MODEL ASSUMES HALF AIRCHANGE PER HOUR "
1020 !"IS THIS OK (Y\N)",\INPUT M9$\IF M9$="Y" THEN 1030 ELSE 1040
1030 A8 = 0.5\GOTO1050
1040 !CHR$(12)\!" ENTER INFILTRATION RATE (AC\HOUR);\INPUT A8
1050 !C$\!"                INTERNAL HEAT GAINS"
1060 !"NO. OF OCCUPANTS IN ZONE",\INPUT O9(Z)
1070 !"LIGHTING GAIN FOR ZONE (KW)",\INPUT L9(Z)
1080 NEXT Z
1100 REM EATING CALCS
1110 W1=0\M1=0\K1=0\REM LOSSES WNDW WALL ROOF
1120 FOR Z = 1 TO Z9
1130 FOR I = 1 TO 8
1140 W1(Z) = W1(Z) + W(I,Z)
1150 M1(Z) = M1(Z) + (M(I,Z)-W(I,Z))\C1 = C1 + C1(Z)
1160 NEXT I
1170 NEXT Z
1180 FOR Z = 1 TO Z9
1190 R1 = R1 + (M1(Z) * U1(Z))\REM WALL LOSS
1200 R2 = R2 + (W1(Z) * U2(Z))\REM WNDW LOSS
1205 K = K + (R1(Z) * U3(Z))\REM ROOF LOSS
1208 NEXT Z\REM R3 IS SIGMA A U R4 IS SIGMA A
1210FOR Z=1TOZ9\W1=W1+W1(Z)\M1=M1+M1(Z)\K1=K1+R1(Z)\NEXT Z
1220 R3 = R2 +R1
1230 R4 = W1 +M1 + K1  \REM R3/R4 USED FOR CALC OF F1 &F2
1240 R5 =R3/R4\R5 = FNR(R5,2)
1250 !C$\!"SIGMA(A*U)/SIGMA(A) IS ",R5
1260 !\!"ENTER F1,F2 ",
1270 INPUT R8,R9
1280 Q8 = R3 * (20) * R8
1290 Q9 = A8 * 0.33 * C1 * (20) * R9
1300 B9 = Q8 + Q9
1310 B9 = (B9 * 0.15) * 0.15\B9 =FNR(B9,2)
```

```
1500 !C$
1510 !TAB(25),"COOLING LOAD DUE TO SOLAR GAIN          "
1520 !\!"GLAZING "
1530!\!\!"UNPROTECTED ",TAB(30),"1"
1540 !"INTERMITTENT BLINDS",TAB(30),"2"
1550 INPUT M9\IF M9 =1 THEN 1570
1560 IF M9 = 2 THEN 1580 ELSE 1500
1570 F$= "CLSU,2" \GOTO3070
1580 F$ ="CLSB,2" \GOTO2000
2000 !C$\ !"TYPE OF GLASS (outside pane-              BUILDING WEIGHT"
2010!"for double glazing)      "
2020 !
2030 !"CLEAR 6mm                                   LIGHT              1"
2040 !"CLEAR 6mm                                   HEAVY              2"
2045 !
2050 !"BTG 6mm                                     LIGHT              3"
2060 !"BTG 6mm                                     HEAVY              4"
2065 !
2070 !"BTG 10mm                                    LIGHT              5"
2080 !"BTG 10mm                                    HEAVY              6"
2090 !"REFLECTING                                  LIGHT              7"
2100 !"REFLECTING                                  HEAVY              8"
2105 !
2110 !"STRONGLY REFLECTING                         LIGHT              9"
2120 !"STRONGLY REFLECTING                         HEAVY             10"
2130 INPUT M8
2140 !C$
2150 !"SINGLE GLAZING"
2160 !"LIGHT SLATTED BLIND OPEN        1"
2170 !"LIGHT SLATTED BLIND CLOSED      2"
2180 !"LINEN ROLLER BLIND              3"
```

```
2190 !
2200 !"DOUBLE GLAZING INTERNAL SHADE"
2210 !"LIGHT SLATTED BLIND OPEN             4"
2220 !"LIGHT SLATTED BLIND CLOSED           5"
2230 !" LINEN ROLLER BLIND                  6"
2240 !
2250 !"DOUBLE GLAZING, MID PANE SHADE"
2260 !"LIGHT SLATTED BLIND OPEN             7"
2270 !"LIGHT SLATTED BLIND CLOSED           8"
2280 !"LINEN ROLLER BLIND                   9"
2290 INPUT M9
2300 DATA 1.00,0.77,0.66,0.95,0.74,0.65,0.58,0.39,0.42
2310 DATA 0.97,0.77,0.63,0.94,0.76,0.64,0.56,0.40,0.40
2320 DATA 0.86,0.77,0.72,0.66,0.55,0.51,0.45,0.36,0.38
2330 DATA 0.85,0.77,0.71,0.66,0.57,0.51,0.44,0.37,0.37
2340 DATA 0.78,0.73,0.70,0.54,0.47,0.45,0.38,0.34,0.36
2350 DATA 0.77,0.73,0.70,0.53,0.48,0.45,0.37,0.34,0.34
2360 DATA 0.64,0.57,0.54,0.48,0.41,0.38,0.33,0.27,0.29
2370 DATA 0.62,0.57,0.53,0.47,0.41,0.38,0.32,0.27,0.28
2380 DATA 0.36,0.34,0.32,0.23,0.21,0.21,0.17,0.16,0.16
2390 DATA 0.35,0.34,0.32,0.23,0.21,0.21,0.17,0.16,0.16
2400 FOR I9 = 1 TO 10
2410 FOR J9 = 1 TO 9
2420 READ F(I9,J9)
2430 NEXT J9
2440 NEXT I9
2450 REM CORRECTING FACTOR IS F
2460 LET F = F(M8,M9)
2470 GOTO 3360
3070 !C$
3080 !"CHOOSE TYPE OF GLASS AND STRUCTURE"
3090 !\!\!"SINGLE GLAZING, LIGHTWEIGHT",TAB(40),"1"
3100 !\  !"SINGLE GLAZING, HEAVYWEIGHT",TAB(40),"2"
3110  !\ !"DOUBLE GLAZING, LIGHTWEIGHT",TAB(40),"3"
3120 !\  !"DOUBLE GLAZING, HEAVYWEIGHT",TAB(40),"4"
3130 !"SINGLE GLAZING WITH EXTNL SLATTED"
3140!"BLINDS USED INTERMITTENTLY,LIGHTWEIGHT",TAB(40),"5"
3150 !\!"DITTO,HEAVYWEIGHT",TAB(40),"6"
3160 INPUT M9
```

```
3170 !C$
3180 !"TYPE OF GLASS"
3190 !"CLEAR 6mm",TAB(25),"1"
3200 !"BTG 6mm",TAB(25),"2"
3210 !"BTG 10mm",TAB(25),"3"
3220 !"REFLECTING",TAB(25),"4"
3230 !"STRONGLY REFLECTING",TAB(25),"5"
3240 INPUT M8
3250 OPEN£1,"ADJU,2"
3260 DATA 0.7,0.6,0.53,0.45,0.16,0.16
3270 DATA 0.58,0.49,0.4,0.34,0.14,0.14
3280 DATA 0.49,0.42,0.37,0.31,0.13,0.13
3290 DATA 0.25,0.21,0.16,0.14,0.09,0.10
3300 FOR I9 = 1 TO 5
3310 FOR J9 = 1 TO 6
3320 READ£1, F(I9,J9)
3330 NEXTJ9
3340 NEXTI9
3345 LET F=F(M8,M9)
3350 REM CORRECTING FACTOR IS F
3360 !C$\!"      ADJUSTMENT FACTOR TO SOLAR GAINS THROUGH SOLID MATERIALS"
3370 !    "      ---------------------------------------------------------------------"
3380   !\!TAB(15),"CONSTRUCTION",TAB(48),"ADJUSTMENT"
3390 ! TAB(40),"TIME LAG",TAB(60),"DECREMENT FACTOR"
3400 !"----------------------------------------------------------------------------------------"
```

```
3410 ! TAB(1),"LIGHT FRAME HEETED & LINED",TAB(44),"0.5",TAB(70),"1.0"
3420 ! TAB(2),"brickwork"
3430 ! TAB(1),"105mm BARE",TAB(44),"3.5",TAB(70),"0.8"
3440 ! TAB(1),"105mm INTNLLY LINED",TAB(44),"4",TAB(70),"0.7"
3450 ! TAB(1),"220mm BARE",TAB(44),"8",TAB(70),"0.4"
3460 ! TAB(1),"220mm INTNLLY LINED",TAB(44),"8.5",TAB(70),"0.3"
3470 ! TAB(2),"concrete"
3480 ! TAB(1),"150mm BARE",TAB(44),"0.5",TAB(70),"0.6"
3490 ! TAB(1),"150mm INTNLLY LINED",TAB(44),"5.5",TAB(70),"0.5"
3500 ! TAB(1),"150mm EXTNLLY LINED",TAB(44),"6.0",TAB(70),"0.4"
3510 ! TAB(1),"200mm BARE",TAB(44),"6.0",TAB(70),"0.5"
3520 ! TAB(1),"200mm INTNLLY LINED",TAB(44),"6.5",TAB(70),"0.4"
3530 ! TAB(1),"200mm EXTNLLY LINED",TAB(44),"7.0 ",TAB(70),"0.3"
3540!"-----------------------------------------------------------------------"
3550 !"Thermal resistance of lining assumed to be less than 0.4mK/W"
3560!"-----------------------------------------------------------------------"
3570 !"***WALLS*** ENTER TIME LAG,DECREMENT FACTOR",\INPUT T5,F2
3580 !"***ROOF***  ENTER TIME LAG,DECREMENT FACTOR",\INPUT T6,F3
3590 !D$
3600 !"SUN HEAT TEMP INCREMENT"
3610 !\!"LIGHT SURFACE",TAB(20),"1"
3620 !"DARK SURFACE",TAB(20),"2"
3630 !\!\!"ENTER WALLS, ROOF ",\INPUT S8,S9
3640 !C$\!"                PLEASE WAIT",
3650 GOSUB 8500
3655 REM P IS COOLING LOAD DUE TO SOLAR GAIN (ADJUSTED & IN KW)
3660 !C$\!"PEAK COOLING LOAD DUE TO SOLAR GAIN OCCURS ON ",D$," AT ",T$
3670 !\!\!"TYPE C TO CONTINUE",\INPUT M7$
4000 REM AC LOADS
4010 REM GLAZING W1 IS TOTAL AREA OF GLASS PER ZONE
4020 T = T3-T1
4030 FOR Z = 1 TO Z9
4040 FOR I = 1 TO 8
4050 W1(Z) = W1(Z) + W(I,Z)
4060 NEXT I
```

```
4065 L7(Z) = W1(Z) * U2(Z)\REM WINDOW HLOSS THIS ZONE
4070 P1(Z) = W1(Z)*U2(Z)*T
4080 NEXT Z
4090 P1 = 0
4100 FOR Z = 1 TO Z9\P1 = P1+ P1(Z)\NEXT Z\REM P1 IS TOT AIR TOAIR H GAIN
4110 P1 = P1/1000
4140 REM WALLS
4150 GOSUB 7010 \REM PICKS UP WALL & ROOF HT INCRMNTS
4160 T8 = T7-T5\IF T8<1 THEN 4170 ELSE 4180
4170 T8 = 1
4180 IF T8<> INT(T8) THEN 4190 ELSE 4200
4190 GOTO 9500
4200 FOR I = 1 TO 8\A(I,11) = A(I,T8)\NEXT I
4210 FOR Z = 1 TO Z9
4220 FOR I = 1 TO 8
4230 P2(Z) = P2(Z) + (((M(I,Z) - W(I,Z)) * U1(Z) * F2)/1000) * (T+A(I,11))
4240 NEXT I
4250 NEXT Z
4260 P2 =0
4270 FOR Z = 1 TO Z9\P2 = P2 + P2(Z)\NEXT Z
4280 REM P2 IS H GAIN THRU FABRIC BY ADMITTANCE APPROACH
4290 REM ROOF GAINS\E9 =1
4320 T8 = T7-T6\IF T8 <1 THEN 4330 ELSE 4340
4330 T8 =1
4340 IF T8 <> INT(T8) THEN 4350 ELSE 4370
4350 GOSUB 9550
4360 GOTO 4380
4370 R(11) = R(T8)
4380 FOR Z = 1 TO Z9
4390 IF R1(Z) = 0 THEN 4400 ELSE 4410
4400 GOTO 4420
4410 P3(Z) = P3(Z) + ( (R1(Z)*U3*F3)/1000 ) * (T+R(11))
```

```
4420 NEXT Z
4430 FOR Z = 1 TO Z9\P3 = P3 + P3(Z)\NEXTZ
4440 REM P3 IS ROOF GAIN
4470REM INFILTRATION GAIN****************************************
4480 REM AIR CHANGE/HR IS A8**CUBE IS C1**SPEC VOL DRY AIR AT ROOM CNDTNIS V7
4490 REM T H DRY AIR EXTNL IS E1** INTNL IS H5**DIFFERENCE IS E3**
4500 FOR Z = 1 TO Z9\C1 = C1 +C1(Z)\NEXT Z
4510 E = ( A8*C1 )/V7
4520 OPEN£3,"HUMID,2"
4530 IF T3 =28 THEN 4570
4540 IF T3 = 29 THEN 4580
4550 IF T3 = 30 THEN 4590
4560 IF T3 = 31 THEN 4600
4570 X= 28 \GOTO 4610
4580 X=32 \GOTO 4610
4590 X=36 \GOTO 4610
4600 X= 42 \GOTO 4610
4610 READ£3%(X-1)*48,D1,D2,D3,D4,D5,D6
4620 E1 =D4
4630CLOSE£3
4640 E3 =E1-H5\REM E3 IS TOTAL HT DRY AIR DIFF EXTNL-INTNL
4650 P4 =E*E3/3600\REM P4 IS SENSIBLE GAIN INFILTRATION
4660 REM GAIN DUE TO MOISTURE DIFF
4670 E5 = H3-H7
4680 P5 = (E*(E5-E3))/3600
4700 REM INTNL H GAINS
4710 FOR Z = 1 TOZ9\O9 = O9+U9(Z)\NEXT Z
4720 REM O8 IS H G FROM OCCUPANTS SET AT 88WATTS\O8 = 88
4730 FOR Z = 1TO Z9
4740 P6 = (O9(Z)*88) +(L9(Z)*1000)+P6
4750 NEXT Z
```

```
4755 P6 = P6/1000
4760 REM GAIN DUE TO MOISTURE IS P7
4765 LET P7 = D9 * 30\ P7 = P7/1000
4770 REM Q1 IS TOTAL H G SENSIBLE
4790 REM Q2 IS TOTAL H G LATENT
4840 REM VENTILATION AIR
4850 P8 = (D9*A1/V7) * (E1-H5)\REM SENSIBLE
4860 P9 = (D9*A1/V7) * (E5-E3)\REM LATENT
4862 Q1 = P+P1+P2+P3+P4+P6+P8
4864 Q1 =FNR(Q1,2)
4866 Q2 = P5+P7+P9
4868 Q2 = FNR(Q2,2)
4869 !"SENSIBLE GAINS",Q1
4870 !"LATENT GAINS",Q2\!"TYPE C TO CONTINUE" \REM FIND PROPTN OUTSIDE AIR
4875 INPUT M9$
4880 A6 = (( P4+P5+P8+P9)/(P+P1+P2+P3+P6+P7))*100
4890 REM AIR QUANTITY
4900 REM PERMISSABLE TEMP RISE IS K
4905 LET K=8
4910 REMS V DRY AIR AT 15 IS V8\V8 =0.815
4920 Q3 =(Q1-P8)/K\REM Q3 IS MASS OF AIR KGS PER SECOND
4930 Q4 = Q3*A6/100\ REM FROM OUTSIDE
4940 Q5 = Q3-Q4\ REM RECIRCULATED AIR
4950 REM T H OF MIXTURE
4960 Q6 = ((Q5*H7) + (Q4*H3))/Q3
4970 REM COOLING LOAD
4980 REM IDENTIFY SPEC ENTHALPY OF MIX AT DEW POINT
4990 REM PLANT EXIT CONDITION ASSUMED AT 14'CD.B. FOR REGRESSION FOR SP ENTH
5000 REM M1 IS MOISTURE CONTENT OF AIR LEAVING PLANT
5010 M1 = C7 -((Q2-P9)/(Q3*2450))
5015 REM*** INSERT OTHER REGRESSN EQTNS FOR DIFF TEMPS OF PLANT EXIT
5100 Q7 = (M1*2527.03)+14.08\ REM SPEC ENTHALPY OF MIXTURE
```

```
5110 Q8 =Q6-Q7\ REM DIFF OF SPEC ENTHALPY
5120 Q9 =Q3*Q8\ REM COOLING LOAD
5130 R9 =Q9 *1.10\ REM ADD 10% FOR H GAIN IN PUMP &PIPING
5135 R9 = FNR(R9,2)
5140 REM R9 IS REFRIDGE LOAD
5150!"REFRIDGE LOAD";R9
5160!\!"BOILER CAPACITY (KW) ",FNR(B9/1000,2)
5170 END
7000  !CHR$(12)\!"THE DATABASE  IS NOT READY FOR ADJUSTMENT YET"
7002 !"PLEASE PROCEED TO MODEL OR EXIT!"
7005 GOTO150
7010 REM READ SUN HEAT TEMP INCREMENTS(LIGHT & DARK SURFACE)
7012 IF S8 = 1 THEN 7020 ELSE 7040
7015 IF S9 = 1 THEN 7060 ELSE 7080
7020 REM 1 IS FOR LIGHT SURFCE SO READ FIRST 8 RECORDS
7030 LET C4 =1\LET C5 =8\GOTO 7200
7040 REM DK SFCE READ RECORDS 9 TO 16
7050 LET C4 =9\LET C5 =16\GOTO 7200
7060 LET C3 =1\GOTO7300
7080 LET C3 =2\GOTO 7300
7200 LET I =0
7205 OPEN£2,"WHILD,2"
7210 FOR C3 = C4 TO C5
7220 I = I+1
7230READ£2%(C3-1)*80,G(1),G(2),G(3),G(4),G(5),G(6),G(7),G(8),G(9),G(10)
7240 FOR J =1 TO 11
7250LET A(I,J) =G(J)
7260 NEXT J
7270 NEXT C3
7275 CLOSE£2
7290 GOTO 7015\REM AS 7145
7300 OPEN£3,"RHILD,2"
7305 READ£3%(C3-1)*80,R(1),R(2),R(3),R(4),R(5),R(6),R(7),R(8),R(9),R(10)
7310 CLOSE£3
7320 GOTO7500
7500 RETURN
```

```
8000 REM SUB TO CALC FULL DESIGN CONDTNS
8010 IF T1 = 20 THEN 8090
8020 IF T1 = 21 THEN 8100
8030 IF T1 = 22 THEN 8110
8040 IF T1 = 23 THEN 8120
8050 IF T1 = 24 THEN 8130
8060 IF T1 = 25 THEN 8140
8070 !"INCORRECT INTERNAL DESIGN TEMP ENTERED"
8080 !"TRY AGAIN. TYPE C TO CONTINUE",\INPUT M9$\GOTO 225
8090 X = 1\GOTO 8150
8100 X = 5\GOTO 8150
8110 X =9\ GOTO 8150
8120 X =13\GOTO 8150
8130 X =17\GOTO 8150
8140 X =21\GOTO 8150
8150 IF H1 = 60 THEN 8180
8160 IF H1 = 50 THEN 8190
8170 IF H1 = 40 THEN 8200
8180 Y = X\GOTO 8210
8190 Y = X + 1\GOTO8210
8200 Y = X + 2\GOTO 8210
8210 OPEN£3,"HUMID,2"
8220 READ£3 %(Y-1)*48,D1,D2,D3,D4,D5,D6
8230 C7 = D3\H7 =D4\V7 = D5\W7 =D6
8235 REM H7 IS TOTAL HT AT ROOM CONDITION C7 IS M C DITTO
8236 REM V7 IS SPEC VOL AT ROOM COND W7 IS WETBULB DITTO
8240 READ£3%((X+3)-1)*48,D1,D2,D3,D4,D5,D6
8250 H5 = D4
8260 CLOSE£3
8270 GOTO340
8500 REM FIND PEAK COOLING LOAD
8510 OPEN£3,F$
8520 REM READ ONE BLOCK OF DATA ATA TIME
```

```
8530X1 =1\X2 =8\L1 =0
8540 I =0
8550 FOR D1 = X1 TO X2
8560 I = I +1
8570 READ£3%(D1-1)*88,S(1),S(2),S(3),S(4),S(5),S(6),S(7),S(8),S(9),S(10),S(11)
8590FOR J = 1 TO 11
8600LET D(I,J) = S(J)
8610 NEXT J
8620 NEXT D1
8630 REM DO CALCULATIONS
8640 L1 = L1 +1
8650 FOR J = 1 TO 11
8660 FOR Z = 1 TO Z9
8670 FOR I = 1 TO 8
8680 L(L1,J) = L(L1,J) +[illegible] *W(I,Z) )
8690 NEXT I \ REM NEXT ORIENTATION
8700 NEXT Z \ REM NEXT ZONE
8710 NEXT J \ REM NEXT TIME
8720 REM NOW READ NEXT [illegible] DATA AND REPEAT
8730 REM THE RESULT OF EACH BLOCK FILLS ONE ROW OF ARRAY L
8740 X1 = X1+8\X2=X2+8\IF [illegible] THEN 8540 [illegible]
8800 CLOSE£3 \REM NOW SORT LOAD CALCS
8810 G =0
8820FOR I = 1 TO 5
8830FOR J = 1 TO 11
8840G =G+1
```

```
8840G =G+1
8850S(G) =L(I,J)
8860NEXT J
8870NEXT 1
8880REM BUBBLESORT
8890M =55
8900M=M-1
8910C=0
8920FOR I = 1 TOM
8930IF S(I)(=S(I+1) THEN8980
8940H =S(I)
8950S(I) = S(I+1)
8960S(I+1) =H
8970C =1
8980NEXT I
8990IF C()0 THEN 8900
9000LET P = S(55)\REM P IS PEAK LOAD NOW FIND WHEN IT OCCURS
9010FOR I = 1 TO 5
9020FOR J = 1 TO 11
9030IF L(I,J)()P THEN 9040 ELSE9055
9040NEXT J
9050NEXT I
9055 LET T7 = J
9060IF 1 = 1 THEN 9110
9070IF I = 2 THEN 9120
9080IF I = 3 THEN 9130
9090IF I = 4 THEN 9140
9100IF I = 5 THEN 9150
9110D$="JUNE 21"\GUTO 9160
9120D$="JULY 23 & MAY 21"\GOTO9160
9130D$="AUG 24 & APRIL 20"\GOTO9160
9140D$="SEPT 22 & MAR 22"\GOTO9160
9150D$="OCT 23 & FEB 20"\GOTO9160
```

```
9160IF J = 1 THEN 9270
9170IF J = 2 THEN 9280
9180IF J = 3 THEN 9290
9190IF J = 4 THEN 9300
9200IF J = 5 THEN 9310
9210IF J = 6 THEN 9320
9220IF J = 7 THEN 9330
9230IF J = 8 THEN 9340
9240IF J = 9 THEN 9350
9250IF J = 10 THEN 9360
9260IF J = 11 THEN 9370
9270T$ = "0800HRS"\GOTO9380
9280T$="0900HRS"\GOTO9380
9290T$ = "1000HRS"\GOTO9380
9300T$ = "1100HRS"\GOTO9380
9310T$ = "1200HRS"\GOTO9380
9320T$ = "1300HRS"\GOTO 9380
9330T$ = "1400HRS"\GOTO9380
9340T$ = "1500HRS"\GOTO9380
9350T$ = "1600HRS"\GOTO9380
9360T$ = "1700HRS"\GOTO9380
9370T$ = "1800HRS"\GOTO9380
9380 REM NOW ADJUST PEAK I BY CORRECTING FACTORS********************
9390 P = P*F\P = P/1000
9400 RETURN
9500 FOR I = 1 TO 9
9510 A(I,11) = A(I,INT(T8)) + SQRT( ((A(I,INT(T8)) - A(I,INT(T8+1)))/2)^2 )
9520 NEXT I
9530 GOTO4210
9550 REM INTERPOLATE ROOF INCRMNT FOR TIME LAG
9560  A1(11) = A1(INT(T8)) + SQRT(((A1(INT(T8)) - A1(INT(T8+1)))/2)^2)
9570 RETURN
9600 !C$
```

```
9610!"                    M O D E L   H I E R A R C H Y "
9620!"                    ******************************"
9630!\!\!\!"Global parameter, tender price"
9640!"(deductive model)",TAB(40),"1"
9650!\!
9660!"Detailed design, economic"
9670!"model (inductive)",TAB(40),"2"
9680 INPUT M9\IF M9 =1 THEN 9700
9690 IF M9 =2 THEN 200 ELSE 9600
9700 CHAIN "ACRE"
9999 END
```

## APPENDIX V

```
10 REM PROG NAME MODELLE ****************
11 REM THIS VERSION DEALS WITH DEPENDENT TERMS
20 REM THIS VERSION 21.06.83****************************************
30 DIM F2$(20),S(100),H1$(50),A$(100)
35 F2$="                              "
50 DIMX(2000 ),Y(100),D9$(40)
80 DIM N$(20),T(20,5)\DEF FNR(V,Y9) = INT((V*10^Y9)+.5)/10^Y9
90 C$=CHR$(12)
95   H1$="XXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXX"
100 !C$
120 !TAB(29),"M O D E L L E"
130 !\!TAB(20),"M O D E L L I N G  L A N G U A G E"
135 !"------------------------------------------------------------------------"
150 !\!"This is the beginning of a suite which runs simulations on given"
160 !"cost models. Any number of terms can be dealt with, but each term of"
170 !"the function must be defined according to the constraints of MODELLE."
175 !
180 !"Functions once entered are stored on file and thus can be run or altered"
190 !"at any time."
195 !"------------------------------------------------------------------------"
198!\!\!
199 !"ENTER TODAYS DATE",\INPUTD9$
200 !TAB(10),"ENTER A NEW FUNCTION",TAB(60),"1"
210 !  TAB(10 ),"RUN SIMULATION ON AN EXISTING FUNCTION",TAB(60),"2"
215 !TAB(10),"QUIT",TAB(60),"3"
220 INPUT M1\!C$\IF M1 =2 THEN 550\IF M1 =1 THEN 230 ELSE 9999
230 !"The function may contain any number of terms"
240 !"The format for each term shall be as follows"
```

```
250 !\!"         K * V"
260 !"where K = constant"
270 !"and   V = parameter for which the distribution is Known"
280 !"ENTER FUNCTION NAME"\INPUT F$
301 !\!"HOW MANY TERMS IN THIS FUNCTION" \INPUT T
310 OPEN£1,"FUNCTION"\GOTO370
320 IF TYP(1) = 0 THEN360\REM ENDMK
325 IF TYP(1) = 2 THEN 350\REM NUMBER
330 REM IT MUST BE A STRING
340 READ£1,N$\GOTO320
350 READ£1,N\GOTO 320
360 REM NOW READY TO APPEND DATA
370 WRITE£1,F$,T
375 FOR I = 1 TO T
380 !C$\!TAB(30),"TERM",I
390 !\!"IS THE SIGN + OR - ?"\INPUT S$
400 IF S$="+" THEN 420\IF S$ = "-" THEN 430
410 !"try again"\GOTO390
420 D1 = 1\GOTO440
430 D1 =0 \GOTO440
440 !\!\!"CONSTANT"\INPUTD2
450!" For the parameter enter the following"
460! "MINIMUM"\INPUT D3
470 !"MOST LIKELY (IF YOU WANT A UNIFORM DISTRIBUTION ENTER 0) "\INPUT D4
480 !"MAXIMUM"\INPUT D5
510 WRITE £1,D1,D2,D3,D4,D5
520 NEXT I
530 CLOSE£1
540 !C$\GOTO 200
550 REM SELECT A FUNCTION
555 !"The following functions are stored"
```

```
556 !"----------------------------------"\!\!
560 OPEN£1,"FUNCTION"\I =0
570 IF TYP(1) =0THEN 605
580 IF TYP (1) = 1 THEN 600
590 READ£1,D1\GOTO570
600 READ£1,N$\!N$\GOTO570
605 CLOSE £1
640 !\!"SELECT",\INPUT F$
642 IF LEN(F$)<=20 THEN 646
644 F$ = F$+F2$(LEN(F$)+1,20)
646 !"HOW MANY RUNS DO YOU REQUIRE IN THE SIMULATION"\INPUT N
648 !\!"NUMBER OF BAND WIDTHS (10-100) ",\INPUT B9\!\!"TITLE OF X-AXIS",
650 INPUT A$
652 GOSUB 8900
654 !C$\!"OUTPUT TO PLOTTER",TAB(25),"1"
655 !"OUTPUT TO PRINTER",TAB(25),"2"
656 INPUT M9\IF M9 =1 THEN P$="PLOTTER"
660 REM READ FILE INTO ARRAY THING
670 OPEN£1,"FUNCTION"
680 IF TYP (1) = 0 THEN 720
690 IF TYP(1) =1THEN 710 ELSE 700
700 READ£1, D9 \GOTO 680
710 READ£1, N$\IF N$=F$ THEN740 ELSE 680
720 !"FILE ERROR: ENDMARK FOUND: TYPE IN FUNCTION NAME AGAIN"\CLOSE£1\GOTO550
740 READ£1, T
750 FOR I = 1 TO T
760 READ£1,T(I,1),T(I,2),T(I,3),T(I,4),T(I,5)
770 NEXT I
780 CLOSE£1
```

```
785 REM ARRAY NOW READY
790 IF P$="PLOTTER" THEN 800
793OPEN£1,"FUNCTION"
794!£1"INDUCTIVE COST MODEL"
795FOR I=1 TO T\!£1T(I,1),T(I,2),T(I,3),T(I,4),T(I,5)\NEXTI
796CLOSE£1
800 REM SIMUL
805 !C$\!"SIMULATING NOW ..."\!\!
810 FOR J1= 1 TO N
815 S=0
820FOR I = 1 TO T
825 IF T(I,4) = 0 THEN 905\REM IF UNIFORM DISTRIB THEN GOSUB 5200
830IF T(I,3) =T(I,4) THEN850
840 GOTO900
850 IF T(I,4) =T(I,5)THEN 870ELSE 900
860 GOTO900
870 REM POINT ESTIMATE  DO NOT GOTO SUBRTN
880V =T(I,4)
890GOTO910
900 GOSUB5000
901 GOTO910
905 M7=T(I,3)+((TI,5)-T(I,3))/2 )
906GOSUB5500
910 IF T(I,1)=0THEN920 ELSE 930
920 T(I,2) = -T(I,2)
930 S1 =T(I,2)*V
```

```
940 S=S+S1
942 IF I () 1 THEN 950
945 IF I$="DEPENDENT" THEN GOSUB 8700 ELSE 950
946!"I= ",I," I1$= ",I1$
950NEXT I
955 I1$=" "
960 LET X(J1) =S
965!
970 NEXT J1
980 REM*************** APPEND SORTATION HERE*****************************:
1000 R1=-10E+09\R2=10E+09
1010 FOR I=1 TO N
1020IF X(I))R1 THEN R1=X(I)
1030IFX(I)(R2 THEN R2=X(I)
1040 NEXTI
1045 LET R9 =(R1-R2)/B9
1046 !"SORTING OUTPUT INTO BAND WIDTHS...",
1050 FOR I=1 TO N
1060 FOR J=1 TO B9
1070 B1=(J-1)*R9 +R2
1080 B2 =J*R9 +R2
1090 IF X(I)( B1 THEN 1115
1100 IF X(I))=B2 THEN 1115
1110 Y(J)=Y(J)+1
1115 NEXT J
1120 NEXT I
1125                 IF P$ ="PLOTTER" THEN GOSUB 8[illegible]00 ELSE 1133
1127                      GOTO 1215
```

```
1130 Y(B9)=Y(B9)+1
1132 !£1,TAB(30),"M O D E L L E"\!£1,D7$
1133 !£1
1134 !£1\!£1\!£1,"function      ",F$
1136!£1,"number of simulations",N\!£1\!£1
1137!£1,TAB(8),"-----COST BAND-----",TAB(44),"--FREQ -",TAB(51),"CUM PROB"
1140 S1=0\FOR I=1 TO B9\S1=S1+Y(I)\NEXTI
1150 S2=0
1160 FOR I=1 TO B9
1170 B1=((I-1)*(R1-R2)/B9)+R2
1180 B2=(I*(R1-R2)/B9)+R2
1182 IF I = 1 THEN 1184 ELSE 1190
1184 B8 = B2 -B1\REM  B8 IS BAND WIDTH
1186 L9 = B1 \REM L9 IS LOWEST PRICE
1190 S2=S2+Y(I)
1194 S3 =S2*100/S1
1196  S3 =INT(S3+ .5)
1198 LET S(I)= S3\Y(I) = INT(Y(I))
1200 !£1,I,TAB(5),%$12F2,B1,TAB(25),B2,TAB(45),%3I,Y(I),TAB(55);S3
1210 NEXTI
1212 !\!\!"CALCULATING MEDIAN AND QUARTILES ..."
1215 GOSUB 7000
1220 IF P$ ="PLOTTER" THEN 1300
1230 FOR K =1 TO 5\!£1\NEXT\!£1,TAB(15),"CUMULATIVE PROBABILITY"
1235 GOSUB6000
1300 GOTO8000
```

```
5000 REM SUBRTN************************************************************
5010 REM THIS SUB TAKES THREE DESCRIPTORS OF A TRIANGULAR DISTRIBUTION
5020 REM (MIN,M L, MAX) & RETURNS A VALUE V SAMPLED FROM THE DISTRIBUTION
5040 A=T(I,3)\B=T(I,5)\C=T(I,4)
5050 A1 =C-A\A2 =B-C
5060 E =(       N/(A2*(A1+A2)))\D=(       N/(A1*(A1 A2)))
5080 R = RND(-1)\R = INT (N*R + 0.5)
5085 !R
5090 IF R)(       N*(A1/(A1+A2))) THEN5110
5100 V =SQRT(R/D)\V=A+V\GOTO5170
5110 R =       N-R\V =SQRT(R/E)\V =B-V
5120 IF I1$="HI" THEN 5140
5130 IF I1$="LO"THEN 5150 ELSE 5160
5140 IF V )=T(I,4) THEN 5160 ELSE 5040
5150 IF V (=T(I,4) THEN 5160 ELSE 5040
5160 RETURN
5170
5500 REM SUBRTN************************************************************
5510REM THIS SUB TAKES THE TWO DESCRIPTORS (A & B) OF A UNIFORM DISTRIB
5520REM AND RETURNS A VALUE V SAMPLED RANDOMLY FROM THE DISTRIBUTION
5525 LET A=T(I,3)\LET B= T(I,5)
5530 R = RND(-1)
5540 R = INT(R*N + 0.5)
5550 V = A + ( ((B-A)/N) * R)
5560 IF I1$="HI" THEN 5580
5570 IF I1$="LO" THEN 5590 ELSE 5595
5580 IF V )= M7 THEN 5595 ELSE 5525
5590 IF V (= M7 THEN 5595 ELSE 5525
5595 RETURN
```

```
6000 REM HISTOGRAM SUB
6025 !£1,TAB(6),"          20          40          60          80          100"
6030 !£1,TAB(6),"-----+----+---------+----------+----------+----------+"
6052 FOR I = 1 TO B9
6055 IF S(I) = 0 THEN6115
6060 LET H = S(I)/2
6070 IF H > INT(H) THEN 6080 ELSE6090
6080 H = H +1\H =INT(H)
6090 !£1,TAB(1),I,TAB(5),"I",TAB(6),H1$(1,H)
6100 !£1,TAB(5),"I",TAB(6),H1$ (1,H) \GOTO6140
6115 REM IF P=0 THEN NULL COLUMN
6120!£1,TAB(1)     ,I   ,TAB(5),"I"
6130 !£1,TAB(5),"I"
6140 NEXT I
6150 RETURN
7000REM SORT SUB
7005 M=N
7010 M =M-1
7020 C=0
7030 FOR I = 1 TO M
7040 IF X(I) <= X(I+1) THEN 7090
7050 H = X(I)
7060 X(I) = X(I +1)
7070 X(I+1) = H
7080 C =1
7090 NEXT 1
7100 IF C<> OTHEN 7010
7105 GOSUB 7200
7120 RETURN
```

```
8090 IF P$="PLOTTER" THEN8100 ELSE 9999
8100 CHAIN"DRAW"
8500 REM SUB*************************************************************
8510 REM CALLED FROM 1125
8515 REM CALC SIZE OF BANDS & FREQ IN EACH
8520 S1=0\FOR I=1 TO B9\S1=S1+Y(I)\NEXTI
8530 S2=0
8540 FOR I=1 TO B9
8550 B1=((I-1)*(R1-R2)/B9)+R2
8560 B2=(I*(R1-R2)/B9)+R2
8570 IF I = 1 THEN 8580 ELSE 8600
8580 B8 = B2 -B1\REM  B8 IS BAND WIDTH
8590 L9 = B1 \REM L9 IS LOWEST PRICE
8600 S2=S2+Y(I)
8610 S3 =S2*100/S1
8620  S3 =INT(S3+ .5)
8630 LET S(I)= S3\Y(I) = INT(Y(I))
8640 NEXTI
8650 RETURN
8700 REM SUB CHECKS IF FIRST TERM HI OR LO
8710 REM ******************** ****************************************
8720 M7 = T(I,4)
8730 IF M7 = 0 THEN 8740 ELSE 8750
8740 M7 = T(I,3) +( (T(I,5)-T(I,3))/2)
8750 IF V > M7 THEN 8760 ELSE 8770
8760 I1$="HI"\!"8760= HI"\GOTO 8790
8770 IF V < M7 THEN 8780 ELSE 8790
8780 I1$="LO"\!"8780= LO"\GOTO 8790
8790 RETURN
```

```
8900 !C$\REM SUB*************************************************************
8910!"MONTE CARLO EVALUATION USUALLY ASSUMES THAT THE TERMS ARE INDEPENDENT"
8920 !"THIS PROGRAM SUITE INCLUDES AN OPTIONAL TECHNIQUE FOR DEALING WITH"
8930 !"TERMS WHICH ARE NOT INDEPENDENT."
8940 !\!
8950!"TERMS INDEPENDENT",TAB(30),"1"
8960!"TERMS NOT INDEPENDENT",TAB(30),"2"
8970 INPUT M9
8980 IF M9 =2 THEN 8990 ELSE 8995
8990 I$="DEPENDENT"
8995 RETURN
9999END
```