ANALYSIS OF CONSTRUCTION ECONOMICS
: a cost simulation model

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ABSTRACT

This thesis concerns the highly complex relationship between cost and design decision-making.

A theoretical cost function is described by examining the output requirements of the design activity, and the constraints placed on the input to the process by current cost generation procedure. The description takes the form of a set of preferred characteristics or alternatively, criteria on which the potential of a future costing process might best be judged.

A particular interpretation of this set of characteristics is described, which produces the tentative specification for a new generation of cost models.

An implementation of the specification resulted in the computer-based cost simulation model ACE (Analysis of Construction Economics). This interactive, knowledge-based cost model is used to investigate a series of cost relationships and cost thresholds, both to exemplify its possible applications, and to produce some means of determining the validity of both the general approach, and the particular interpretation which ACE represents.

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"If I have seen further it is by standing on the shoulders of giants"

Sir Isaac Newton (circa 1675)

PREFACE

This thesis is concerned with the relationship of cost to design decision-making. It addresses the problem of how best to provide a designer with a sufficient quality and quantity of cost information to enable him to give adequate consideration to the cost consequences of each design alternative throughout the design process.

The problem is one of cost generation, cost interpretation and cost communication.

A problem, however, will never exist in isolation, but be surrounded by other problems in space and time (1). In this respect the theory of systems has proved remarkably successful in unraveling the secrets of nature: it now pervades most approaches to problem solving. The basis of systems theory is expounded in Appendix I, but essentially states that a problem can be considered in isolation provided its interactions with other problems are adequately defined. Where neighbouring problem sturctures are themselves ill-defined, this compounds the complexity of the analysis, prodigiously.

Building economics is particularly starved of knowledge, and this fact determines that almost any investigators within the realms of construction cost estimating should consider also the whole question of a quantity surveying 'science': consideration of the external characteristics and properties; of how the internal structure behaves and interacts; of such fundamental aspects even as the criterion to be used in determining a scientific status (2).

The Scope of The Thesis

> "There is an excitement in exploring the dirt tracks of a little known region, which is lost when the motorway is built". (3)

A similiar excitement applies to constructing a theory of building economics. The subject is both novel and unprescribed making it a stimulating and rewarding field in which to undertake research. The concomitant to such freedom is that research can often become introverted; inordinately concerned with inconsequential detail. An intermediate level is called for, somewhere between the 'motorway' and the 'dirt track', which allows an occasional foray both downwards - to consider the mechanics of the function being studied - and upward - to understand what role the function plays in the overall schema. The intermediate level will develop from 'dirt tracks' and form the basis of future 'motorways'.

In building economics, even these intermediate levels are ill-defined, and in consequence although this thesis generally is structured to progress from a process (Part One) to the mechanics (Part Two) it has of necessity been an iterative evolvement. For example, the requirements identified in Chapter 3 could only be made in the knowledge of how they might be interpreted (one such interpretation being given in Chapter 5). Further, both the list of criteria proposed in Chapter 4 as being the important characteristics to look for in future cost models, and the interpretation of that list, in Chapter 5, could not fail to be modified in the light of the experience gained in early implementations of the computer program ACE (Analysis of Construction Economics) described in Chapter 6. Thus, while the first few chapters shape the latter ones, these early chapters themselves have been influenced by what appear from the order of this thesis, to be subsequent discoveries.

CHAPTER 1 looks at the context of the work and introduces the concept of the building economist as a self-organising system: as an entity more akin to the animal (being perceptive to change and acting to take advantage of, or to reduce the harm from, such change) than to the inanimate (which has neither mobility, nor the capacity to perceive). This view clearly indicates the nature of the overall problem as being bi-dimensional (on the one hand the internal structure which constitutes the system itself; on the other hand the external structure of interactions with peripheral and exogenous systems), and this is reflected in the aims of the research and the research method.

CHAPTER 2 engages the problem of how best to consider the fundamental aspect to this thesis: the costing function. An input/output model is proposed, based on a view known as cybernetics in which the behaviour of an adaptive system simply can be taken as a processor of information. Information is input, controlled through feedback, and output.

CHAPTER 3 concerns the output requirements placed on the costing function: what information is required, in what form, and when? The role of the costing function is taken to be a 'servicing' of design. The output requirements then flow naturally from the dictates of design method and the design activity. A comparatively large body of research work now exists in this field, unfortunately without producing any definitive description. With no definition of design method there can be no definition of the cost data requirements of design. Some means of assessing alternative costing techniques is needed however and several requirements are proposed. They are not intended as an absolute arbiter, but as a set of guide lines with which to judge the potential of any particular approach to cost estimating. Appendix II details an extensive survey of existing costing techniques and relates each to the requirements of design. It is suggested that their universally poor performance points to some indiscretion when dealing with the input constraints.

CHAPTER 4 takes a fundamental look at the complete cost generation process and shows how the cost data it produces results from a series of complex assumptions about labour output, plant efficiency, material costs, market conditions, etc., and is only notionally allocated to the unit of finished work. All of these are inherently inaccurate assumptions; it is apparent however that they are far from purely random inaccuracies and, as such, are less likely to conform to the basic patterns of statistical stability. It is argued that the concepts and techniques of probability theory may be inappropriate when dealing with such 'structured' uncertainty (4); and might instead be better equated with the recent developments in fuzzy-set theory. An example of how a 'fuzzy' approach to cost uncertainty might be accomodated is given in Appendix III. The implications of this interpretation are summarised as a series of constraints placed on the costing function.

Part One concludes with a list of the preferred cost function characteristics. The list is intended to focus attention upon the most significant aspects of the problem.

Naturally various interpretations of a set of characteristics are possible. CHAPTER 5 details one such (typical) interpretation by considering each of the characteristics from Part One in turn, and producing a detailed specification for the next generation of cost models.

CHAPTER 6 examines the practicability of this specification through a description of the knowledge-based cost simulation model ACE (Analysis of Construction Economics). A validation exercise largely encourages further development both of the model, and of the approach generally. A retrospective appraisal of the model provides important insights for those who would follow a similar course of research.

CHAPTER 7 details a number of investigations into various cost relationships and cost thresholds which, to an extent, display the logical 'form' of the model. It is then for the light of experience to determine the validity of the theory on which ACE is formulated. This validation cannot be once and for all in a positive sense, but in a negative sense the model is not disproved, perhaps, for the time being.

CHAPTER 8 summarises the research and draws conclusions. The outlook is generally very optimistic; but of equal importance, the work has also identified a number of areas within which significant research endeavour, at the present juncture, might best be left to other disciplines.

References follow each chapter and appendix to which they relate. Because of the wide range of subjects covered, the BIBLIOGRAPHY is partially annotated and arranged by topic.

REFERENCES

1 ACKOFF R L
"Scientific Method: Optimising Applied Research Decisions", Wiley, 1962.

2 POPPER K R
"Conjectures and refutations", Routledge and Keegan Paul Ltd., 1963.

3 ARBIB M A
"The Metaphorical Brain", Wiley-Interscience, 1972, p.10.

4 KAUFMANN A
"The Science of Decision-Making", World University Library, 1968.

PART ONE: THE COSTING FUNCTION - A PROCESS

CHAPTER ONE: INTRODUCTION

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1.1 The Context of the Work

Darwin showed how it is possible to consider an entity within what is effectively an exogenous frame, the frame being defined by all previous transformations of that entity. A 'transformation' is an event characterised by an often volatile reorganisation within the entity and concomitant change in the relationship between the entity and its environment. It is this relationship which forms the exogenous frame. For instance, the reptile first evolved from an otherwise wholly aquatic creature because the fin transformed into a leg. In more abstract terms, consider an irregular rectilinear body acting as the exogenous frame (see Figure 1.1). Its progress down an inclined surface (or through 'time') will not be a smooth continuum, but rather a series of positional shifts (i.e. transformations) which will each cause a temporary increase in the activity of any contents of the body as they reorganise to accomodate a changed attitude to the environment.

These transformations, clearly equivalent to the "paradigm shift" of Kuhn (1), may be caused in any of three ways:

(i) The entity itself may induce a change (see Figure 1.1(a)).

(ii) An external force may be applied to the body as a whole (see Figure 1.1(b)).

(iii) Both internal and external forces may act in unison; it is in this case that a transformation is likely to produce the most explosive change (see Figure 1.1(c)).

One can consider the quantity surveying profession as just such an evolving body: the contents of the body are the many practitioners, committees, sponsors, etc.; the exogenous frame is the professional relationships with other design disciplines, the public, the law, etc. Useful parallels can then be drawn with the previous abstract example.

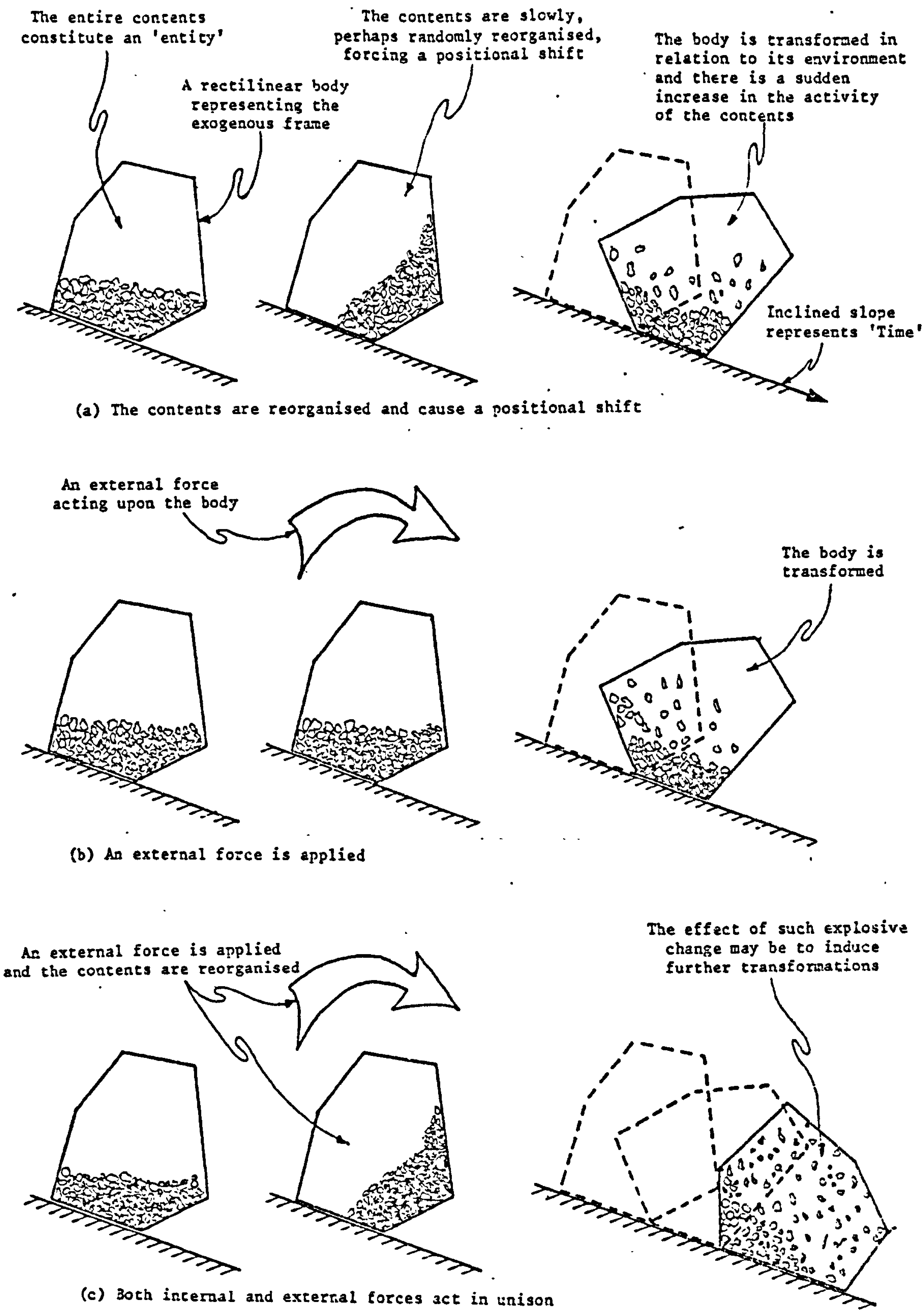


Figure 1.1: An abstract concept of how transformations may be caused

The most fundamental equivalence is that there exists two very distinct aspects of the profession; on the one hand its internal structure, and on the other its relationship with the external environment. Fundamental because the profession will be transformed, if not by its own effort then by external force, it will evolve with or without pre-knowledge of what is to come. If, then, the profession wishes to grow, or even to influence its evolution, it must recognise the significance of factors outside just as much as inside the discipline, aiming to harness each to optimum efect.

In evaluating the environment of any research work within building economics, consideration must first be given to the state (the present configuration and the stability) of both of these factors.

1.1.1 External factors

The SITE Report (2) stated:

"Of all the factors affecting the professions, social and political trends are probably the most difficult to monitor and assess. The structure of society in the United Kingdom is a complex kaleidoscope in which changes may be imperceptible except over a long period of time. The structure is obviously influenced by the growth and redistribution of wealth, the size of the population, the broadening of educational opportunities, the power-lobbies of organised capital and labour, the impact of new technology including computers and silicon chips, the need to revitalise British industry, problems of unemployment and changes in the pattern of living, including greater opportunities for leisure activities."

The list is far from exhaustive but serves to illustrate the range of external factors which impact upon the quantity surveying profession. For example, client pressures and intervention through legislation has demanded a higher level of competence and conduct by professional advisers. To maintain the appropriate standards the

R.I.C.S. now ranks continuing professional development high in its list of priorities for the 1980s and recommends a minimum of 20 hours of study in any year (3). Also, the trend towards a "corporate" state with greater public involvement in many aspects of professional activity can but fuel the call for an abolition to the structured fee scale which characterises the profession at present (4).

Other influences include the economic trends of continuing inflation, flagging productivity, uncertainty and lack of confidence by investors in the industry, and the recurring manifestations of the 1973-74 oil crisis. These economic factors tend to be cyclical, but have reached such troughs recently that the Institute was forced to undertake a policy of lobbying both the Government and the industry as a whole.

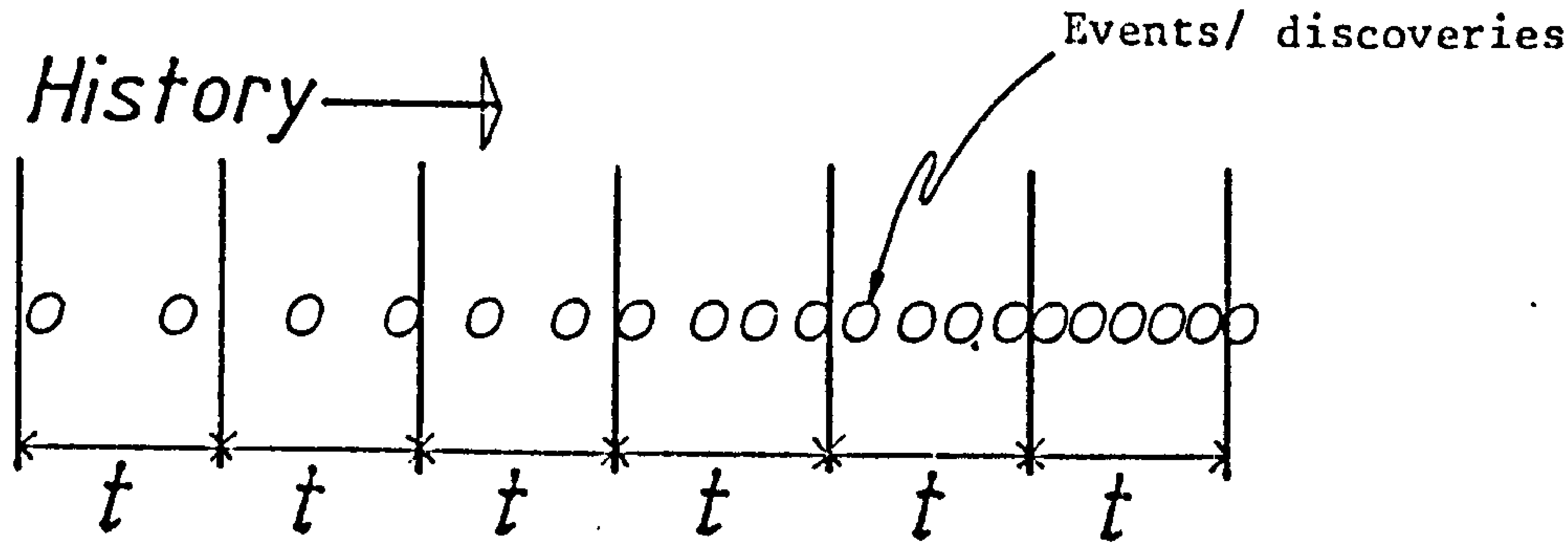
The 'Group of Eight' (set up in 1977 to brief Members of Parliament of all parties on construction industry affairs) was undoubtedly instrumental in shaping the March 1982 budget which revealed an expected rise in construction expenditure of 13 per cent, to £10.25 bn. in 1982/83; up to £70 million was earmarked for joint public/private sector developments giving the prospect of a 30 per cent increase in local authority capital spending on housing; extensions to industrial building allowances were made to encourage the building of new rented accommodation; there are new stamp duty thresholds of special help to first-time house buyers; index-linked capital gains and capital transfer taxes; and an increase in home improvment grants from 75 per cent to 90 per cent, with the £100 million rise in local authorities' capital spending allocation to pay for them being a positive incentive when the state of the nations housing stock is causing great concern. The prelude to an upturn in the construction industry's economy perhaps, but the recession has cut very deep, with the industry's workload at its lowest for 25 years (5).

It is however in the technological sphere where change might be expected to compound at the fastest rate.

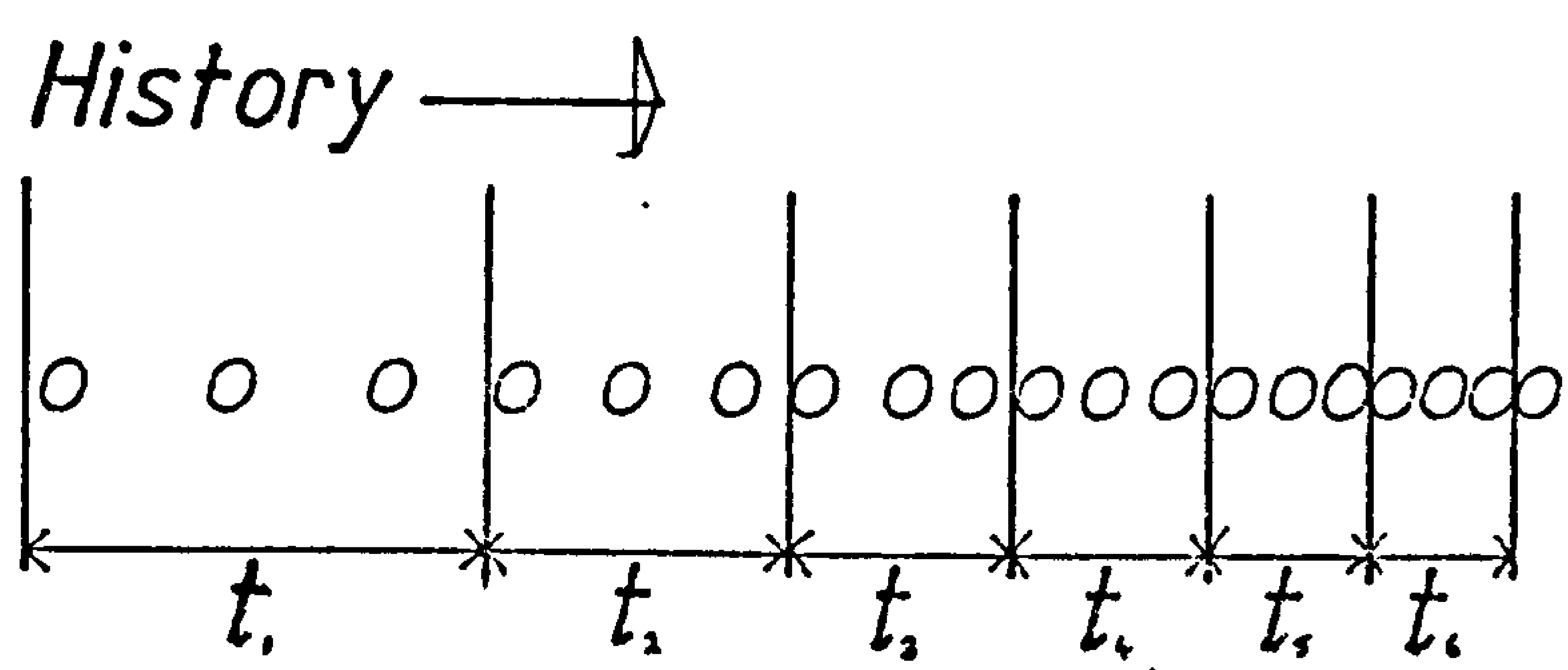
The theory of relativity in physics states that time is not homogenous for all bodies in motion, but depends upon the speed of the moving body. This phenomenon, in which the passing of time slows down as the speed of the body increases, is called the 'contraction of time'. It is conceivable that another form of contraction is occuring in terms of technological change. If each new discovery was charted throughout history, then the same period of time will be richer in events the later it occurs (see Figure 1.2(a)). If instead of dividing time into equal periods it is divided into intervals each containing the same number of events, then the duration of each of these intervals will become smaller and smaller (see Figure 1.2(b)). Equating this representation with the phenomenon of time contraction clearly indicates that change in technology is indeed speeding-up.

It is apparent also that it is the considerable increase in quality and quantity of information available through oral and/or visual communications which has provided the vehicle for such change. The wheel, gunpowder, the printing-press, when they were invented, had an immediate effect on the ideas and living conditions of certain people but for centuries remained unknown over large areas of our planet. Nowadays, on the contrary, the historical and geographical impact of technological progress is almost simultaneous on individuals and groups throughout the world. Thus, though technological progress has always had important repurcussions previously, owing to the more extensive distribution of information and the comparatively large accumulation of knowledge, its effect is now quicker and less diffuse.

External factors are exerting strong pressure upon the quantity surveying profession, sufficient, one might expect, to transform the discipline as it exists at present. The internal structure, however, may be arranged either to encourage, or to discourage, these external influences. It is of interest to discern where such emphasis is placed.



(a) History divided into equal time periods, shows the later periods to be richer in events



(b) History divided into intervals containing an equal number of events, shows the period of each to be increasingly smaller

Figure 1.2: Alternative representations of technological progress (After A KAUFMANN, "The Science of Decision-making", World Uni. Lib., 1968, p20)

1.1.2 Internal factors

Diversification into various spheres of engineering, as opposed to just the construction elements of a project, has been prompted by the setting-up of a Q.S. (Civil and Heavy Engineering) Committee, a Q.S. (Engineering Services) Committee, a Joint Documentation Board for Industrial Construction and Works, the inclusion of a civil and heavy engineering option in the R.I.C.S. Test of Professional Competence, etc. The propensity towards integrated design, multi-disciplinary offices, design and build contracts, earlier involvement of the quantity surveyor in the design decision-making, etc., is commonly felt to have resulted from external pressures, with the profession generally paying only lip-service. Yet who would doubt that diversification has been forced by a shrinking construction market, or that fully integrated design is implausible without the general consent of the profession. As either factor might influence the profession, and either might be to the advantage or detriment of the other, it is necessary to consider all aspects of change as being appreciable; any aspect could prove to be the catalyst, either for a direct transformation in itself, or for the switch in emphasis which promotes a subsequent transformation.

Diversification has already been exemplified through the variety of quantity surveying involvement in engineering, but is is apparent that the traditional role is also being extended. Overseas work is bouyant, with the recently published Principle of Measurement (International) for Works of Construction being utilised on a wide range of overseas contracts. Further, quantity surveying involvement is being sought in a considerable number of developed and developing countries, often even those in direct competition with United Kingdom firms. Perhaps the standards established by quantity surveyors in construction markets such as the Middle East have left these other countries feeling short of know-how on the contracts, tenders and measurements side (6).

Traditional facets of the quantity surveyor's involvement in the design activity have also taken on new dimensions. The oil crisis of the past decade has induced profound change in attitudes towards energy conservation. Existing skills, suitably applied, allow the quantity surveyor to play an important role in the rational development of alternatives, through the analysis of energy production costs and more importantly the cost in use of particular energy types (7). Yet confusion still exists in the subject areas of accounting practices, real costs, and investment criteria. Indeed the question has been posed (8): "is the quantity surveyor interested in this areas of endeavour or not?"

Somewhat similarly, there is a general inertia towards the use of computers.

For three years now, monthly articles have been published in the Chartered Quantity Surveyor; the QS (Research and Development) Committee has organised numerous "Hands-on" days; a guide entitled "Chartered Quantity Surveyors and the Micro-Computer" has been published; not to mention general media coverage. The number of practitioners responding to such initiatives continues to be disappointing and of the 5 per cent of members making any use of the new technology (9), a vast majority are confined to the production of fee acounts, standard packages for salaries, PAYE and VAT, and word processing (10) - hardly the 'nub' of quantity surveying.

Thus, while certain internal factors are being well supported and intended to compliment external factors, others are not having the degree of effect one might have imagined from their impact on other disciplines. There exists the real danger that this shortfall is caused, not by any lack of external pressure nor by rational consideration, but through a breakdown in, or resistance to, the mechanics of change. For while it has proved comparatively trivial for a quantity surveyor to become conversant with building practice overseas, or with industrial or civil engineering, the particular disciplines of physical energy or computing science appear totally alien. Perhaps an explanation for this phenomenon lies in the following:

(i) The traditional quantity surveyors training is through apprenticeship and gives little appreciation of, or respect for, the rigour of scientific method. With the setting-up of a recruitment group (11) to investigate recruitment to the profession and to suggest means of improving both the number and standard of trainees, it is expected that future quantity surveyors will be more ready and better able to accept scientific rigour. Certainly the Brett-Jones Report on education (12) concluded that -

"...it will be a cardinal objective of educational policy to encourage and enable candidates to develop an original analytical approach to the solution of problems and to improve the standard of their communicative skills".

(ii) The transfer of information within the profession is inadequate. The following have all made significant contributions to the dissemination of information, but much improvement is still needed to ease communication with and between the professions' grass roots:

* the recently improved format for the Chartered Quantity Surveyor
* the Building Cost Research Conference sponsored by the Association of Heads of Departments of Surveying in Polytechnics
* the QS (Research and Development) Forums
* the decision by Building Cost Information Service to set-up a computer data base as an aid to cost planning and estimating

1.1.3 Summarising the context of the work

The quantity surveying profession is clearly a self-organising entity: a living body, actively monitoring and reacting to its environment.

It is apparent also that this entity is in a state of evolution. The transformation is being accentuated in certain respects because the structure and make-up of the profession is well suited to cosmetic changes of the traditional quantity surveying function. However, the professions failure to respond positively to other factors suggests:

(i) that it is unaware such factors exist

(ii) that it does not wish to respond, or

(iii) that it is incapable of response.

Surely it is inconceivable that the quantity surveying profession should be ignorant of such colossal and widely publicised issues, and in view of the ramifications, wholly irrational to oppose them. Indeed, as Kaufmann states (13):

"The greatest evil of a civilisation lies in its refusal to re-examine itself, to adapt itself to its own creations, to shake of complacency and to steer itself along the path of adventure. Threatened from without and even more from within, a rigid civilisation cannot resist, and worse still, it no longer has any reason for existing".

However, just as it is disfunctional for an animal's brain to detect a certain foodstuff if its body cannot metabolise it, so it is inadequate simply to inform a profession of an energy crisis or silicon revolution without providing the capacity for action. Organisational changes are evolving and, encouragingly, a call to develop the science of quantity surveying to provide a sounder academic basis has already been made (14).

These factors, however, are more directly the concern of the Institute, and the profession it represents. The individual cost researcher must take as his mandate: "the provision of a vehicle for rapid transformation of the profession once the organisational changes commensurate with improved communication and an acceptance of scientific rigour, have permeated".

1.2 The Aims of the Research and the Research Method

The context of the work indicated clearly that strong external pressures are being brought to bear upon the profession generally. It further suggests that the internal fabric of the profession is being re-shaped to accomodate these external factors. The utility of this process will be influenced greatly by the tools and techniques then available. To re-use the analogy; 'a road is being built to carry a particular pay-load, the researcher must ensure that a suitable vehicle then exists to convey it'.

This however does not yet sufficiently distinguish the problem, and though consideration at this level is necessary, the principle concern will be in respect of the relationship between building cost information and design decision-making. Again, the problem could be further distinguish by considering it in even greater detail, but it is apparent that the only full definition of this and of any other problem is the solution of that problem.

For a stage in research as early as this, an expression of the problem is required which does not place so much reliance upon its own solution. A possible expression is indicated by Ackoff (15) in his consideration of the distinction between scientific and non-scientific (or 'common-sense') enquiry. He argues that the superiority and distinction of scientific enquiry dervies from the fact that is is controlled. A process is controlled to the extent that it is efficiently directed toward the attainment of desired objectives. It follows that initial research need not necessarily define the problem fully, but can merely be directed toward some set of goals, hypotheses, or laws.

The question then arises of how such goals, hypotheses, or laws might be formulated.

Research on directed thinking has evolved within two main traditions. One tradition has its roots in the Behaviourism of Watson and Hull: that thinking is a completely objective system where the emphasis is placed on trial-and-error with reward stamping in, or reinforcing, the correct response; that thinking is a mechanical reinforcing, the correct response; that thinking is a mechanical progression from one idea to another associated idea, the association having been formed by contiguity, similarity, etc.

The other main tradition has its roots in the Wurzburg School (1901-13) and in Gestalt psychology. They suggest that chains of associations are insufficient to explain problem solving, and postulate instead that there are mechanisms in the brain for converting sensory information into a model of the environment, and for utilising this model in the solution of problems; modifying its own internal structure by the transformation of the representational system as a whole (16).

It is difficult to find crucial differences between the predictions which follow from the theoretical notions of either of these two traditions, and this fact gives some explanation for the inability of each to prove the other wrong. It further suggests that the formulation of goals, hypotheses, or laws, might come as equally from the progressive gathering of facts, as from the sudden insight.

The most apparent distinction would seem to lie in the initiation of a process which either aims to extract pattern from a finite data set (the inductive methods), or which aims to refute a given conjecture (the deductive methods). It is usual to call an inference 'inductive' if it passes from a singular statement (sometimes called a 'particular' statement), such as accounts of the results of observations or experiments, to universal statements such as hypotheses or theories. Such processes have also been coined the 'bottom-up' approach. Simon (17) has shown how it is possible to define this process as a process for recording in parsimonious fashion, sets of empirical data from which discovery proceeds through retrospection (18). Popper (19), on the contrary, contends that the 'principle' of induction (i.e. accepting the logic of basing a universal statement on experience) is only sound if one first accepts a principle of induction, and so on ad infinitum. In short, that the principle of induction leads either:

(i) To an infinite regression, or
(ii) To the doctrine of apriorism.

He argues for the superiority of deductive logic and thereby for the advantages of having unjustified (and unjustifiable) anticipations or insights at the commencement of research. A process known also as the 'top-down' approach.

That both the alternative approaches can be, and have been, exemplified with accounts of previous scientific discoveries, suggests that certain conditions might favour one above the other. A scientist engaged in a piece of research in physics, for example, can attack his problem straight away. He can go at once to the heart of the matter: to the heart, that is, of an organised structure. Indeed he has to go directly to the problem, because the structure has so many levels of existing doctrines making-up its hierarchy. To proceed from the general to the specific in such an environment would require many many speculations. Better in this instance to consider and accumulate facts at the branches of the hierarchy which can then feed into the next level up. Research in subjects such as building economics, however, is not so conditioned. There is no generally accepted problem-situation, and the system hierarchy is yet to be defined beyond one or two levels. Given this situation, knowledge should progress most rapidly through wholly tentative solutions whose only control is criticism and the 'learning' gained through mistakes. This is how to become better acquainted with the problem, and thereby better able to propose more mature solutions.

A top-down approach is indicated.

Before expounding the initial hypotheses, or aims, which led to the research work here-in reported, a further note on the utility of deductive reasoning is appropriate. In considering the 'hypothetico-deductive' scheme, Popper succeeds in isolating a fundmental misconception within science generally, this being arguably the most significant attribute of deductive reasoning: the fact that there is no criterion of truth (20). Succinctly, he elucidates the dangers of adopting a doctrine in which truth is ever manifest. Of adopting 'truth' as veiled perhaps, but which when revealed naked before our eyes:

(i) We have the power to see,

(ii) The power to distinguish it from falsehood, and

(iii) To know that it is the truth.

He goes on to suggest that this doctrine should therefore be rejected, and instead that (21):

> "... all we can do it grope for the truth even though it is beyond our reach. We may admit that our groping is often inspired, but we must be on our guard against the belief, however deeply felt, that our inspiration carries any authority, divine or otherwise. If we thus admit that there is no authority beyond the reach of criticism to be found within the whole province of our knowledge, however far it may have penetrated into the unknown, then we can retain, without danger, the idea that truth is beyond human authority."

It follows from this, that there can be no ultimate statements in science; that there can be no statements in science which cannot be tested, and therefore none which cannot in principle be refuted by falsifying some of the conclusions which can be deduced from them. This places great emphasis on the testing of hypotheses, and can all be summed up by saying that the criterion of the scientific status of a theory is its falsifiability, or refutability, or testability. The scientific status of this thesis should therefore be assessed on the rigour with which it attempts to refute or test the hypotheses on which it is based.

In proposing the hypotheses and aims of the research it should be noted that in such a problem environment as building economics, the first moves are going to reveal many more problems than they will solve (22). The initial hypotheses are going to change and continually be refined as the research progresses. In this respect the hypotheses presented here, at this early stage, are little more than crude statements of intent, influential considerations, general preconceptions and assumptions; but hypotheses none-the-less.

Hypotheses are nets: only he who casts will catch (23).

1. 'To restate, the principle concern of this thesis is with the relationship between building cost information and design decision-making'. There is no particular justification for this, simply that the cost advice provided by traditional techniques has been criticised by the full range of design professions over a number of years, not least by quantity surveyors themselves (24).

2. 'Any proposals should evolve from current practice'. A classic failure in this respect was the 'Operational Bill' developed by the then Building Research Station (25). In something of a one-man crusade, Skoyles toured the country unceremoniously tearing in half the Standard Method of Measurement, and exalting the virtues of an operational format for tender documents. But the Operational Bill represented such a radical divergence from current practice that even the BRS was forced to concede a 'half-way house' (26). It may now be argued that certain sections of SMM 6 are very much operationally orientated, but it is wholly apparent that change is occuring through gradual evolution, not sudden revolution.

3. 'Greater use should be made of the computer, and in this respect the experience of research groups such as ABACUS and EdCAAD will be invaluable'. It is almost inevitable that computers will impact upon all aspects of human endeavour. A very simple explanation for this lies in the relationship of labour costs, to computer costs. It is apparent that in western economies labour costs in respect to productivity are tending to increase in real terms, and can be expected to continue to do so except perhaps in times of very severe recession. Computer costs, on the contrary, are falling dramatically and even when included

with all peripheral equipment and operating costs, the real costs are still decreasing. Certainly in terms of micro-economics, then, it is becoming cheaper to use the computer than to rely entirely on human resources.

ABACUS is a research and consultancy unit attached to the Department of Architecture and Building Science in the University of Strathclyde. It was established ten years ago and its current members have, between them, over one hundred man years' experience of computer use in building design applications. The suite of programs they have developed cover a full range of applications from whole school, hospital, or airport design, through general appraisal packages and on to detailed energy and visual impact models (27). When the superb computing facilities which are available through the group are added to this, then their direct involvement in computer-aided design research becomes fundamental.

4. 'The work should propogate a science of quantity surveying and provide the framework for otherwise discrete research endeavours'. The call to develop a science of quantity surveying has come from, among others, the Institution itself (28). However a research effort does not have the singular purpose of answering a question or solving a problem, it must also aim to test, evaluate, and improve the research procedures employed. The products of scientific inquiry then are an improved body of knowledge, and a more effective set of procedures for adding to that knowledge (29). It is suggested to make the most of the comparatively small amount of research undertaken so far in building economics, that the research endeavour should be homogenised. This calls for due consideration to be given to the utility, and thereby the general aplicability, of any tool, technique, or method developed.

5. 'The role of cost information is to service design and it is unacceptable to treat cost estimating as an end in itself'. The main role of a cost estimate is, usually, to predict and translate a cost expressed in terms of an operation (being a piece of work that can be completed by a man, or a gang of men, without interruption from others (30)), to a cost expressed in terms of an activity (being an expression of the building users requirements of a space): i.e. to translate cost information from the language of construction to the language of design. The direction is important, clearly indicating that design is the ultimate determinant, with cost information a mere transitory stage.

6. 'The quality and quantity of cost information available during the early stages of design, should be improved'. Pareto's law of distribution states that "the effect of any given action will decrease in significance the further along a complex process it occurs". Indeed, that 80% of total effect will be committed by the first 20% of decisions (see Figure 1.3).

It is also the case that the cost of changing a decision will increase the later in the design process it occurs. This is because of the greater amounts of abortive work, and the time involved in cross-checking drawings, etc. to maintain integrity.

Combining the two effects, the potential for cost saving is shown to be far greater during the early stages of a design (see Figure 1.4). In many instances however the architect is not made aware of any cost plan in the early stages or, when a cost plan is circulated, often the assumptions on which the cost is based are not revealed (31).

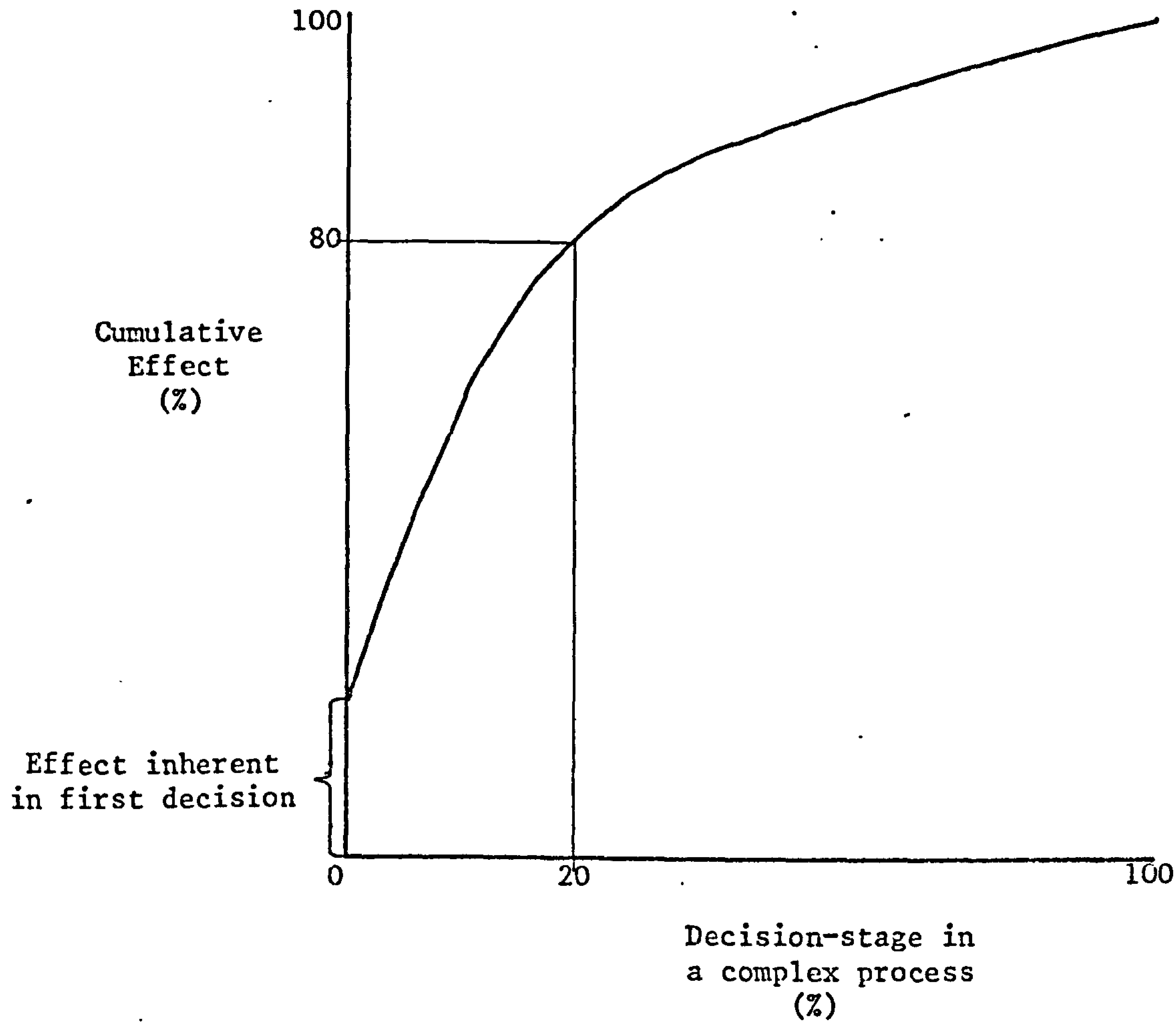


Figure 1.3: Pareto's Law of distribution

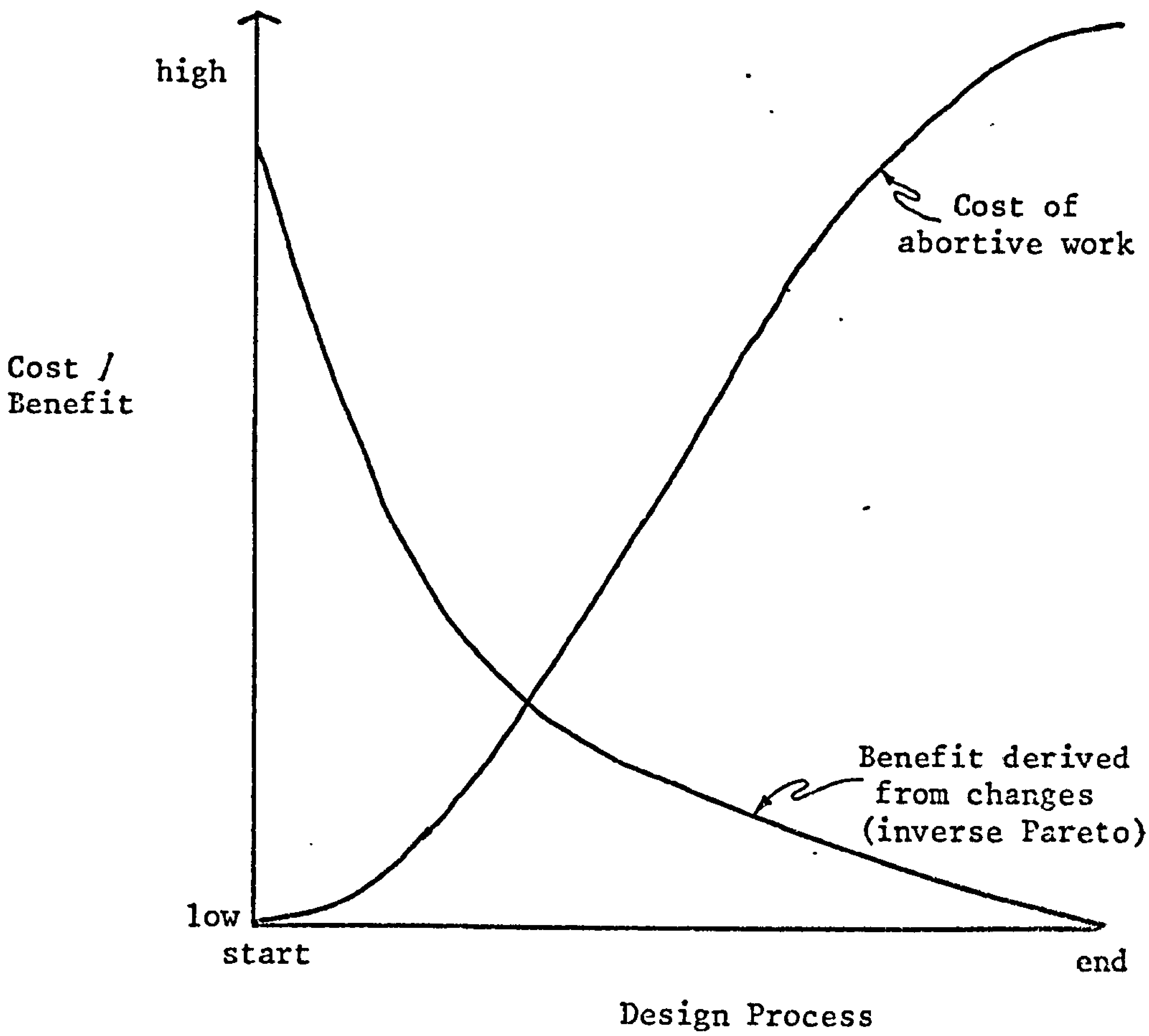


Figure 1.4: The cost/benefit profiles for design decision changes

7. 'The use of the term 'cost' shall denote a sum payable to the client for the contractors undertaking to expedite the works. This thesis will only consider the initial costs of a project'. Throughout the construction industry there is still a misuse of the words cost, price, and value, to such an extent that it is necessary to clarify their use within this thesis (32).

Confusion occurs when a word that has a simple, clear meaning in a general context is used in a context which is specific and concrete (33). At a general level, each of the above terms can easily be distinguished:

* 'cost' is an absolute and quantified measure of the demand made upon scarce resources in that it is what has to be given up to achieve something.

* 'price' is a market interpretation of cost between a particular source of demand (e.g. the buyer) and a particular source of supply (e.g. the seller), at a given point in time.

* 'value' is an abstract quantity only of meaning when applied 'to' something, 'by' someone. The value to a given observer of any commodity, is an interpretation of the quantitative and qualitative benefits applied by that observer.

At a more specific level however the meanings of each term overlaps to such an extent that effectively they become meaningless. For example, the 'cost' of a project to a developer is the 'price' he pays to the contractor, and may also set the property's 'value' to him on the open market. Cost planning is really price planning, material prices are really production costs, etc. Some of these misnomers are so often used in practice that, for instance, the use of the term 'price control' would cause confusion whilst 'cost control' is instantly recognised as a technique for controlling prices!

Though possibly incorrect in its pure sense, the term 'cost' is used in this thesis to refer to the sum paid by the project client/building owner. Where used to connote, say, the cost to the contractor, this will be specified.

Even this is not sufficient however since the term may refer to initial cost (the amount paid for the completion of the works), finance cost (the interest paid on borrowed collateral), or running cost (maintenance, repairs, etc.). The lack of accurate records to indicate the cost of repayment of capital and interest, the cost of annual and cumulative maintenance, the cost of additions and improvements to the nation's building stock, comparative output levels for building users, etc. (34), has determined that consideration in this instance be given only to the initial cost of a project, the tender price.

8. 'A cost estimate should express an appropriate consideration for the uncertainty inherent both in the estimating process, and in the tendering procedure it reflects.' It has always seemed an oversimplification, intuitively at least, to develop a cost estimate from a range of historical projects, and to provide only a single value within that range without giving also an indication of the variance encountered. Recently a number of authors have suggested that probability theory might provide an expression of cost which is more indicative of the inherent uncertainty. Following from this it was expected that not only would probability express the

uncertainty but that it could also be applied to generate the uncertainty. In the subsequent research of this thesis the expectation proved to be optimistic.

9. 'The lack of knowledge relating to building economics needs to be supplemented by increasing the capacity to 'learn by discovery'. It is apparent that if even the experienced quantity surveyor has only a limited knowledge of building economics, then the quantity surveying student, architect, and others possibly naive in terms of building economics, will be acutely ignorant of cost relationships and cost thresholds. Such knowledge can only be gained through a repeated experience of how building economics is structured; of the dynamics of cost.

Experience in practice is all too slowly gained, and then, not without the cost of gaining less experience in other aspects of quantity surveying. A means of replicating the way in which building economics is structured would allow the student to interrogate various cost relationships at will; to experience the intricasies of building economics in the relative calm of the class room; to discover, for himself, the 'rules of thumb' so often applied in practice (35). It is hoped to promote and encourage such a means throughout this thesis.

10. 'The design activity needs to be integrated'. The conventional means of recording design information, briefs, drawings, schedules, specifications, and so forth, contain a number of drawbacks and inefficiencies:

(i) Information is not integrated and requires correlation between its different forms (36)
(ii) A great deal of redundant information may be generated and remain in existence

(iii) Each profession or discipline involved in the design requires a different sub-set of the information, in different formats, incurring an overhead in the subsequent co-ordination of information (37)

(iv) As the design proceeds information becomes obsolete yet the high cost ensures that revision is undertaken infrequently

(v) It is argued that a great deal of time is spent non-productively in translating information from one state to another (38)

All of these problems are, of course, exacerbated as projects become larger, involving longer development time and more design disciplines.

1.3 Summary

To introduce the work the quantity surveying profession is considered as an evolving entity, thus identifying two significant aspects to the context of the work:

(i) There are external influences which impact upon the profession and exert significant pressure on the organisational structure as it exists currently.

(ii) There is an internal structure which at present appears well suited to superficial changes in the traditional functions, but which is failing to respond positively to other factors.

It is suggested that the necessary organisational changes are permeating, and that the concern of an individual cost research should therefore be to provide the tools and techniques (the 'vehicle') with which to then expedite a suitable transformation of the profession; to elicit maximum effect from the external forces.

Scientific method demands a more distinctive expression of the problem than this. By efficiently directing the research toward the attainment of desired objectives, the need to distinguish the problem uniquely is obviated. It remains only to choose between a 'bottom-up' approach (where the research emphasises the collection of a finite data set from which a pattern might be extracted through inducation), and a 'top-down' approach (where the research lays emphasis on the testing of a hypothesis through falsification of a series of deductions drawn from this hypothesis). The problem-situation indicates that a top-down approach might be most suitable.

The initial aims of the research are recognised as subject to continual refinement and change as the research progresses, but none-the-less they do justify formal statement.

1. The principle concernis with the relationship between building cost information and design decision-making.
2. Any proposals should evolve from current practice.
3. A greater use should be made of the computer and, in this respect, the experience of the research group ABACUS.
4. The work should propogate a science of quantity surveying and provide the framework for otherwise discrete research endeavours.
5. The role of cost information is to service design, and it is unacceptable to treat cost estimating as an end in itself.
6. The quality and quantity of cost information available during the early stages of design should be improved.
7. This thesis is to consider only the initial costs of a project.
8. A cost estimate should express an appropriate consideration for the inherent uncertainty.
9. There ought to be an increased capacity to learn by discovery.
10. The design activity needs to be integrated.

REFERENCES

1 KUHN T
"The Structure of Scientific Revolutions", University of Chicago Press, 2nd edition, 1970.

2 POLICY REVIEW COMMITTEE OF THE RICS
"Surveying in the Eighties", RICS, 1980, p.6.

3 ANON
"CPD for QSs", in CQS, July 1982, p.376.

4 LAYFIELD F Sir
"Why the RICS is Fighting the OFT", CQS, July 1981, p.394.

5 RICS
"The 114th Annual Report of the General Council 1981/82", CQS, August 1982, p.4-5.

6 VICKERS C
"Finland moves to QS Methods", CQS, March 1981, p.282.

7 MARSHALL R
"A Role in Rational Energy Use", CQS, April 1982, p.262.

8 O'SULLIVAN P
"Energy Conservation: Some Economic Questions", in 'Building Cost Techniques: New Directions', P S Brandon (Ed.), E & FN Spon, 1982.

9 BENSASSON S
"Micros in Construction", Design and Construction Computing Association, Cambridge Press Ltd., 1980.

10 HUNT G
"Back to Basics", CQS, May 1982, pp.314-315.

11 RICS
"Annual Report - 1980-81", RICS, 1981, p.14.

12 SPECIAL (REVIEW OF EDUCATION POLICY) COMMITTEE
"Review of Educational Policy", RICS, June 1978.

13 KAUFMANN A
"The Science of Decision-Making", World Universal Library, 1968, p.231.

14 POLICY REVIEW COMMITTEE OF THE RICS
Op Cit., p.9.

15 ACKOFF R L
"Scientific Method: Optimising Applied Research Decisions", Wiley, 1962, p.3.

16 WASON P C and JOHNSON-LAIRD P N (Eds.)
"Thinking and Reasoning: Selected Readings", Penguin Books, 1968.

17 SIMON H A
"Models of Discovery", in 'Boston Studies in the Philosophy of Science, Vol.LIV', R S Cohen and M W Wartofsky (Eds.), Reidel Publishing Co., 1977. Chapter 5.

18 HANSON N R
"Patterns of Discovery", Cambridge University Press, 1958, p.71.

19 POPPER K R
"The Logic of Scientific Discovery", Hutchison, 1968.

20 POPPER K R
"Conjectures and Refutations", Routledge and Kegan Paul Ltd., 1963, pp.3-30.

21 POPPER K R
Op Cit., 1963, p.30.

22 CRICKMAY C L and JONES J C
"Design I - Imagination and Method", Technology Foundation Course, Units 32-34, The Open University Press, 1972, p.8.

23 NOVALIS
cited in "The Logic of Scientific Discovery", K R Popper, Hutchinson, 1968.

24 FLANAGAN R
"Tender Price and Times Prediction in Construction Work", PhD Thesis (unpublished), University of Aston, 1980.

25 SKOYLES E R
"Introduction of Operational Bills", BRS, Current Paper CP/D32, 1963.

26 SKOYLES E R
"Introducing Bills of Quantities (Operational Format), The Quantity Surveyor, May/June, 1968, pp.139-146.

27 ABACUS
"Papers, reports, Manuals, Publications", ABACUS.

28 POLICY REVIEW COMMITTEE OF THE RICS
Op Cit., p.9.

29 ACKOFF R L
Op Cit., p.5.

30 SKOYLES E R
Op Cit., 1963.

31 UNIVERSITY OF READING
"Construction Cost Data Base",PSA, 1980, Vol.1, p.60.

32 SKOYLES E R
"Prices or Costs", The Quantity Surveyor, Vol.33, No.9, April 1977, pp.165-168.

33 JORDAN N
"Themes from Speculative Psychology", Tavistock Publication, 1968, pp.44-65.

34 TRENTON H P
"Terotechnology: The Right Life Span", Building, 25 April 1975, pp.95-97.

35 LAWSON B
"How Designers Think", Architectural Press, 1980.

36 DEPARTMENT OF THE ENVIRONMENT
"Structuring Project Information", HMSO, 1972.

37 PROJECT INFORMATION GROUP
"Project Information - Its Content and Arrangement", DOE, 1978.

38 ROSENTHAL D et al
"Integrated CAAD Systems", BOCAAD, No.33, August 1979, pp.30-46.

CHAPTER TWO: AN INPUT/OUTPUT MODEL OF THE COSTING FUNCTION

CHAPTER TWO: AN INPUT/OUTPUT MODEL OF THE COSTING FUNCTION

2.1 Introduction

This thesis addresses the problem of how best to provide a designer with a sufficient quality and quantity of cost information to enable him to give adquate consideration to the cost consequences of each design alternative: it concerns the costing function.

The costing function is a complex process involving human intuition and expert judgement (1).

In dealing with a complex problem it is generally useful to make a model of the reality. The model is a representation of reality and can be used to accumulate knowledge about the problem structure. (The concepts of both systems and models are an integral part of this thesis. A detailed description of the theory and application of these important concepts is included in Appendix I).

The classic concept of the world (or reality) as consisting of matter and energy has had to give way to the notion of a world which consists of three components (2):

(i) energy
(ii) matter, and
(iii) information

Without information, the living organisms observed in nature and in control systems produced by man (i.e. those representing organised systems) are unthinkable. These systems are not only organised but they may remain in this state with the progress of time, and moreover, do so without losing their organisation as would otherwise be expected in accordance with the second law of thermodynamics. The only possible mechanistic explanation of this fact is that the system is continuously drawing information from the outside world which, when processed, is used to control the activity of the system.

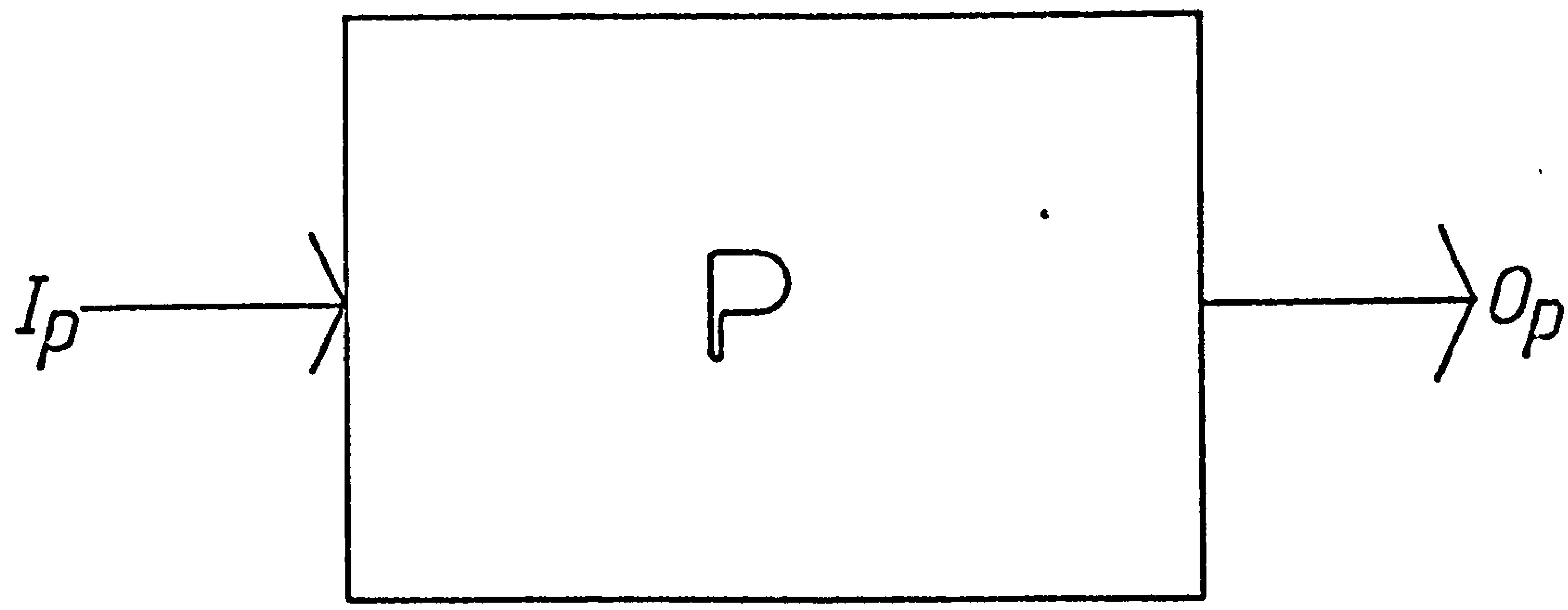
Cybernetics is the theory of information processing systems (3): the science of control. It provides the means to consider information as an individual physical quantity apart from its carrier. The information processing system is then deemed to deal solely with the input, transformation and output of that information.

It is apparent that consideration of the complex costing function might be improved significantly by treating it as an information processing system and applying the concepts of cybernetics.

2.2 The Fundamentals of Cybernetics

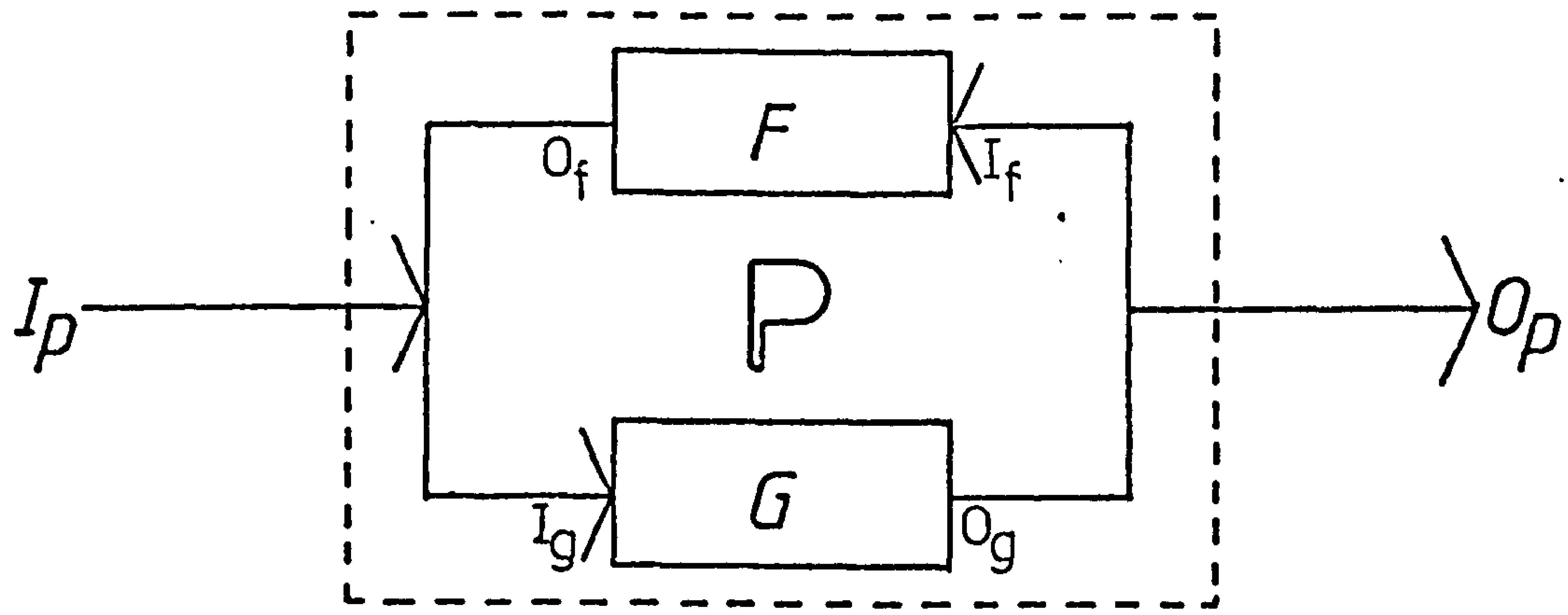
An information processing system is defined by the information entering the system and the information leaving the system. It is possible to regard such a system, or system component, as the 'black box' illustrated in Figure 2.1. The concept of a black box is a useful one because it opens up the possibility of objective study of the system whose structure is either unknown, or too complex for conclusions to be drawn about it simply from its behaviour (4).

The distinction of an organised system is the ability to realise self-control: to be self-organising. The simple representation illustrated in Figure 2.1 must therefore be refined into an assembly of the controlling (feedback) and the controlled (generative) parts of the system, as is shown in Figure 2.2. The controlling part, or the feedback, is an important aspect of the cybernetic approach. In essence, the feedback mechanism will evaluate selected parameters in the system output, decide what, if any, regulation is necessary to subsequent inputs, and then execute such regulation (5). For example, consider a refrigerator - the internal temperature must be monitored and compared with the maximum and minimum allowed (the evaluation function); based on this, a decision must be made to either switch-on or switch-off the cooling mechanism (the decision function); the cooling mechanism will then either reduce the temperature or allow it to rise further (the regulation function). Such a representation is further illustrated in Figure 2.3.



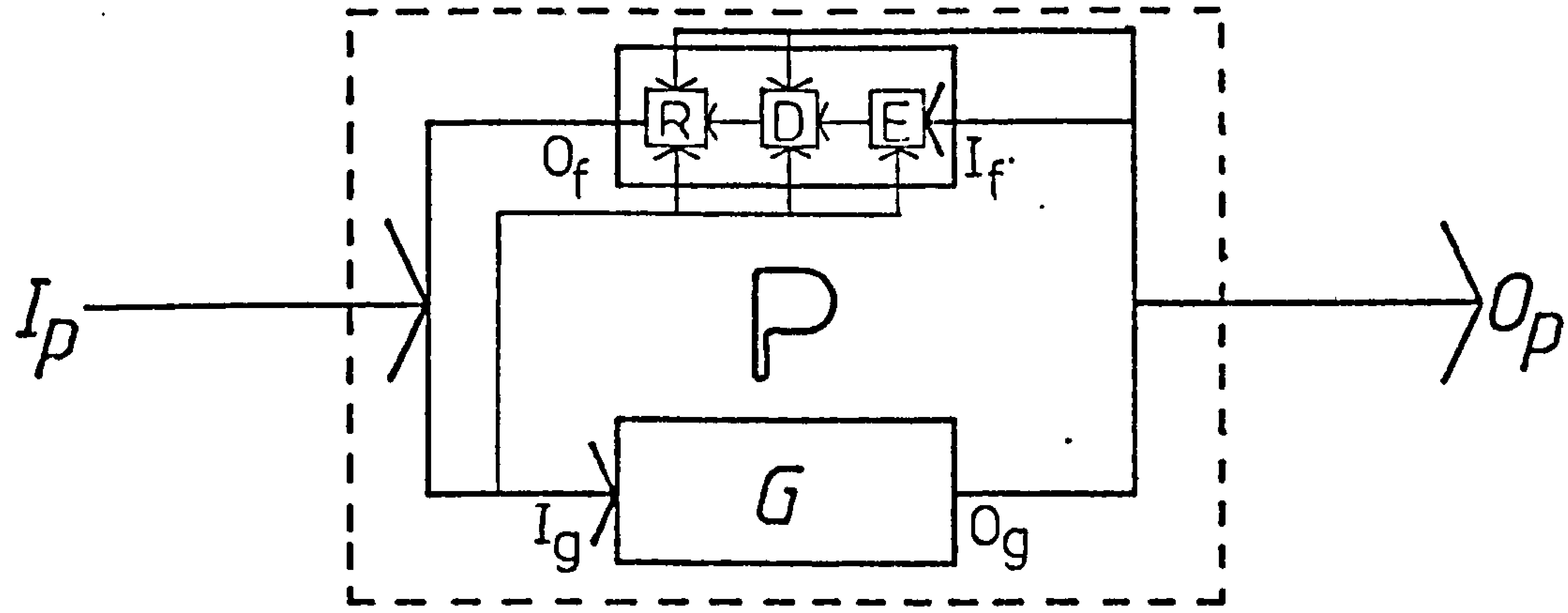
The function of P (the costing process) is defined by Ip (the information entering the system) and Op (the information leaving the system). P is then a 'black box'.

Figure 2.1: The costing process as an information processing system



Within an information processing system the transformation of an input to an output is achieved by controling the generative process. Here, G represents the generic function which generates specific cost information from specific inputs. F represents the feedback function which evaluates the cost information produced and regulates the input flow Ig.

Figure 2.2: An information processing system containing generic and feedback functions



The output Og(t) produced at a given moment t, depends on the input information Ig(t), which is in effect the history of the system up to the moment t. In regulating input Ip, the feedback function is controling the effective input Ig. To control, the function must first evaluate (E) the effects on Og for previous Ig in time, by comparing particular process parameters with predetermined values. Given this evaluation a decision (D) must be made to determine the best corrective strategy; which prompts a regulation (R) of the input data by adjusting various control valves.

Figure 2.3: An information processing system in which the feedback function contains evaluation, decision, and regulation functions

The cybernetic model so developed, however, is very abstract. Let the behaviour of a system be determined by its input values $Y_1, Y_2, \ldots, Y_m$ and the output values $X_1, X_2, \ldots, X_n$.

Different systems can have the same set of input and output values and react similarly to external actuations. These systems are called isomorphous. Obviously, isomorphous systems are indistinguishable from each other to an observer who has access only to the input and output values.

The conditions of isomorphism of the systems A and B can be expressed by the following:

if

$$Y_{1A}(t) = Y_{1B}(t),\ Y_{2A}(t) = Y_{2B}(t),\ \ldots,\ Y_{mA}(t) = Y_{mB}(t)$$

then

$$X_{1A}(t) = X_{1B}(t),\ X_{2A}(t) = X_{2B}(t),\ \ldots,\ X_{nA}(t) = X_{nB}(t)$$

for any instance of time t. For example, consider a simple network, as illustrated in Figure 2.4(a), the four nodes of which either 'fire' or do 'not fire' at each time t on some fixed time scale. Each node will itself only fire at time t + 1 if at least the requisite number (the 'threshold') of inputs have fired at time t (the requisite number being inscribed on each node). Thus, nodes 1 and 2 in Figure 2.4(a), both having a threshold of 1, just function as delay elements - their output pattern is precisely the input pattern one interval earlier. Node 3 fires at t + 1 if at least one of x_3, x_4, or x_5 fires at t. Node 4 fires if at least 2 of its inputs fire in the previous interval. Thus if all of x_3, x_4, and x_5 are quiet, the output of the whole network will fire at time t + 2 only if x_1 AND x_2 fire at time t, whereas if any of x_3, x_4, or x_5 fires at t, then the output will fire at time t + 2 only if x_1 OR x_2 or both fire at t. Thus if any of x_3, x_4, and x_5 is active, node 4 behaves like an 'OR circuit'; if none is active, it behaves like an 'AND circuit'.

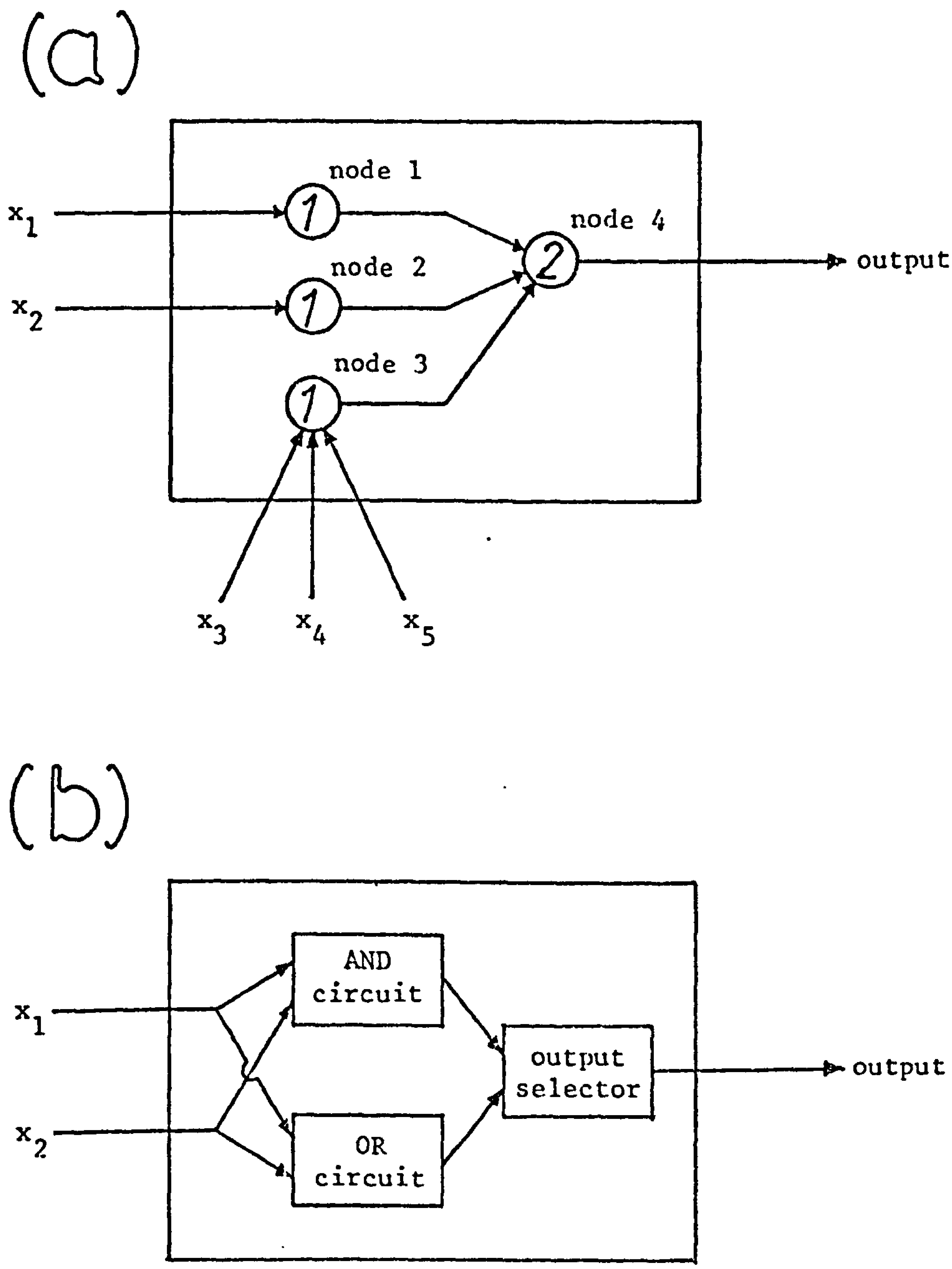


Figure 2.4: An illustration of the fact that two systems with the same function may possess quite distinct internal structures

If x_3, x_4, and x_5 are unknown, perhaps because they come from other subsystems which are not being studied, then one might deduce that the system can compute the AND function and the OR function, but that it requires some output selector to determine which of these results becomes the output of the system. Figure 2.4(b) illustrates this point by separating the AND circuit and the OR circuit. However in the actual network of Figure 2.4(a) the AND and OR circuits cannot be separated.

Study of a system by the black box method cannot lead to an unequivocal conclusion on its internal structure, because the behaviour of a given system considered as a black box does not differ from that of all other systems with which it is isomorphous. It is important to remember that for any chosen system an infinite number of systems which are isomorphous with it, can also be chosen (6).

2.3 Exposition

The black box method of cybernetics has proved particularly important in defining a complex system. The approach is to judge a system on its external properties rather than by investigating the fine structure and properties of the finer components which make up the object system. Subsequently, it is both possible and desirable to define the costing function in terms of its input information and its output information; as an information processing system. It would appear expedient also, to compare alternative costing techniques in similar terms.

The costing function, however, should not be considered as an end in itself: it is, rather, a communication vehicle between design and construction and subordinate to both. It follows that the input and output of the costing system is effectively prescribed by existing construction and design practice. To define an appropriate costing function then demands only that the output requirements and input constraints of current practice be described. The following two chapters will consider each in turn, producing the definition of an appropriate costing function in Chapter 4.

The role of cost estimating is to service design; to predict and translate a cost expressed in terms of operations (being a piece of work that can be completed by a man, or a gang of men, without interruption from others) to a cost expressed in terms of activities (being an expression of the building users requirements from a space). Priority has therefore been given to the requirements of the design activity; to the output.

REFERENCES

1 FLANAGAN R
"Tender Price and Times Prediction in Construction Work", PhD Thesis (unpublished), University of Aston, 1980.

2 LERNER A Ya
"Fundamentals of Cybernetics", Chapman and Hall, 1972, p.4.

3 WIENER N
"Cybernetic or Control and Communication in the Animal and the Machine", 2nd edition, MIT Press, 1961.

4 EVANS C R and ROBERTSON A D J (Eds)
"Cybernetics: Key Papers", Butterworths, 1968.

5 AMKREUTZ JHAE
"Cybernetic Model of the Design Process", CAD Vol. 8, No. 3, July 1976, pp.187-192.

6 LERNER A Ya
op cit, p.27.

CHAPTER THREE: THE OUTPUT REQUIREMENTS

CHAPTER THREE: THE OUTPUT REQUIREMENTS

3.1 Introduction

The role of cost estimating is held to be a servicing of design. The cost information requirements of the design activity will therefore weigh heavily in the definition of an appropriate costing function.

At its most general level, design is seen as making explicit proposals for how a change from some existing state to some future state might be achieved (1). No further distinction of design is possible (most particularly in architectural design) without encountering the antipathy of artistic creativity and scientific rationality. Design commentators describe it thus: a pragmatic art (2); a means of resolving a conflict which exists between logical analysis and creative thought (3); a mixture of rational and intuitive techniques (4); as neither replicable nor systematic (5); a rational means of making the built environment meaningful (6); etc. Indeed the predominant issue in architectural conferences over the past two decades, at least, has been that of "art vs. science" (7).

In general literature concerning design, terms such as design activity, design process, design method and design problem are very often used to mean equivalent things. In this thesis they are distinguished as:

(i) the design activity - a global term for all actions of design.

(ii) the design process - a framework within which design decision-making is sequenced. The strategic level of the design activity.

(iii) the design method - a technique selected at particular instances in the design process to improve the appreciation of a design problem.

(iv) the design problem - the context of the design; its objectives, its constraints, etc.

Obviously the terms are highly interrelated. It is hoped that by making this distinction, however, each term will contribute its own set of characteristics and thereby generate a more comprehensive set of design requirements for cost information.

The design activity is a global term and subsumes the characteristics of the others.

3.2 The Design Process

Initial attempts to understand the design process witnessed a number of alternative models being proposed. All early models have one characteristic in common: they all view the design process as a sequence of well defined activities (8). One which attracted quite wide commentary in architecture, through its adoption by the Royal Institute of British Architects, is the so-called 'Plan of Work' (9). This model comprises the following twelve stages, often simplified into four:

A	Inception)	briefing
B	Feasibility)	
C	Outline proposals)	sketch plans
D	Scheme design)	
E	Detail design)	
F	Production information)	working drawings
G	Bills of quantities)	
H	Tender action)	
J	Project planning)	
K	Operations on site)	site operations
L	Completion)	
M	Feedback)	

The characteristic of the model is that the stages are sequential and not iterative; the return from a later stage to an earlier stage is recognised as failure in the management of the design activity.

Markus (10) references 'a chronological sequence advancing from the abstract and general to the concrete and particular': what he terms the design morphology. This model is further developed by Markus, and subsequently Maver (11), to include the essential stages of analysis, synthesis, appraisal and decision - one of the simplest and most common observations about designing, and one upon which many writers agree (12). Thus, the total framework (illustrated in Figure 3.1) comprises a vertical dimension of the sequential design morphology and a horizontal dimension, iterative and cyclic in nature.

In practical design problems however a linear design process is untenable; the design process cannot be considered simply as a predetermined succession of procedures with clear commencement and terminal points before which no interest in the particular goal exists and after which no development is possible (13). Lawson (14) maintains that the ill-defined nature of many design problems often necessitates much back tracking and circularity in appraisal, especially in cases where the original perception of the problem was inaccurate or incomplete: feedback is required between stages. Newell (15) makes the point that even if a 'stage' model did typify the normal process, this is still just one arrangement which the designer may or may not wish to use. If any conceivable strategy, list of operations, or route is permissable in finding a solution, then none can be prescribed as mandatory (16).

This inability to define a design problem in absolute terms is important. In practice the design process is terminated either when it no longer seems worth the effort of going further because the chances of significant improvement are small or when one of the major limiting factors of time, information or money runs out. In theory there can never be a definitive formulation of the design problem because it is always possible to consider it at a more detailed level, or at a different time step. It follows that it is always possible for a particular design solution to fail a future test in some, as yet unknown, respect. Similarly, a design solution cannot be deemed as correct or false in absolute terms, only as better to worse on some personal value scale (17).

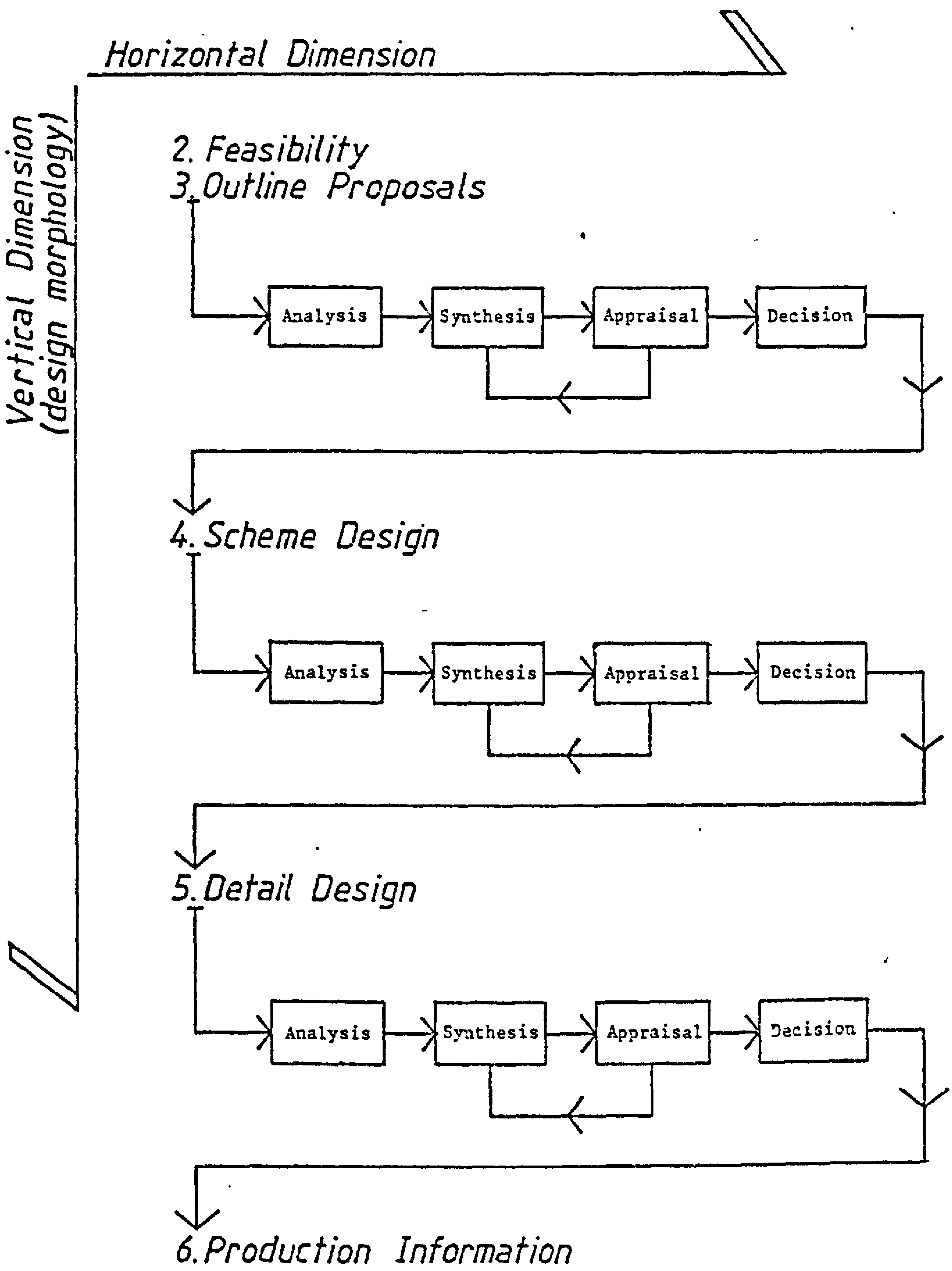


Figure 3.1: The total framework for a design process (After T W MAVER, "Appraisal in the building design process" in "Emerging methods in environmental design and planning" edited by G T MOORE, MIT Press, 1970, pp195-202)

In recent years the theoretical agruments have been supplemented increasingly by empirical evidence. In one experiment, Lawson (18) compared the design strategies of final year architectural students and science students at a similar stage of postgraduate education. The two groups showed quite consistent and strikingly different strategies. While the scientists focussed their attention on discovering a rule which governed the acceptability of a problem solution, the architects sought to achieve the particular solution they desired: the scientist adopted a generally problem-focussed strategy, setting out specifically to study the problem structure; the architect adopted a solution-focussed strategy aimed at revealing the nature of the problem by trying various solutions. For the designer then it would seem analysis, or understanding the problem, is much more intregrated with synthesis, or generation of a solution.

Eastman (19) also has used protocol analysis to show how even the more experienced designer will explore a problem through a series of attempts to create solutions. Again, no meaningful division was found between the analysis and synthesis in these protocols but, rather, that there is a simultaneous learning about the nature of the problem and the range of possible solutions. The designers 'discover' the problem as they critically evaluate their own solutions.

Darke (20) has also found this tendency to structure design problems by exploring aspects of possible solutions. Faced with a complex problem Darke shows how an architect tends to latch onto a relatively simple idea early in the design process and then to use this idea to narrow down the range of possible solutions: the designer is then more able rapidly to construct and analyse a scheme. Again there is this close, perhaps inseparable, relationship between analysis and synthesis. Indeed, Darke uses this empirically gained evidence to supplement theoretical work by Hillier et al (21). An alternative to the analysis-synthesis model is proposed based on a generator-conjecture-analysis design process:

(i) First decide what you think might be an important aspect of the problem.

(ii) Develop a crude design on this basis, and

(iii) Examine it to see what else you can discover about the problem.

3.2.1 Comment

It transpires that early models of the design process have more relevance to scientific problem solving than to architectural design. Both theoretical and empirical evidence suggests that the design process should be taken as an embodiment of vertical and horizontal dimensions.

The vertical dimension, or design morphology, proceeds from the general to the specific through various permutations of design stages, none of which are likely to represent a definitive formulation of the design problem.

The horizontal dimension applies an iterative method as new information and new insights are gained.

The characteristics of the design process are therefore that:

(i) It is not always a linear process.

(ii) Both prediction and circularity are important

(iii) There is unlikely to be any definitive formulation of the problem.

(iv) There is no absolute test of a design solution.

3.3 The Design Method

3.3.1 Tradition

The 18th century saw a transition in the structure of the building industry from a craft base to an industry in which design and construction are quite disparate. Initially the separation of designing from making had the effect not only of isolating the designer but also of making him the centre of attention. The self-conscious recognition of individuality had a deep effect on the process of form-making (22): subsequently schools of architecture would encourage students to design in the manner of a particular individual and successful designers had to acquire a clearly identifiable image. By the late 19th century many architects in this country were vociferiously unhappy about the growing influence of the Royal Institute of British Architects, which they felt threatened to regulise and control what had become an 'individual art'.

Jones (23) summarises both strengths and weaknesses in this rigidity of architectural style in a description of 'design by drawing'. Because the designer did not actually make an object, he had to represent it in another way. By far the most common and influential way of representing designs has been by drawing. The complete drawing of a design gave the architect great manipulative freedom, sufficient indeed to make far more fundamental changes and innovations than would ever have been possible in the vernacular process. Such a system worked well while design remained largely dominated by consideration of aesthetics. The designer could see from his drawings just how a final solution would look.

The disadvantage of designing by drawing is that problems which are not visually apparent tend not to come to the designer's attention. Architects could not 'see' the social, economic or political problems associated with new designs simply by looking at their drawings. It became apparent that if design was to continue separated from construction, and also to continue a rapid rate of change and innovation, then new design methods were urgently required. The aim was to promote a more rational and explicit basis for the design activity: to combine the designer's artistic modes of thought with scientific doubt and rational explanaton.

3.3.2 The first generation

In a now famous work, Alexander (24) argued that it is far too optimistic to expect anything like satisfactory results from a drawing board-based design method. Using an early step-by-step model of the design process Alexander's method involved first listing all the requirements of a particular design problem and then looking for interactions between these requirements. The interactions between each pair of requirements are then labelled as either positive, negative or neutral depending on whether they complement, inhibit or have no effect on each other. A typical designer using Alexander's method would first list all the requirements of his/her design and then state which pairs of requirements interact either positively or negatively. All this data would then be input to a computer program which looks for clusters of requirements heavily interrelated. Effectively, the problem is structured by breaking it down into sub-problems, each relatively simple for the designer to understand and to solve.

Alexander's work has been heavily criticised, not least by himself (25), and an excellent review of its failings can be found in Broadbent (26). In fact the reason for the failure of Alexander's early work results from his erroneous assumptions about the true nature of design problems. Its extraordinary lasting effect on design thinking is all the more remarkable since there is only the one other reported attempt to use the method and that did not result in any obvious success (27).

Another quite well known method was developed by Page (28). He proposes that designers should adopt what he calls a 'cumulative strategy' for design. This involves setting carefully considered objectives and criteria of success for the performance of a design solution. Page's strategy then calls for the designer to collect a variety of what he calls 'sub-solutions' for each criterion and then to discard the solutions which fail to satisfy all the criteria.

For example, a window designer would produce a series of alternative design solutions, some intended to achieve a good view or good daylighting, others to avoid solar gain, high cost and so on. Thus, the strategy is intended to reduce the amount of time spent on the synthesis of bad solutions by minimising the number of misfits considered.

Such an approach however does not seem borne of a clear understanding of the nature of the design problem. Because design problems are so multi-dimensional they are also highly interactive. Enlarging a window may well let in more light and give a better view but this will also result in more heat loss, greater cost, and may create problems of privacy. It is the very interconnectedness of all these factors which is the essence of design problems rather than the isolated factors themselves.

Others contributed to the early theories of design, most notably Asimow (29), Archer (30), Gregory (31), and Luckmann (32). All such models advocate the definition and use of formal techniques frequently borrowed from operations research. (To supplement the critical analysis by Broadbent cited earlier see a review of the models by Jones (33)).

Thus, first generation models can be characterised by:

(i) A heavy reliance on formal mathematical methods.

(ii) The requirement to over-simplify a particular sub-system within the total design problem, chosen on the basis of numerical amenability.

(iii) Little or no attention being paid to the systemic nature of the design problem or to the formulation of the broad design objectives.

3.3.3 The second generation

Early design methods, unfortunately, were to prove just as inadequate as designing by drawing (34). The issue no longer seemed to be one of protecting the individuality and identity of designers but, rather had become the problem of exercising what Jones (35) called 'collective control' over the designers' activities. The underlying aim now focussed on bringing the design activity out into the open so that other people could see what was going on and contribute to it information and insights that were outside the individual designers' knowledge and experience. Somehow the whole process had to become more public, open to inspection and evaluation; design was to be externalised.

The main agitating force in this respect is termed 'user participation' (36). Watts and Hirst (37) have identified several of the issues raised by user participation in design:

(i) Design participation involves the redefinition of the architects' role in society. The traditional relationship between users and providers - or sponsor, architect and user - is questioned, suggesting that the traditional hierarchial structure of authority precludes effective user participation. Participation here is seen as power-sharing (38).

(ii) Users do not speak the same language as that shared by the architect and sponsor's respresentative. The users know what they want, but cannot make their requirements explicit in architectural terms. This emphasises participation as communication and suggests that a common language needs to be developed (39).

(iii) The communications aspect can be further emphasised, but focussed upon developing tools for communicating design-decisions, to replace the traditional sketch as a means of visual communication (40).

Second generation design methods tend to address one or other of these issues.

Rittel (41), for example, recognised that argumentations plays a critical role in formulating a design problem. In the design method he proposes, issues are raised by all parties involved in decision-making. The parties define positions, gather evidence and prepare arguments for each issue, and debates and arguments develop; when an issue is resolved the decision reflects input from every position. Most decisions are in effect negotiated, meaning that the method of arriving at better decisions is not a process of optimisation in the operations research sense; it is, rather, a process of negotiation and compromise between parties with different views. The architect is no longer in a position of supremecy, but shares the responsibility and the risk in design decisions with the users and sponsors.

This does not, however, escape the inabilities of lay users to articulate their arguments in the language of design, and vice versa. Attempts have been made to discover what meaning people attach to built forms through both theoretical (42) and empirical (43) studies. The study of different linguistic or cultural systems by seeing them as systems of signs available for communication within that culture, is termed semiotics. Overtly, the built environment itself can be considered as a combination of signs or codes: that is, as a language (44).

For an architect to produce a factory and for a lay person to recognise it as a factory, necessitates a two fold classification of the universe of the signifier:

(i) Firstly the characterisitcs of the social function of a factory has to be opposed to the characterisitcs of other social functions such as those of a school, an office, etc.

(ii) In a second act of classification the characteristics of a particular account of the social function of the factory are opposed to the characteristics of other possible accounts of the social function of the factory.

Experiments by Krampen (45), however, suggest that the selection of distinct 'signs and codes' is extremely difficult and that the architectural detail necessary successfully to distinguish even between buildings, is great.

Alexander (46), having abandoned the concept of decomposition which was so integral to his first generation model, retains the concept of pictorial diagrams. In his new model a 'specialist' designs a pattern, which is a diagram describing what the 'specialist' knows and considers important about the issue. He then 'gives' the pattern to the 'object designer', who is usually the client and/or the user of the future object. In this process the 'specialist' also explains the reasons for the particular pattern and the object designer either accepts or does not accept the pattern. If the pattern is accepted it becomes part of the designer's own knowledge; he accepts the knowledge contained in the pattern and adds it to the kowledge he already possesses. If the pattern is not accepted the designer simply proceeds on the basis of his previous knowledge.

Alexander's model operates on the basic assumption that everyone is a designer having a considerable set of his/her own patterns: that everyone makes design decisions, no matter how incorrect or ill-informed the patterns are. The purpose of patterns designs by 'specialists' is to correct existing patterns that might lead to failure, or to add new and better patterns.

The basis of second generation methods of course is in psychological theory, and like psychological theory they are influenced by such global theories as Freudian psychoanalaysis, Kohlers' Gestalt theory, Lewin's idea of 'life-space', Watson's behaviourism, and so on (47). The array of theoretical view-points presented (most are summarised in Barker (48)) display the fundamental problem of studying human beings by techniques which were developed for the physical sciences: the dangers of leaving out - as behaviourists do - everything that cannot be studied by such methods (49). A naive notion that by operating without preconceptions a behaviourist can be labelled as non-ideological and that behaviourism is then simply a set of methods with which to achieve specific empirical results.

Behaviourists, of course, not only do operate from within the bounds of a rigid and systematic theory, but it is precisely their refusal to recognise and acknowledge the theory-laden quality of their endeavour which is most disturbing (50). As Maver quips (51):

> "the 'enfant terrible' - intellectual rigour - goes our with the bath water"

3.3.4 Comment

The seeds of design method were sown in the nineteenth century respect for professions and the twentieth century faith in technology.

First generation models were motivated by the common unease shared by designers about the inadequacy of their models of reality. The model of scientific method proved irresistable.

Unfortunately, the early models were altogether too formalised for the systemic nature of the problem.

Second generation models were such a vehement swing away from rationality that they consisted more of 'theories that needed to be, than of theories that were ' (52). Mann and Hagevick (53) do not consider any of these models as anything like adequate for most design solutions.

Maver (54) proposes that the concept underlying third generation models is simply one of explicit appraisal: the 'designer' generates a design hypothesis which is 'tested' or 'appraised' on as many cost and performance attributes as are considered appropriate. The profile of cost/performance attributes is evaluated by the 'designer' who then, on the basis of this information, iteratively modifies the design hypothesis. Having squarely acknowledged that design decision-making involves subjective value judgement then that judgement, by whomsoever, must be made from the best possible explicit and objective information base.

Of course other 'third generation' design methods have also been proposed by, for example, Gero (55), Negroponte (56), Canter (57), et al. What does appear obvious is that future models will very likely be first and second generation hybrids ranging from the formalism of speculative housing design through to the subjectivity of a hospital or school design.

The characteristic of design method then can only be its variability: the range of bias from wholly formal to wholly informal technique. The aim still is to combine artistic modes of thought (be it from architect or user) with scientific doubt and rational explanation.

3.4 The Design Problem

3.4.1 Characteristics and components

As Simon (58), March (59) and others identify, science is a process about understanding the present in contrast to design which is a process about inventing the future: a future, in this sense, inevitably confounded by many doubts and uncertainties. The function of design is to control and allay such uncertainties, which a designer will attempt to do by generating a large number of solutions with the intention of revealing problems rather than solving them. Clearly, design problems and design solutions are going to be inexorably interdependent. The more one tries to isolate and study a design problem the more important it becomes to refer to design solutions: problems may well suggest certain features of solutions and these solutions in turn create new and different problems. As the appreciation of a problem changes so the goals and objectives which direct the problem solver change also: the design problem will be dynamic.

A problem will usually originate with a client or user; someone in need who is unable to solve the problem, or perhaps even fully to understand it, without help. The role of a designer is simply to recognise the needs of the client and fulfill them as well as possible. The situation involves three sources of possible constraints:

(i) The client or user - the brief, etc.

(ii) The designer - professional expression, etc.

(iii) The legislator - building regulations, etc.

Each constraint is expressable in terms of an objective. The client may wish a sunny lounge, the designer to continue an interesting street facade, the legislator to have less than 15 per cent glazing, etc. In fact there are usually many objectives, often ill-defined, mostly conflicting, and it is the function of the designer, or design team (comprising also perhaps the client, user, etc.), to select the combination of all these features which will give the most satisfactory performance. It is quite likely that these criteria are not all equally important, the legislator being more absolute perhaps than the client. But the real difficulty is that the criteria are not easily related to one another. Obviously certain objectives are readily quantifiable, such as the percentage of glazing, but what of the aesthetic qualities of a street facade?

Not only does design involve the measurement of quantitative and qualitative criteria; it must also attempt to balance quantities measured in different scales using different metrics.

In every day life, numbers and scales of measurement tend to be used very carelessly. In fact it is common to employ several quite distinct ways of using numbers without really being aware of the differences (60). Designers cannot afford to be so careless since they must frequently use all of these different kinds of measurement scales simultaneously. In design there are often so many variables which cannot be measured on the same scale, that value judgements seem inescapable.

The word 'value' can be employed for two different meanings:

(i) Where it is attributed to an entity - the 'value' of that entity might be high or low.

(ii) Where it is an entity in itself - freedom, health, democracy, are all 'values' within themselves.

In design the former meaning applies, and having a value or not is the most primitive scale of value. It would also seem that certain properties of value systems and structures apply generally:

(i) If stated in general terms value systems are very stable through time - 'man should be good' is valid in perpetuity.

(ii) The converse of (i), if stated in terms of classes or situations, value systems are very dynamic through time, and differ from person to person. Beauty varies with different epochs, fashions, etc.

(iii) There are almost no value categories which apply universally. They are fundamental according to a certain class of problem situation and not to all situations. Many things admitted in war are not also admitted in peace.

Rittel (61) warns that any attempt to establish a normative value system valid for everyone is futile. He argues that it is only meaningful to establish a scale of values based on empirical findings and that, even here, the systems of evaluating are themselves a judgement. It is, he claims, impossible to establish a clear-cut separation between the object situation and the evaluator's image of that situation (see also Daley (62)). Certainly the review of numerical methods of evaluating multiple objective alternatives by Grant (63) reinforces the view that at least part of any value judgement is subjective and must therefore involve the human design decision-maker.

Additionally, it has been shown that designers' value systems may themselves be affected by the design process as the designer negotiates between his objectives and what he finds is possible (64): again this points to a dynamic, interactive design problem.

Finally a consideration of the structure of a design problem.

As with any complex system the structure of a design problem can be anticipated as hierarchical. Eberhard (65) suggests that there are two ways in which the number of alternative solutions are increased:

(i) By escalation - where the designer retreats back up the hierarchy to some higher level incorporating a greater proportion of the potential solution space. For example, in consequence of trying to design a better classroom layout, the problem might be escalated into redesigning the political structure of the country to bring particular pressure on education authorities, and so on.

(ii) By regression - where the designer jumps to other branches of the hierarchy, again incorporating a greater proportion of the potential solution space. For example, in consequence of trying to design a better classroom layout, the problem might be regressed into redesigning the basic concepts of teaching method.

In fact both escalation and regression often go together.

To summarise, it is apparent that the characteristics of the design problem are those of what Rittel and Webber (66) term 'wicked' problems:

(i) Relevant criteria will change throughout the life of the design artifact or system.
(ii) Any design solution must be appraised on a large number of ill-defined, disparate and conflicting criteria.
(iii) The number of alternative feasible solutions is so large as to be effectively infinite.

3.4.2 Perception and creativity

The fact is that design problems are those which someone has chosen to state. If an unstated problem is 'solved', there is no awareness of 'solution' (67). Problems then are closely related to the persons who choose to state them. Previously, three sources of possible constraints were identified:

(i) The client or user.
(ii) The designer.
(iii) The legislator.

Each will impact upon the design problem individually, but the actual design decision-maker is particularly significant: this may be a client or design team, but can be taken to exhibit the characteristics of a designer. Two forms of interaction will occur:

(i) The influence of a problem on the designer's subsequent decisions - how a designer perceives the problem.

(ii) The innate capacity of a designer to solve problems - his creativity.

Both forms of interaction concern cognitive psychology, the study of problem solving and creativity; in short of thought itself. This area of psychology is particularly ill-defined with many contrasting theories and explanations. Perhaps the two most notable traditions are:

(i) The behaviourists to whom thinking is a completely objective system of response to stimuli and their reinforcement (68).

(ii) The Gestalt psychologists for whom the emphasis of thinking lies not in a mechanism, but in a process of organisation; the way an external world is represented inside a person's mind (69).

Certain factors are consistent however. For example, when something new is encountered it is not treated as something totally new. Instead there exist certain expectations; it is anticipated that at least some aspects will be familiar and anything with absolutely no familiar aspects is disliked and even feared (70). Expectation is determined by a particular individuals's image of what the world means to him, his understanding of the world. When a person encounters a new situation (or makes a substantial change in his view of the present problem) he selects from memory a substantial structure (Bartlett (71) calls it a 'schema', Minsky (72) a 'frame'). This is a remembered framework to be adapted to fit reality by changing details as necessary.

Rittel (73) makes the following statements:

(i) All behaviour depends on the image and it determines behaviour.

(ii) The history of the image is part of the image.

(iii) The image is changed by messages it receives. This changes may be to stabilise it, or to completely restructure it.

(iv) The image is resistant to change and it can be observed that favourable messages are accepted while unfavourable ones may be rejected. Prejudices are of this type.

(v) Within the image there are many scales of evaluation for particular purposes, some valid at certain times, others not; all stored or built into the image.

(vi) Any perception is mediated through a sieve of value systems, established by the image. There are no such things as facts except where they are 'made' - factum - by those who accept them into their image.

(vii) Images are often socially shared. There is a coincidence between various persons, they are not private, and this can be checked by the success of symbolic communication between persons.

Ward (74) points out that a person is particularly sensitive to correlation between new experience and his expectations, or his 'images'. The sensitivity can lead to conflict.

To briefly explain, if a person is blocked in a drive towards a goal, he experiences frustration, which increases and fragments his drive. He becomes more determined. However, if this blocking is continued, he begins to adopt a reticence towards the goal which manifests itself in avoidance of the issue. 'Conflict' refers to the experience beyond this point, where ongoing and avoidant attitudes towards the goal co-exist within the person simultaneously: this can lead to aggression, regression and other non-goal-directed side effects. The point at which frustration becomes conflict is called the 'frustration threshold', which can be altered according to past experiences. For example, if a person is subject to a constant series of conflict experiences the probability that future experiences will be conflicting is increased: the 'frustration threshold' of the person has been lowered. On the other hand when a person never experiences conflict situations his motivation to achieve success begins to outweigh his motivation to avoid failure. Simply, where no conflict is perceived, conflict is sought, but the frequently conflicted person 'plays-safe'.

The images then are in effect data-structures for representing a particular category, or stereotyped situation. To 'categorise' is to render discriminantly different things equivalent, to group objects and events into classes, and to respond to them in terms of their class membership rather than their uniqueness (75). Thus, instead of using a colour lexicon of the estimated seven million discriminable, a person gets along with about a dozen common colour names.

Creativity is most often associated with the generation of some new option or insight that didn't previously exist. Whereas the usual political way of overcoming conflict in solving a problem is compromise, the creative way is conflict resolution or 'transformation'. The most important requirements for a successful transformation are:

(i) The freedom to change sub-goals in order to find feasible ways of avoiding major compromises.

(ii) The speed with which the feasibility and consequences of any particular choice of sub-goals can be predicted.

Unfortunately, the almost universal tendency is for experience to have a mechanising effect on individual thinking (76). That is, each problem is not viewed afresh but rather is first classified according to types of problem already encountered, and the solution selected accordingly. Only if the problem type cannot be recognised is there any serious attempt to study it in any depth. Luchins and

Luchins (77) call this strong positive transfer of methods of solution the Einstellung effect. For example, Green (78) has shown that after correctly unscrambling 'lecam' (camel), 'nelin' (linen), 'nedoz' (dozen), and 'sdlen' (lends) subjects are much more likely to rearrange 'pache' into 'cheap' than into 'peach'.

Such mechanised, channelised thinking is the very opposite of what is required to improve perhaps already successful design products (79). It is this stimulus which has provided two of the most famous of all creativity 'techniques'; Brainstorming (80) and Synectics (81). Both these techniques are based on the simple idea of using a group of minds acting in concert so as to avoid the deficiencies of personal logic (82), namely;

(i) Ignoring alternatives.
(ii) Pre-weighting alternatives.
(iii) Ignoring information.
(iv) Ignoring goals.

3.4.3 Comment

The design problem has been inexerably linked to the constantly changing design solutions and as such must constitute a dynamic system.

The objectives and goals which direct the problem solver have been shown to be multiple and ill-defined, and their measurement dependent upon human value judgements.

The structure of the problem is hierarchial and incorporates a large number of possible solutions, increased by 'escalation' and 'regression'.

A designer's perception of the problem can have quite serious ramifications, some of which were mentioned by Rittel and Ward; all of which are determined by the designer's 'schema'; his expectations.

Creativity is achieved by conflict resolution which entails transforming the schema to provide some new insight.

The characteristics of a design problem are therefore:

(i) The temporal variation in objectives.
(ii) The multi-variate nature of the design objectives.
(iii) The magnitude of the solution space.
(iv) The need to minimise conflict.
(v) The need to accomodate transformations.

3.5 Criteria for Judging the Output of a Costing Process Based on the Information Requirements of Design

3.5.1 The requirements

The characteristics of design can be summarised from the previous section as:

Section 3.2 - the design process

A. It is not always a linear process.
B. Both prediction and circularity are important.
C. There is unlikely to be any definitive formulation of the problem.
D. There is no absolute test of a design solution.

Section 3.3 - the design method

E. Design method can range from wholly formal to wholly informal techniques.

Section 3.4 - the design problem

F. The temporal variation in objectives.
G. The multi-variable nature of the design objectives.
H. The magnitude of the solution space.
I. The need to minimise conflict.
J. The need to accomodate transformations.

Clearly this does not represent a definitive description of design, rather, it illustrates the great variability of design activity. With no definition of design there can be no definition of the cost data requirements of design: there is no fixed set of global output rules with which to describe a costing function.

Some form of assessing alternative costing techniques is however needed, and several requirements have been proposed. They are not intended as an absolute arbiter, but more as a set of guide lines for judging the potential of a particular approach. The more closely a technique matches the requirements, the more likely it will provide useful and appropriate cost information.

No attempt has been made to rank the guide lines as the emphasis will surely change for different contexts.

Consideration is given to each individual requirement in an attempt to explain their intent, they are in effect general headings. The origin of each attribute is indicated by the letter corresponding to the relevant characteristic, as listed above.

3.5.2 The criteria

It is suggested that the utility of any particular costing process can be considerably predetermined by how well it manages to:

(i) <u>Minimise conflict</u>

- information is expected to be consistent. If particular advice is given at the beginning of a design process it is expected that the same advice will hold at a later stage. (I)

- information should be presented in as familiar a form as possible. This will invariably give preference to graphical representations. (I)

- the amount of information presented to a designer at any one time should be limited by his immediate requirements. Different design methods will require varying amounts of explicit information, which will be further affected by changes in design objectives throughout the design process. (E,F)

(ii) Assist in solution generation

- design is a prescriptive activity. To prescribe, it must be possible to model and/or otherwise predict the consequences of alternative design solutions. (B)

- few people can deal with more than three or four objectives at any one time, but the multi-variate nature of design often produces many more dimensions to the problem. Since objectives may be in direct conflict with each other, an ability to automate the 'knock-on' effect of a sub-problem would be of considerable assistance in solution generation. (G,I)

- design problems after an inexhaustable number of solutions. The more alternatives considered the more refinement one can expect of the eventual solution. If a realistic proportion of the total solution space is to be considered the designer will require some assistance in generating alternative solutions. (H)

- the designer is expected to contribute problems as well as solutions. These problems emerge as new insights or options, as the designer transforms the existing problem definition. Clearly a problem may be transformed in infinite variety, and in consequence a designer needs some indication of the direction in which successful solutions might lie. (J)

(iii) Relate the project to other comparable projects

- design problems cannot be comprehensively stated. It follows that any solution can never be perfect and is more easily criticised than created. Designers must accept that they will almost invariably appear wrong in some ways, to some people. Their only means of justification is comparison with other projects. (C)

- since design problems defy comprehensive description the design process cannot have a finite and identifiable end. The designer's job is never really done, and he can always try to do better. A design is judged as good or bad in relation to other projects. (D)

- there are no established methods for deciding how good or bad solutions are, and the best test of most design is still to wait and see how well it works in practice. The only viable alternative is to relate the proposed project to other projects which already exist in practice. (D)

- design problems are generated by several groups or individuals with varying degrees of involvement in the decision making process. Designers from different fields, or possibly even different designers from the same field, are likely to suggest different solutions to the same problem because they perceive problems differently. The transfer of information from one person's 'image' to another person should be kept as objective as possible, at least in terms of the anticipated accuracy of the information. Some indication needs to be given as to the variability of information, and to how close a particular item is to the mean; that is, how an item of information relates to the 'family' of comparable items in other projects. (G)

- there is a whole range of feasible solutions each likely to prove more or less satisfactory in different ways. Just as the making of design decisions remains a matter of judgement and comparison, so does the appraisal and evaluation of solutions. (G)

(iv) <u>Link the user to a central data base</u>

- design problems involve numerous groups or individuals, to varying degrees. The duplication of information by separate individuals would be reduced greatly if the information were stored in a central, multi-access data base. (G)

- if a design is to satisfy all relevant legislature, statutory requirements, codes of practice, company strategies, etc., then a record of them all must be maintained. The level of information handling inherent in such a procedure indicates a rapidly increasing bureaucracy. (H)

(v) <u>Be quick</u>

- time is often a major limiting factor in design and a shortage can result in consideration only being given to a very small proportion of the total solution space. (H)

- a basic requirement for the successful transformation of a design problem is the speed with which the feasibility and consequences of any particular choice of sub-goals can be predicted. Information should not interrupt the 'flow' of a design process. (J)

(vi) <u>Be adaptable</u>

- in design there is no single sequence of operations which will always guarantee a result. In fact controlling and varying the design process is one of the most important skills a designer must develop (83). (A)

- it is central to much of present day thinking about design that problems and solutions are seen to emerge together. This means that various back-tracking and iteration occurs, and this will be different for each project. (B)

- the design problem is hierarchical and can be tackled on a wide range of levels, unfortunately there is no objective or logical way of determining the right level. (G)

- it is a function of the designer to balance the trade-offs and compromises allowed between objectives. The designer may quickly become frustrated if a particular balance is excluded by an inflexible costing process. (I)

(vii) Be dynamic

- design is a dynamic process with decisions being made and subsequently changed. (B)

- the formulation of a design problem proceeds in symbiosis with the generation of design solutions. As it is unlikely that any one formulation will be definitive, the problem structure must be dynamic; this is the essence of transformation. (C,J)

- both objectives and priorities are quite likely to change during the design process as the problem structure varies. (F)

3.5.3 The performance of current cost estimating practice and approaches to cost modelling

A comprehensive review of current cost estimating practice and approaches to cost modelling is contained in Appendix II. The intention of this review is to exemplify the range of approaches and techniques in the following classes:

(i) Current practice.
(ii) Automated costing processes.
(iii) Statistical analyses.
(iv) Parametric studies.
(v) Theoretical analyses.
(vi) Simulation.
(vii) Optimisation.

The critique of each approach follows the guide lines established above, and can be summarised as follows.

(i) Current practice: the only real value of current practice would appear to be that the quantity surveyor shields the designer from the true complexities of cost. Information is in a familiar form, and cost estimates can be produced even for the most innovative design solution.

(ii) Automated costing processes: by automating the costing process, several of the limitations observed in current practice can be overcome, but only at the cost of reduced flexibility and restricted validity.

(iii) Statistical analyses: statistical analyses have the clear advantage over all other techniques in that they can relate a proposed project to other, comparable projects. However, such techniques are often greatly restricted by the lack of suitable data and the accuracy tends to deteriorate quickly over time. Despite this, they are capable of prescribing design solutions and can assist greatly in solution generation.

(iv) Parametric studies: parametric studies have generally failed to meet any of the requirements. The range of validity is even more restricted than statistical analyses, and they are of little use except where the level of provision is well defined and relatively static. However, given favourable conditions they are quick and simple to use, making them quite useful as predictors of cost relationships.

(v) Theoretical analyses: to date, theoretical analyses have all but failed completely to relate to the requirements of design. This, despite the fact that a theoretical model is a prerequisite of all practical applications of cost modelling: few will state the theoretical base formally.

(vi) Simulation: simulation models would appear to have fared better than most, primarily because they are very much akin to current practice, but with the added bonus of being computer-based. By promoting the use of a prefered estimating technique earlier in the design than at present, the cost information becomes more consistent and engenders a more dynamic decision-making process. Somewhat unfortunately, the mechanisms of those models developed already are inflexible and their empirical base dictates considerable caution in any direct application.

(vii) Optimisation: the utility of optimisation models show a marked down-turn as the problem definition becomes more complex, certainly in terms of the 'dimensionality' (that is the number of disparate criteria on which a solution is judged). The explicit expression of an objective function is likely to be alien to many designers and will cause conflict, most especially when objectives change during the course of a project. The concept of optimisation however is a very powerful one and the capacity to prescribe optimal or near optimal solutions for discrete micro-problems should not lightly be dismissed.

That so many attempts at cost models should all fail to meet fully the requirements of design (see also Figure 3.2) suggests that the cost output achievable is constrained in some respect by the way in which cost is generated, and that these constraints are being over-simplified. A further indication is given by the fact that the use of any model is restricted by the variability and relevance of its input data.

3.6 Summary of Output Requirements

The output requirements of a costing function can be expressed in terms of several proposed criteria, used to judge the potential of alternative cost estimating techniques.

(i) Does it minimise conflict?

(ii) Does it assist in solution generation?

(iii) Does it relate a project to other comparable projects?

(iv) Does it link the user to a central data base?

(v) Is it quick?

(vi) Is it adaptable?

(vii) Is it dynamic?

	Current Practice	Automated Costing Process	Statistical Analysis	Parametric Study	Theoretical Analysis	Simulation	Optimisation
1. Does it minimise conflict ?	S	LS	F	F	F	S	LS
2. Does it assist in solution generation ?	F	S	S	LS	LS	LS	S
3. Does it relate project to other comparable projects ?	F	F	S	F	F	F	F
4. Does it link the user to a central data base ?	F	S	F	F	LS	LS	LS
5. Is it quick ?	F	S	S	S	F	S	S
6. Is it adaptable ?	S	F	F	F	F	F	F
7. Is it dynamic ?	F	F	F	F	F	LS	F

Where: S - satisfactory
LS - limited satisfaction
F - failure to satisfy

Figure 3.2: The performance of current cost estimating practice and approaches to cost modelling

REFERENCES

1 MAVER, T W
"Models and Techniques in Design", Design Methods and Theories, Vol.13, No.3, July 1979, pp.173-177.

2 SUCKLE
"By Their Own Design", Granada, 1980.

3 BROADBENT, G
"Design in architecture", John Wiley, 1973.

4 ARCHER, L B
"An Overview of the Structure of the Design Process", in 'Emerging Methods in Environmental Design and Planning', G T Moore (Ed.), MIT PRess, 1970, pp.285-307.

5 KRAUS, R I and MYER, J R
"Design: A Case Hitory", in 'Emerging Methods in Environmental Design and Planning', G T Moore (Ed.), MIT Press, 1979, pp.11-20.

6 ABEL, C
"In defence of rationality in design", Design Methods and Theories, Vol.13, No.3, July 1979, pp.107-112.

7 MAVER, T W
"Architectural Design-Interrleations among Theory, Research and Practice - Summary of Sessions", International Conference in Istanbul, chaired by T W Maver, 24 August 1978.

8 BAZJANAC V
"Architectural Design Theory: Models of the Design Process", in 'Basic Questions of Design Theory', W R Spillers (ed.), North Holland, 1974, pp.3-19.

9 RIBA
"Handbook of Architectural Practice and Management", RIBA Publications, 1967.

10 MARKUS T A et al
"Building Performance", Applied Science, 1972.

11 MAVER T W
"Building Appraisal", in 'Computer Applications in Architecture' J S Gero (Ed.), Architectural Science Series, 1977, pp.63-94.

12 JONES J C
"Design Methods (seeds of human futures)", Wiley-Interscience, 1973, p.63.

13 GERO J S
"A System for Computer-Aided Design in Architecture", in 'Artificial Intelligence and Pattern Recognition in Computer-Aided Design', J C Latombe (Ed.), North Holland, 1978, p.316.

14 LAWSON B R
"How Designers Think", Architectural Press, 1980, p.28.

15 NEWELL A
"Discussion of Papers by Dr Gagne and Dr Hayes", in 'Problem Solving: Research, Method and Theory', S J Klienmuntz (Ed.), Wiley, 1960, pp.171-182.

16 KRAUSS R I and MYER J R
Op. Cit.

17 ARCHER L B
"The Structure of the Design Process", in 'Design Methods in Architecture', G Broadbent and A Ward (Eds.), Architectural Association, 1969, pp.76-108.

18 LAWSON B R
"Cognitive Strategies in Architectural Design", Ergonomics, Vol.22, No.1, January 1979.

19 EASTMAN C M
"On the Analysis of Intuitive Design Processes", in 'Emerging Methods in Environmental Design and Planning', G T Moore (Ed.), MIT Press, 1970, pp.21-37.

20 DARKE J
"The Primary Generator and the Design Process", in 'New Directions in Environmental Design Research', W E Rodgers and W H Ittelson (Eds.), Proceedings of EDRA 9, 1978, pp.325-337.

21 HILLIER B et al
"Knowledge and Design", in 'Environmental Design: Research and Practice', W J Mitchell (Ed.), Proceedings of EDRA 3, 1972.

22 ALEXANDER C
"Notes on the Synthesis of Form", Oxford University Press, 1964.

23 JONES J C
Op Cit.

24 ALEXANDER C
Op Cit.

25 ALEXANDER C
"The State of the Art in Design Methodology", an interview in Design Methods Group Newsletter, Vol.5, No.3, March 1971, pp.3-7.

26 BROADBENT G
Op Cit., Chapters 13 and 14.

27 HANSON K
"Design from Linked Requirements in a Housing Problem", in 'Design Methods in Architecture', G Broadbent and A Ward (Eds.), Architectural Association, 1969, pp.37-44.

28 PAGE J K
"Environmental Research Using Models", Architects Journal, 11 March 1964, pp.587-593.

29 ASIMOW M
"Introduction to Design", Prentice Hall, 1962.

30 ARCHER L B
Op Cit., 1969.

31 GREGORY S A
"The Design Method", Butterworths, 1966.

32 LUCKMAN J
"An Approach to the Management of Design", in 'Design Methods in Architecture', G Broadbent and A Ward (Eds.), Architectural Association, 1969, pp.128-135.

33 JONES J C
"Design Methods Compared", Design, No.212, August 1966, pp.32-35; No.213, September 1966, pp.46-52.

34 DALEY J
"A Philisophical Critique of Behaviourism in Architectural Design", in 'Design Methods in Architecture', G Broadbent and A Ward (Eds.), Architectural Association, 1969, pp.71-75.

35 JONES J C
Op Cit., 1970.

36 JOHNSON J
"A Plain Man's Guide to Participation", Design Studies, Vol.1, No.1, July 1979, pp.27-30.

37 WATTS J and HIRST M
"User Participation in the Early Stages of Building Design, Design Studies, Vol.3, No.1, January 1982, pp.11-18.

38 CLELLAND J
"One Alternative: Solon", Architects Journal, 30 August 1978.

39 EISEMAN T
"Simulation and Requirements for Citizen Participation in Public Housing", Environmental Behaviour, Vol.7, No.1, 1975.

40 WEINZAPFEL G
"The Fatio Experiment", Architecture Machine Group, MIT Press, 1975.

41 RITTEL H W J
"Some Principles for the Design of an Educational System for Design", Journal of Architectural Education, Vol.XXVI, No.1-2, Winter-Spring 1971, pp.16-26.

42 GANDELSONAS M
"Linguistic and Semiotic Models in Architecture", in 'Basic Questions of Design Theory', W R Spillers (Ed.), North Holland, 1974, pp.39-54.

43 BROADBENT G
"Architectural Objects and their Design as a Subject for Semiotic Studies", Design Studies, Vol.1, No.4, April 1980, pp.207-216.

44 BROADBENT G et al
"Meaning and Behaviour in the Built Environment", Wiley, 1980.

45 KRAMPEN M
"The Recognition of Building Function - An Experiment in Architecture Semiology", Design Methods and Theories, Vol.13, No.3-4, July-December 1979, pp.151-152.

46 ALEXANDER C et al
"Pattern Language", Oxford University Press, 1977.

47 LEE T
"Phsychology and Environment", Methuen, 1976.

48 BARKER R
"Ecological Psychology: Concepts and Methods for Studying the Environment of Human Behaviour", Stanford University Press, 1968.

49 RODGERS W E and ITTELSON W H (Eds.)
"New Directions in Environmental Design Research", Proceedings of EDRA 9, 1978.

50 DALEY J
Op Cit.

51 MAVER T W
Op Cit., 1979.

52 BECHTEL R B
"Enclosing Behaviour", Hutchinson and Ross, 1977.

53 MANN L and HAGEVICK C
"The 'New' Environmentalism in Behavioural Design", American Institute of Planning Journal, September 1971.

54 MAVER T W
"Computer Aided Design: Applications in Architecture", in 'Human Interaction with Computers', H T Smith and T R Green (Eds.), Academic Press, 1980, Chapter 8, pp.203-229.

55 GERO J S
"The Application of Sequential Decision-Making in Optimisation Problems in Architecture", Computer Report CR23, University of Sydney, 1973.

56 NEGROPONTE N
"The Architecture Machine", MIT Press, 1970.

57 CANTER D et al
"Environmental Interaction: Phychological Approaches to our Physical Surroundings", University of Surrey, 1975.

58 SIMON H A
"The Sciences of the Artificial", MIT Press, 1969.

59 MARCH L
"Logic of Design and the Question of Value", in 'The Architecture of Form', L March (Ed.), Cambridge University Press, 1976, pp1-40.

60 LAWSON B R
Op Cit., 1980, p.49.

61 RITTEL H W J
"The Universe of Design", University of California, Spring 1964, p.99.

62 DALEY J
"Design Creativity and the Understanding of Objects", Design Studies, Vol.3, No.3, July 1982, pp.133-137.

63 GRANT D P
"The 'How-To' of Decision-Making", Design Methods and Theories, Vol.10, No.4, 1976.

64 LERA S G
"Empirical and Theoretical Studies of Design Judgement: a review", Design Studies, Vol.2, No.1, 1981.

65 EBERHARD J P
"We Ought to know the difference", in 'Emerging Methods in Environmental Design and Planning', G T Moore (Ed.), MIT Press, 1970, pp363-367.

66 RITTEL H W J and WEBBER M M
"Dilemmas in a General Theory of Planning", Policy Sciences, 4, 1973.

67 SHELLY M W and BRYAN G L
"Judgements and the Language of Decisions", in 'Human Judgements and Optimality', M W Shelly and G L Bryan (Eds.), Wiley, 1864, pp.3-36.

68 WATSON J B
"Behaviourism", 2nd Edition, Norton, 1930.

69 WASON P C and JOHNSON-LAIRD P N (Eds.)
"Thinking and Reasoning: Selected Readings", Penguin Books, 1968.

70 JONES P F
"Four Principles of Man-Computer Dialogue", CAD Vol.10, No.3, May 1978, pp197-202.

71 BARTLETT F C
"Remembering", Cambridge University Press, 1961.

72 MINSKY M
"A Framework for Representing Knowledge", in 'The Psychology of Computer vision', P H Winston (Ed.), McGraw-Hill, 1975 pp.211-277.

73 RITTEL H W J
Op Cit., 1964, p.16.

74 WARD A
"Rightness and Wrongness in the Physical Environment", in 'Design Methods in Architecture', G Broadbent and A Ward (Eds.), Architectural Association, 1969, pp.166-178.

75 BRUNER, J S et al
"A Study of Thinking", Wiley, 1956, p.1.

76 MAIER N R F
"Reasoning in Humans II: The Solution of a Problem and its Appearance in Consiousness", Journal of Comparative Psychology, Vol.12, 1931, pp.181-194.

77 LUCHINS A S and LUCHINS E H
"New Experimental Attempts at Preventing Mechanisation in Problem Solving", Journal of General Psychology, Vol.42, 1950, pp.279-297.

78 GREEN B F
"Current Trends in Problem Solving", in 'Problem Solving: Research, Method and Theory', B Kleinmuntz (Ed.), Wiley, 1966, pp.3-18.

79 CRICKMAY C L and JONES J C
"Design I - Imagination and Method", Techonology Foundation Course, Units 32-34, Open University Press, 1972, p.8.

80 OSBORN A F
"Applied Imagination", 3rd Edition, Charles Scribner, 1957.

81 GORDON W J J
"Synectics: The Development of Creative Capacity", Harper Row, 1961.

82 CHURCHMAN C W and EISENBERG H B
"Deliberation and Judgement", in 'Human Judgement and Optimality', M W Shelly and G L Bryan (Eds.), Wiley, 1964, pp.45-53.

83 LAWSON B
Op Cit., 1980, p.89.

CHAPTER FOUR: THE INPUT CONSTRAINTS

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4.1 Introduction

The structure of the building industry is characterised by the 18th century transition from a craft base in which articifer combined design and construction, to the current practice of two disparate organisations (1). With almost two centuries of separate development, each side of the industry is seen to have created its own distinct language; the designer deals in terms of activities (being an expression of the building users requirements from a space) while the contractor will deal in terms of operations (being a piece of work that can be completed by one man, or gang of men, without interuption from others). Clearly there is a need to translate a cost expressed in operational terms to a cost in terms of an activity, and this makes the design/construction interface particularly complex. While the contractor may be said to have an advantage in basic cost knowledge, it is the quantity surveyor who has the particular expertise to translate project cost data into terms which are relevant at an early stage of design (2).

The vehicle for cost communication between construction and design is the bill of quantities, the primary account of the construction industry (3). This is, despite the fact that it only really professes to be a document which provides a uniform basis for obtaining a tender (4). Based on the Standard Method of Measurement (5), the bill of quantities is grouped into work sections which enable it to fit in with the departmental sub-divisions of a contractual organisation, and thereby to simplify construction planning (6). Alternatively, each item in the bills of quantities can be allocated to a particular element. An element, for the purposes of this thesis, is defined as a component that fulfills a specific function, or functions, irrespective of its design, specification or construction (7); for example the roof, external walls, the frame, etc.

Figure 4.1 illustrates the way in which cost progresses from an operational base to an activity base via the bills of quantities item. It is apparent that the unit of finished work (the 'language' of the bills of quantities) is being used as a common vocabulary to which both operations and activities can be related.

4.2 Cost Generation

4.2.1 The process of cost generation

The process of cost generation must go through two phases:

(i) phase one is tender estimation - where the operational cost is translated into a bill of quantities unit rate.

(ii) phase two is cost analysis - where the bill of quantities unit rate is translated into an activity cost.

It is accepted that the mechanics of this process will vary given different contractual arrangements (e.g. design and build, cost plus, firm price, etc.) and even given different construction types (e.g. system building, monolithic structure, repetitive work, etc.). However, the significant characteristics are expected to remain consistent and apply equally to all projects. The basis for this contention is that:

(i) All cost estimating uses equivalent cost data

(ii) The same estimators will be involved in a variety of contractual and constructional types

(iii) The vast majority of bills of quantities are prepared using the Standard Method of Measurement

(iv) All cost analyses follow the same basic principles

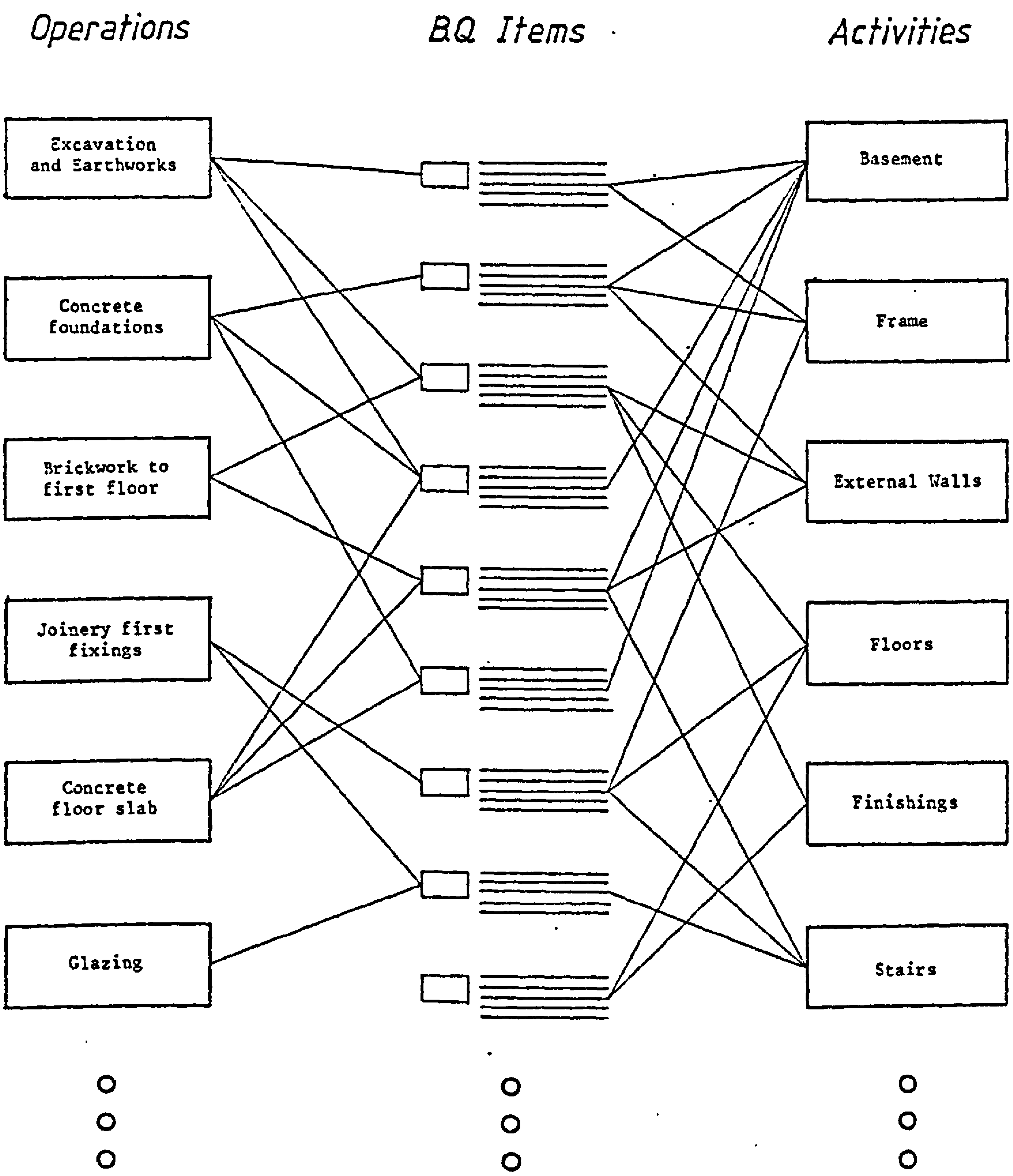


Figure 4.1: The translation of cost from an operational base to an activity base

A fundamental assumption therefore is that the rates included in the bill of quantities result from estimated costs rather than purely speculative prices. Some authors cast doubt on the validity of such an assumption (8). They argue that in a market situation such as competitive construction tendering, the overriding objective is to quote a tender price marginally lower than that of the second lowest bid. Tendering is concerned with predicting this price, and estimating purely a means of checking that the contractor is likely to be able to complete the building at a lower cost: a credible argument perhaps, but few, if any, contractors are likely to admit to such a practice.

This investigation will consider what is held to be the 'typical' cost generation process, as illustrated in Figure 4.2.

4.2.1.1 Phase one: how the operational cost is related to a bill of quantities unit rate

On receipt of contract documents the first action (presuming a positive decision to tender has been made) is to dispatch quotation enquiries to sub-contractors for those sections of the work unsuited to the 'in-house' organisation. Sub-contracted work usually corresponds to (9):

* Site clearance
* Asphalt work
* Joinery manufacture
* Steelwork
* Suspended ceilings
* and the like

Following a site visit where necessary the remaining work is arranged into work packages, or operations, according to the site conditions and choice of construction method. An operation may, for example, be to construct brickwork from foundations to ground floor level or to complete the joinery first fixings, but in all cases the content of each operation will be unique to the particular project.

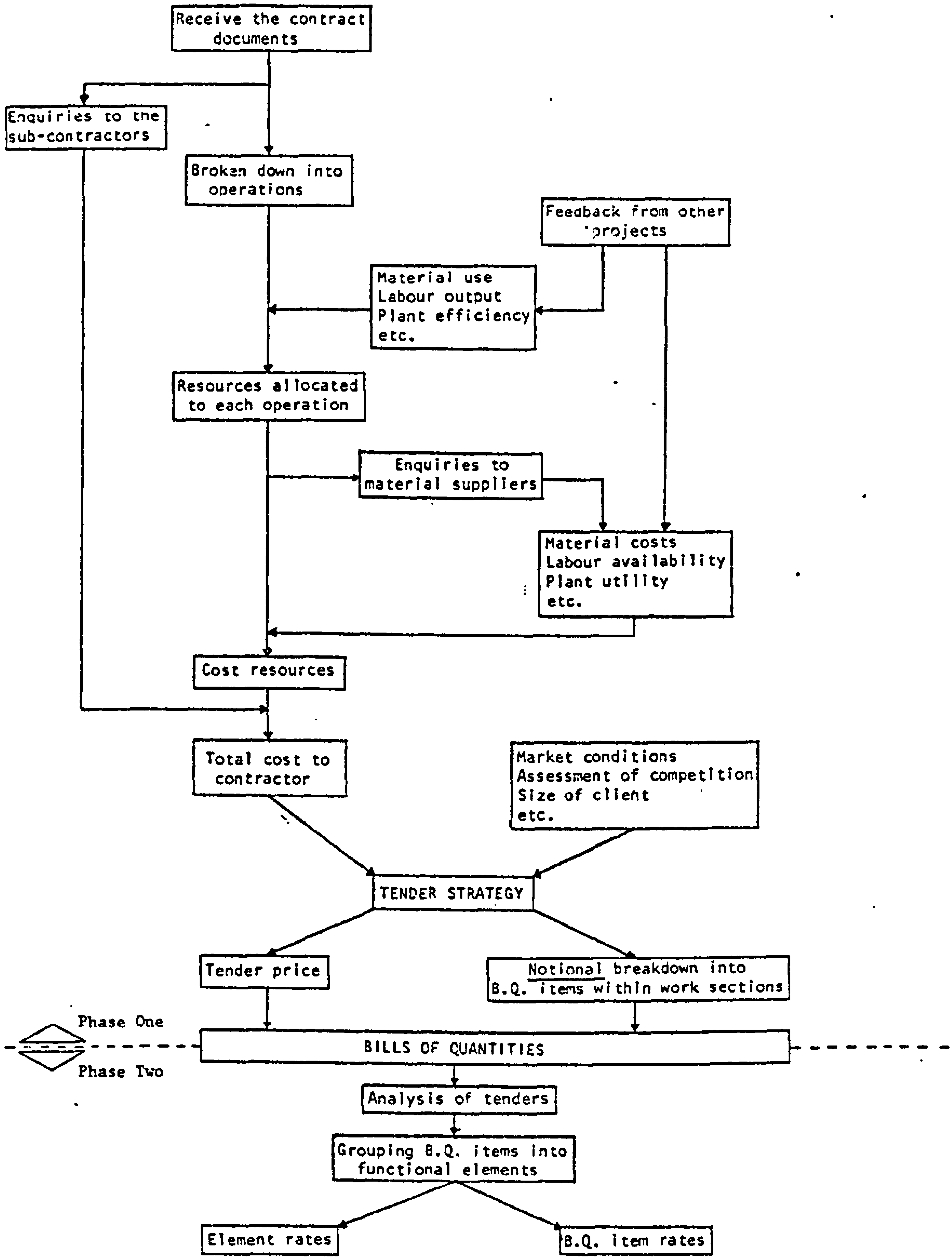


Figure 4.2: The cost generation process

To benefit from historical cost data, in theory at least, each bespoke operation must be further analysed in terms of its constituent resources. But each resource is also dependant upon the context of a particular project and should really be considered in even further detail; possibly to the level of quantifying the mass to be moved, the distance it is to be moved, and the time required to move it (10).

In practice the level of detail is constrained by the increasing cost associated with identifying and controlling smaller and smaller units of measurement (11). Figure 4.3 illustrates how the total value of a given degree of division is a balance between the cost of identifying and controlling a particular unit and the inaccuracy this produces in a tender estimate.

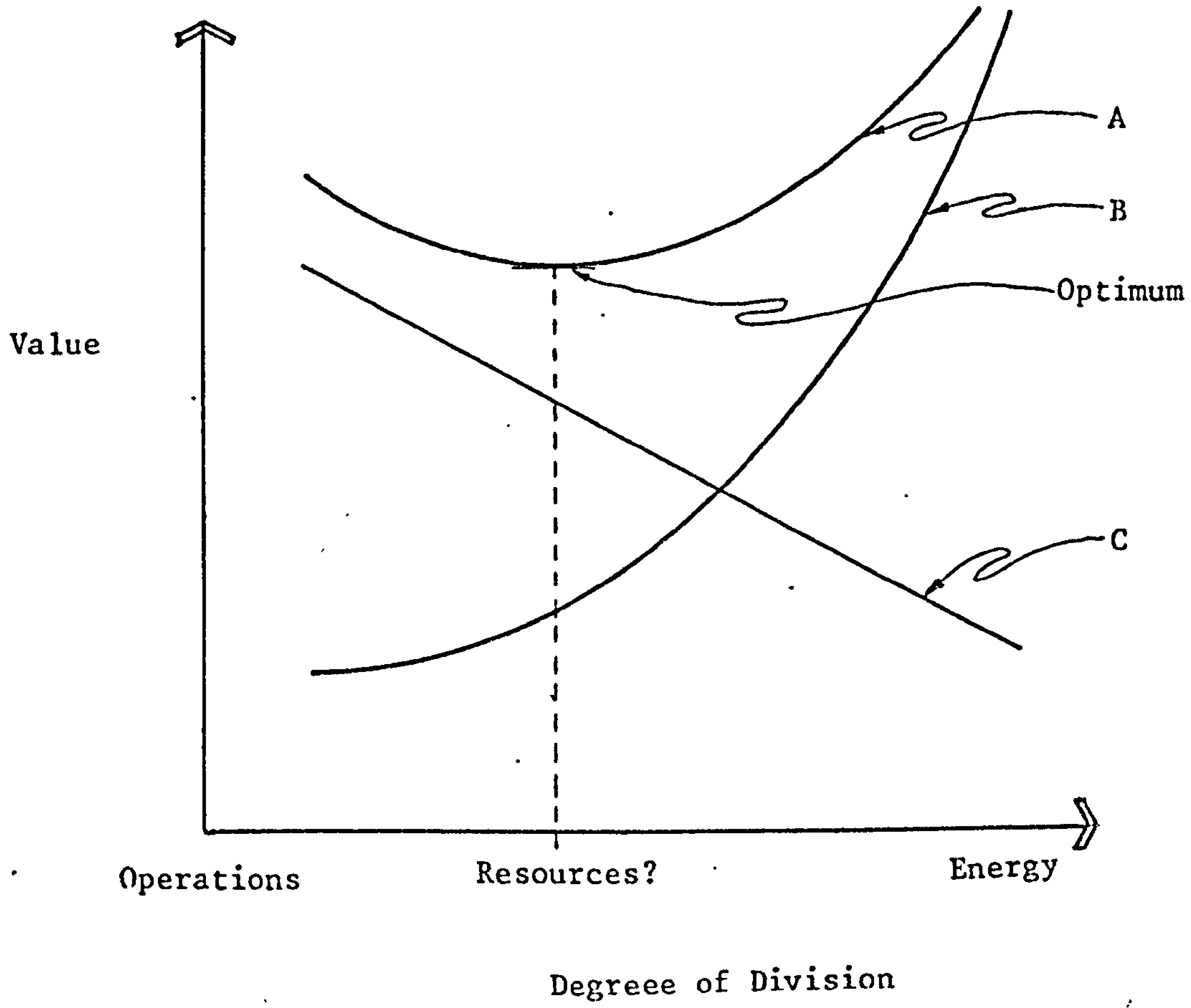
As information technology progresses, so the costs of control will decrease and the balance shift towards a more detailed degree of division: the optimum identified in Figure 4.3 will move to the right. With current standards of information processing most contractors would appear to categorise work in terms of (12):

(i) labour
(ii) materials
(iii) plant
(iv) sub-contract work

It is apparent however that even at this level of detail the inaccuracies are quite substantial.

(i) Labour: the labour content of any operation is derived from a standard output rate adjusted to suit the conditions of each particular project.

The output rate for a given operation is generally considered to be based on an analysis of time sheets for similar operations on previous projects. Unfortunately, the inaccuracy of such a procedure may not be insiginficant.



where A = Total value of a given degree of division
B = Cost of identifying and controling
C = Inherent subjectivity (inaccuracy) of an estimate

Figure 4.3: The relationship between the degree of division of work and its value to the contractor in estimating future costs

The primary purpose of a time sheet is to determine the bonus payable to workers and their charge hands. The sheets are completed by the respective chargehand daily, and the work booked to the operations worked upon that day. But not all work is 'bonusable' and the obvious temptation is to book as much time as possible to non-bonusable tasks, so that the hours booked to bonusable work are artificially understated. The recorded work is therefore inflated against the bonus target and the chargehand and his men receive higher bonus payments than are rightfully theirs; in practice of course it is not always as simple as this.

A further reason why 'standard' output rates may be misleading is in the allowance made for delays. Contractors are expected to make allowances for foreseeable delays, but the information on output rates for previous projects will invariably include extensions of time granted for exceptionally inclement weather, architect delays, etc., and the frustrated and uneconomic working so caused. It is inconceivable that these factors can be separated from the 'normal' output rates (13).

(ii) Materials: it is more difficult to control, and therefore estimate, the material content of an operation than anything else (14). Variations are caused through wastage, breakages, theft, loss, short deliveries, remedial work, delays in the recording system, etc. Only carefully compiled and comprehensive records enable all of these variances to be calculated, and the cost of undertaking such work would probably far exceed the potential savings.

(iii) Plant: a schedule of the larger items of plant will usually be determined by the construction method. The efficiency of large plant is often quite well documented, but can be highly misleading if a machine of the specified capacity somehow becomes unavailable.

(iv) Sub-contract work: with the tendency to sub-contract more work an increasing proportion of each project will be outside the control of the estimator who will have little or no records of the likely performance of particular sub-contractors.

Pricing of the resources is generally more straight forward although particular conditions of contract - an unstable client, unusual locations, etc. - may severely complicate the task.

(i) Labour: basically, the labour is priced at a rate per hour derived from the Working Rule Agreement for the particular trade and location (15). To this trade union negotiated, guaranteed minimum rate there are several emoluments paid by the employer to or on behalf of the operatives (e.g. employers contribution to National Insurance, graduated state pension, annual holiday credits, wet time, sick pay, etc.).

(ii) Material: material prices are obviously not governed by any national agreement and, most especially during rapid inflation, costs are usually obtained by quotation. Material costs do however offer an advantage to the contractor in that payment is by means of monthly credit accounts (generally at the end of the month following that in which materials are delivered). It is not unusual for a builder to delay payments beyond even the agreed settlement data and thereby earn quite considerable interest from earlier valuations by the client. Such savings should be allowed for in the pricing of materials for use within a project.

(iii) Plant: charges for plant are dealt with in one of two ways; either as an hourly or weekly hire charge, or as a depreciated cost. The cost of plant is therefore relatively static and can often be estimated quite accurately.

(iv) Sub-contract work: pricing of sub-contract work is the prerogative of the sub-contractor, however, profit and attendance on such work is recoverable by the main contractor and must be estimated as part of the tender 'build-up'.

The respective quantities of each resource are then multiplied by the derived costs and added to sub-contract quotations to give the estimated cost of the project of the contractor.

Even this cost however is not the figure to appear on the tender document, since the contractor must also cover the cost of establishment overheads and make some degree of profit from the venture.

The mechanics of tender adjudication are not well understood by cost advisers and jealously guarded by contractors. The general procedures are usually held to have three main functions, however (16):

(i) to assess the level of overheads and profit to be recovered if the long term objectives of the firm are to be satisfied. This means that market competition, the 'desirability' of the project, capital outlay, etc., must all be evaluated. It is therefore very much a decision for management.

(ii) to select the most suitable sub-contractor. The lowest tenders are checked against the risk of that particular sub-contractor proving to be unreliable.

(iii) to check the assumptions made by the estimator and planner in pricing and planning the project. The balance between labour, materials and plant will be assessed to ensure a reasonable use of the resources available. Construction method will be compared with the general cost breakdown to optimise cash flow, because the level of investment needed to complete a project may be reduced substantially by improving the passivity of cash outlay. For this reason also, rates in the bills of quantities relating to those parts of a building which are executed first (such as excavation and earthworks) may be loaded. A 'loaded' rate is one for which the rate entered in the bills of quantities (and on which valuations are based) exceeds the estimate of cost to the contractors for that work. Similarly, the contractor may anticipate variations during the course of a contract, and load any items which are likely to increase in quantity. The total figure remains unaltered by reducing rates for later work, or on items for which omissions are more likely.

Tender adjudication is however likely to occur late in the tendering process and discrepancies between tender rates and the tender total are often compensated for in the pricing of preliminaries (17). Preliminary items may be shown as separate costs per unit rate, as lump sums, or allocated proportionately among other items within the bill of quantities. In any event, significant alterations to the total tender price can be achieved by adding or removing a lump sum to the preliminary section.

Clearly the breakdown of the tender price between bills of quantities items is extremely notional.

The estimating process has thus been shown to produce bills of quantities in which even the tender price is based on variable and inherently inaccurate assumptions about labour output, material use, plant efficiency, etc., and in which unit costs may be distorted by loading as part of tender strategy, firm policy, or just fundamentaly inaccurate cost data.

4.2.1.2 Phase two: how the bill of quantities unit rate is related to the cost of an activity

In the bill of quantities, items are generally grouped in accordance with the 'Standard Method of Measurement for Building Works' work categories. To be of use in comparing the cost of achieving various functions in one project with that of achieving equivalent functions in other projects, the items must be rearranged. This process of rearrangement is termed cost analysis, and it is obvious that a uniform set of rules should be established, if users are to benefit fully from cost data prepared outside their own organisations.

A 'standard' procedure was first published by the Building Cost Information Service of the Royal Institute of Chartered Surveyors in 1969 (18) and now enjoys a wide measure of acceptance: certainly the basic principles are adopted generally (19).

Three levels of detail are recognised:

(i) the total cost, related to the project and/or to the square metre of gross internal floor area.

(ii) the elemental cost, related to the square metre of gross internal floor area and/or to a parameter more closely identifiable with the element function.

(iii) the costs of a particular form of construction within the element (a feature) shown by 'all-in' unit rates. All-in unit rates are derived for groups of bills of quantities items which are considered as one; they are summations of those individual unit rates which comprise the group.

In preparing the 'standard' form of cost analysis it was considered important for the detailed costs at each level of the analysis to equal the cost of the relevant group at the preceding level. This consideration has proved largely incompatible with the CI/SfB system of classifying data used by many architects, since the CI/SfB 'elements' do not fulfil a specific function, or functions, irrespective of their design, specification or construction (the definition of 'element' used on cost analysis) and would therefore have costs distributed among several 'elemental groups' (20). For example, the total roof costs might be distributed among CI/SfB 'group elements' (2-) primary element, (3-) secondary element, (4-) finishes, and (5-) services.

Patently more formalised than the estimating process, the allocation of each bill of quantities item to a funcational element is still based on an individuals' interpretation of very general principles. The relationship of activities to these items must therefore remain inherently subjective.

4.2.1.3 Comment

Although the cost of an activity is ultimately dependent upon the cost of an operation, the relationship is expressed in terms of a language (the bill of quantities 'item') which uses an imprecise syntax: the rules governing how an operational cost is related to the bill of quantities item (tender estimation), and how the bill of quantities item is then related to an activity (cost analysis), are never completely manifest. If the syntax is not mechanical then the language can have no absolute terms, and the generation of cost cannot be deterministic.

The cost data emanting from such a generative process is clearly uncertain: uncertain of the estimating process - what assumptions were made about labour output, material use, plant efficiency, and how unit costs are distorted by loading as part of tender strategy, firm policy or just fundamentally inaccurate cost data; uncertain of the cost analysis - and the inherently subjective application of very general principles. It is suggested that input constraints on the costing function will be influenced significantly by the nature of this uncertainty.

4.2.2 The uncertainty of cost generation

4.2.2.1 The variability

Of the two phases identified in the cost generation process it is apparent that the greater degree of variability lies in tender estimation, and in consequence, the majority of research into cost variation relates to tender pricing.

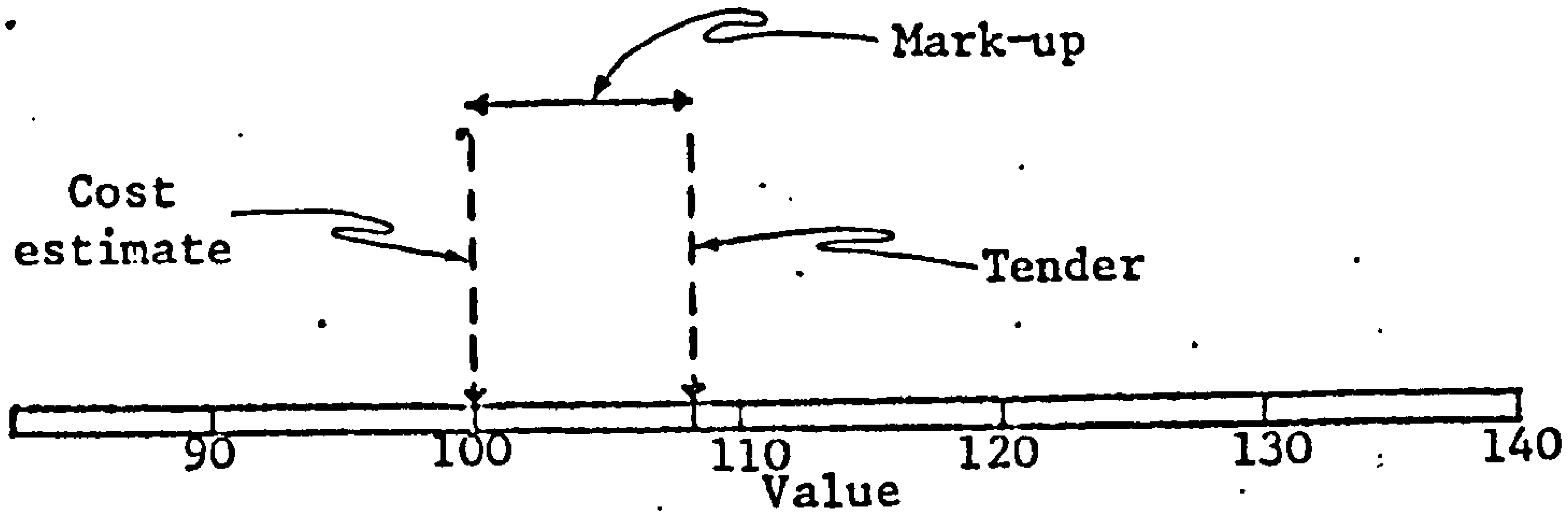
As indicated in section 4.2.1.1, and indeed as is commonly theorised, tenders comprise values allocated to two mutually exlusive components:

(i) the cost estimate
(ii) the mark-up or tender adjudication

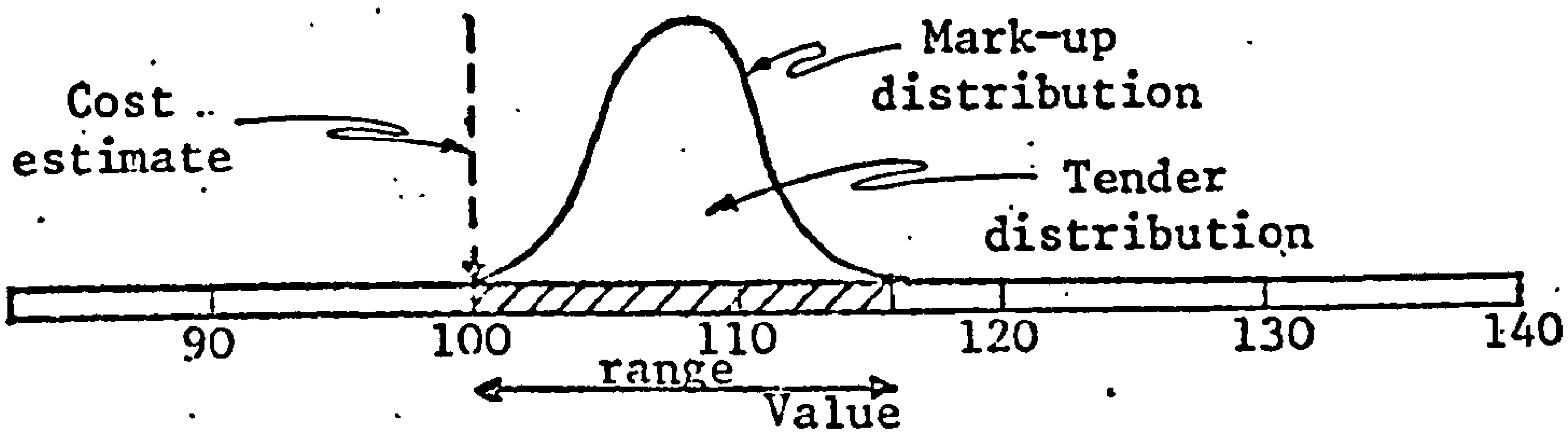
Skitmore (21) describes the four possible combinations of fixed and variable cost estimates and mark-ups as illustrated in Figure 4.4:

(i) Model 1 - a fixed estimate with fixed mark-up
(ii) Model 2 - a fixed estimate with variable mark-up
(iii) Model 3 - a variable estimate with fixed mark-up
(iv) Model 4 - a variable estimate with variable mark-up

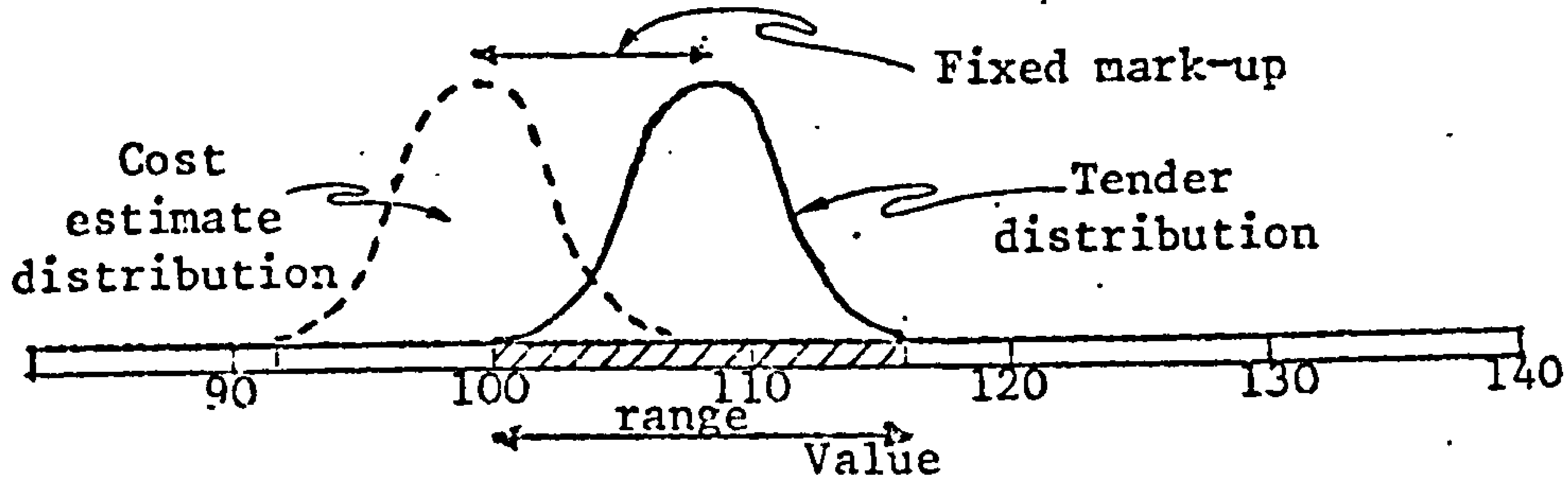
While all reseachers appear to recognise the mark-up component of a tender as being variable (indeed the Chartered Institute of Builders consider it the main manipulative strategic variable in a competitive environment (22)), Beeston (23) claims that variation in the cost estimate is less important than that it should be correlated with actual cost as closely as possible: that the average error does not have to be zero neither has it to be known, provided that it is applied equally to all projects. Analysis of the accuracy of builders' estimating however suggests that the variation could be as much as 162-188 per cent (24) which is patently incongrous with a 'standard, objectively calculated cost estimate'. It is apparent, rather, that the process of construction cost generation will produce a tender distribution which varies very much in the pattern of Model 4.



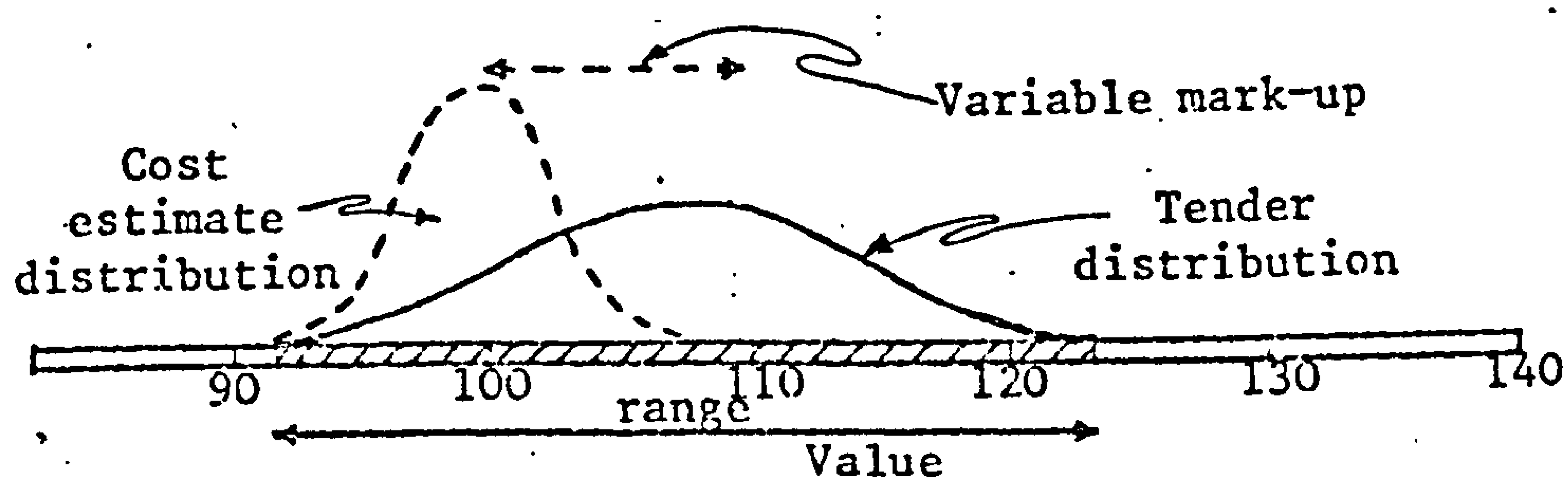
<u>Model 1</u>: A fixed cost estimate and fixed mark-up. In this case all tenders would be identical.



<u>Model 2</u>: A fixed cost estimate using absolute assumptions of resources, but varying the mark-up dependent upon tender strategy, etc.



<u>Model 3</u>: A variable cost estimate, but with a fixed mark-up representing identical management policies and market assessments for all contractors.



<u>Model 4</u>: A variable cost estimate and variable mark-up, most representative of the general tendering process outlined.

Figure 4.4: The four models of tender variability (From Skitmore M, "Why do tenders vary", CQS, December 1981, p128)

Assessment of the actual variations in tender price usually ranges from 7 to 9 per cent, the restricted range being a function of what is commonly, referred to as 'swings and roundabouts'. Variations in individual bill of quantities item rates are often much greater: typical figures for the trades within bill of quantities have been given as (25):

- excavating 45%
- concreting 15%
- bricklaying 26%
- carpentry 31%
- plumbing 23%

Recent surveys also suggest that in only 36 per cent of cases would the tender be within 10 per cent of actual cost to the contractor (26), and only 50 per cent of the time would estimates be in the range of +4 to +14 per cent of actual costs (27).

Given this overall variability, a number of attempts have been made to model the situation using probability theory and statistical analyses.

4.2.2.2 Modelling the uncertainty

With the vast majority of attempts to model uncertainty concerning themselves with the 'mark-up' component of tender estimation, emphasis has tended towards what are termed 'bidding models'. Essentially these models are frequency distributions formed from statistical analyses of previous tender submissions. Typically, Beeston (28) shows how, by expressing the recorded deviation of an individual contractors previously estimated costs from the lowest bids for those projects, an index can be produced which indicates the probability of a subsequent tender bid being successful. For example, Figure 4.5 is a hypothetical illustration of just such a statistical analysis, shown here as an exponentially smoothed cummulative frequency distribution. If the tenderer aims to win a

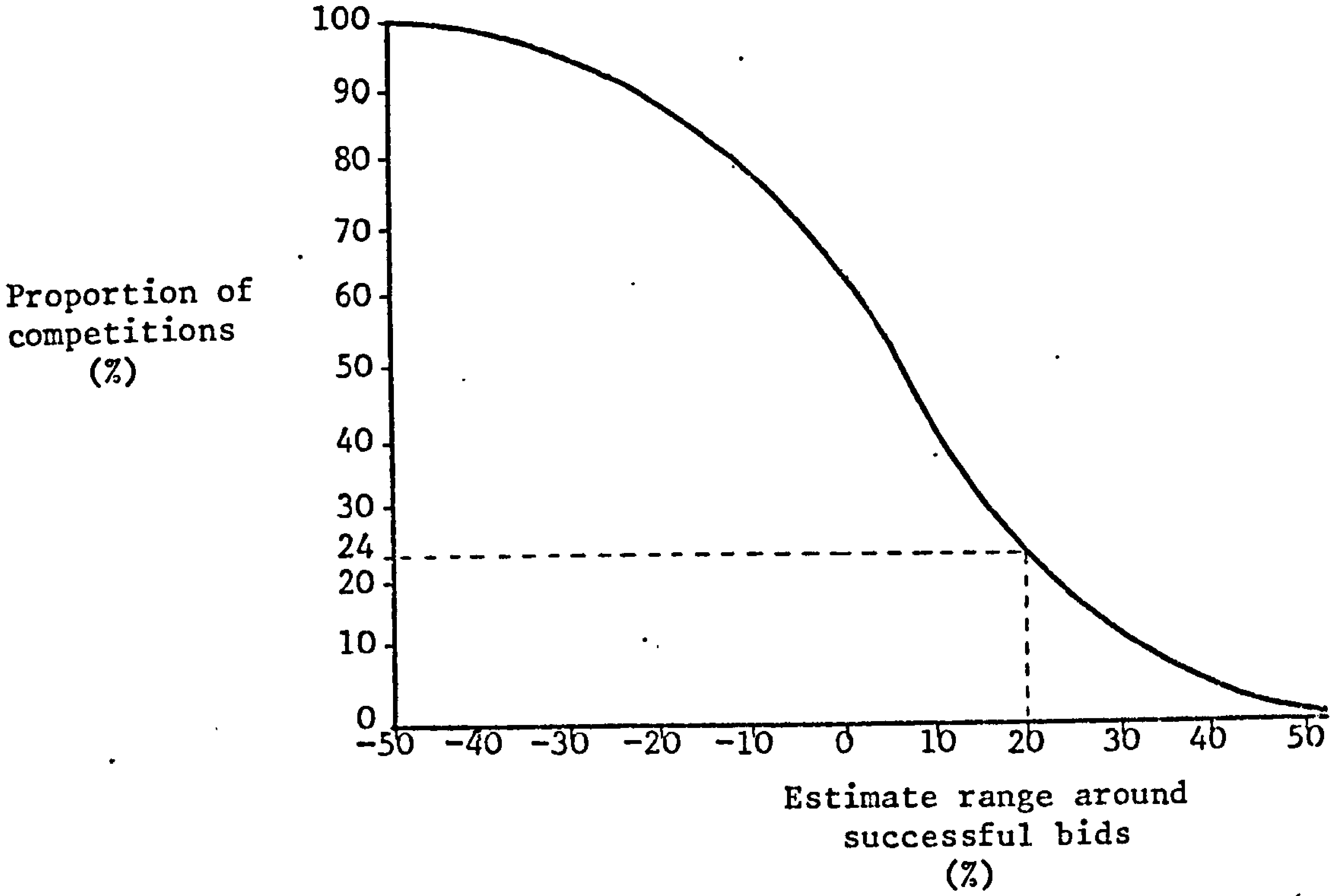


Figure 4.5: Cumulative frequency distribution for D
where $D = \frac{\text{lowest bid - estimated cost}}{\text{estimated cost}}$ %

fifth of the competitions which he enters then his 'keeness', or desired probability of winning, is 20 per cent. While more complex adjustments would be needed in practice, suffice it in this example to say that the tenderer should then bid 1.24 times his estimated costs (as per Figure 4.5), or

$$\text{bid} = \text{estimated cost} \times \left[1 + \frac{D}{100}\right]$$

In addition to the questionable assumption of a fixed estimate already noted, Skitmore identified four simplifying assumptions common to all bidding models (29):

(i) collusion and cover prices are considered a sufficiently infrequent occurrence as not to invalidate the model

(ii) bids are treated as being drawn at random from a distribution of possible bids

(iii) the bids are distributed normally

(iv) the model is static and stable

The most significant assumption with regard to uncertainty is clearly number two: that bids are treated as being drawn at random.

Even where emphasis is switched to cost estimation, still the uncertainty is inextricably linked to randomness (30).

The assumption that uncertainty - whatever its nature - can be equated with randomness has been questioned in an increasing number of applications (31). The justification for making such an assumption in modelling the uncertainty of cost generation is generally based on either:

(i) a veneration of probabilistic and statistic techniques (for example by McCaffer (32), Wilson (33) and others); the techniques have proved immensely powerful in other fields, why not in cost generation?, or

(ii) the self-amplifying prestige of successive applications of the assumption (for example by Skitmore (34), Johnson (35), and others); others have utilised the techniques in analysing cost generation, why not I?

Such justification is considered insufficient.

4.2.2.3 Comment

The uncertainty inherent in the cost generation process has been attributed largely to the first phase of tender estimation. This phase then being further divided into:

(i) the cost estimate
(ii) the mark-up, or tender adjudication

Each of the sub-divisions were shown to be typically quite significantly variable. Attempts to model the uncertainty which produces this variability have relied absolutely on the application of probability theory and statistical analysis. The use of these techniques has dictated that the uncertainty of cost generation be equated with randomness.

The nature of the uncertainty in cost generation is important. Simply to accept it as being random, and therefore determined largely by chance, is particularly objectionable when no obviously practical model has yet manifested itself, and while alternative interpretations do exist. The intention should be to consider the nature of cost generation and to relate this to the various interpretations of uncertainty available: the current trend, rather, is armed with a particularly effective hammer to treat everything as a nail!

4.2.3 Alternative interpretations of uncertainty

4.2.3.1 Interpretations based on probability theory

In the classical approach to probability theory an event, A, is defined as a member of a σ-field, A^* of subsets of a sample space, U. Thus, if P is a normed measure over a measurable space, (U, A^*), the probability of A is defined as P(A), the measure of A, and is a number in the internal [0,1].

Such statements as 'the probability of throwing double-six with a pair of true dice is one in 36', 'that there is slightly better than even probability of any given unborn infant being a boy', and 'that there is now very little chance that Britain will withdraw from the Common Market', can all be regarded as expressing judgements of probability. It is to be noted, however, that each of these examples illustrates a different kind of judgement of probability:

(i) the first is an example of what is often called a judgement of a priori probability - it relates to the mathematical calculus of chances.

(ii) the second is an example of a statistical judgement - it estimates the actual frequency with which some property is distributed among the members of a given class.

(iii) the third is an example of what Ayer (36) describes as a 'judgement of credibility' - it evaluates the degree of confidence one is entitled to have in the truth of some proposition or in the occurence of some particular event.

A point to be made about probability is that no conclusions on any matter of fact can be derived solely from the calculus of chances. There are no such things as the laws of chance in the sense in which a law dictates some pattern of events. In themselves the propositions of the calculus of chance are simply mathematical truisms. If, for example, the existing ratio of heads to trails on the toss of a coin is m:n, then the result of the next toss will be to change it either to m+1:n or to m:n+1.

No matter what numbers m and n may be, and however much one exceeds the other, only these two abstract possibilities exist. If 1000 successive heads are thrown, the probability of the next toss being a tail is still only a half. It may be the case that the coin is biased and that it would be more rational to regard the odds on each occasion as being in favour of heads, but this is then an empirical assumption based on statistical judgement.

Statistics is essentially the logic of aggregation. From some sample of the total class of events in which there is an interest, the properties found are extrapolated to be distributed in much the same proportion among the members of a further sample or throughout the class as a whole. But if it were found that heads came up in the ratio of three to two, say, in 50 tosses of a penny, is one bound to regard this as a typical answer? The answer in this case of course is 'no', because in default of physical evidence that the penny is biased, one might rather expect that if the series of tosses were continued the balance would be redressed. The reason for this expectation is based on a wider range of statistics, from a general hypothesis about the distribution of heads and tails based on previous experience.

So it is with statistics, that if suitable assumptions about the constitution of the universe are made then from such premises the fairness of a sample can be deduced. It may be fair to rely on biological laws of genealogy for the assurance that a particular unborn child will have blonde hair. On the other hand, it would be foolish to place similar reliance on a statistical correlation between children's hair colour and the parents' choice of washing-machine, say. It is apparent that what is needed for the application of the calculus of chances is a finite set of logically equal possibilities, which are fulfilled in the long run with equal frequency. It is becasue these conditions are supposed to be at least roughly satisfied in games played with coins, dice, cards or roulette wheels that they are characterised as games of chance.

Statistics requires only that a set of objects has a property corresponding to a point on a continuous scale, or of adopting at any point in time one of two fixed states, say. Statistics can then make good predicitons about the behaviour of such aggregates, since in large enough samples these will approach the statistical stability needed for the application of the calculus of chances. Where properties interact in a more complex way the behaviour will be ascribed increasingly to chance in an absolute sense, this is the sense in which 'by chance' is contrasted with 'by design'. It does not imply that such events are not connected in a law-like way or that no law connecting them will ever be discovered, but only that no such laws yet figure in accepted systems of beliefs. As more laws connecting such events are discovered then the process will less easily conform to basic patterns of statistical stability and in consequence the rigours of probability theory become less applicable. There is what Zadeh (37) has called a 'principle of incompatibility'. Stated informally, the essence of this principle is that as the complexity of a system increases, the ability to make precise and yet significant statements about its behaviour diminishes until a threshold is reached beyond which precision and significance (or relevance) become almost mutually exlusive characteristics.

The interpretation of uncertainty in terms of probability theory clearly demands that the process be expressed in a statistically stable form. Statistical 'evidence' is not an absolute test and must always be weighed against a more general experience. Given these conditions however a large number of systems have been studied most satisfactorily and with impressive rigour and precision.

4.2.3.2 Interpretations based on possibility theory

Unlike probability theory which is based on the black/white view of the universe under Boolean logic, the recently developed theory of possibility (38) stems from the intuitionistic logic established by Brouwer (39) and multivalued logic formally investigated by Lukasiewicz (40). The basis of possibility theory was born out of a notion of 'fuzzy' sets, independently developed and established by Zadeh (41).

Fuzzy sets theory in Zadeh's sense contends that certain instances of uncertainty, rather than being a result of chance alone, in fact emanate from another source, distinct from randomness, in numerous decision processes. As a machinery for explaining this other source of uncertainty, or imprecision, Zadeh introduces a particular collection of objects such that there does not exist a sharp transition from membership to non-membership and vice-versa. Such a collection he terms a fuzzy set. In this way, fuzziness may be seen to involve sets in which various membership grades, intermediate between non-membership and full-membership, are existent.

Suppose U is a space of objects: $U = \{w/w \in U\}$. Then a fuzzy set A in U is characterised by a membership function $\mu_A(w)$ which associates with each element of or point w in U a real number in the interval $[0,1]$. The value $\mu_A(w)$ represents the membership grade of w in A. It is then usual to represent the fuzzy set A by a collection of ordered pairs $(w, \mu_A(w))$, for $w \in U$. That is,

$$A = \{(w, \mu_A(w))/w \in U\}$$

$\mu_A(w)$ is a real-valued function defined on the (non-fuzzy) set U, so that for every $w \in U$, the number $\mu_A(w)$ reflects a subjective willingness to consider w as a member of A; $\mu_A(w)$ is a statement of truth for the proposition of 'w is a member of A'. Since the range of $U_A(W)$ has been stipulated as $[0,1]$ it follows that to let $\mu_A(w) = 1$ indicates a complete acceptance of w as a member of A, and to let $\mu_A(w) = 0$ indicates a total rejection of w as a member of A, for all w in U. Similarly, the interval $[0,1]$ can be replaced by the set $\{0,1\}$ in which case A becomes an ordinary (non-fuzzy) set with a characteristic function: $\mu_A(w) = 0$ whenever $w \notin A$ and $\mu_A(w) = 1$ if and only if $w \in A$.

Clearly subjectivitiy is greatly emphasised in fuzzy set theoretic analysis of a sytem, which has in consequence been applied mainly to the formalisation of semantics (42). It is argued that in the case of natural languages, most of the words occuring in a sentence are names of fuzzy rather than non-fuzzy sets, and that the logic behind human reasoning is not the traditional two-valued or even multivated logic, but a logic of fuzzy truths, fuzzy connections, and fuzzzy rules of inference. For example:

(i) X is a large number. Y is much larger than X. How large is Y?

(ii) Gill is very beautiful. Is Gill more beautiful than I?

(iii) That house is much more expensive than most of the others in this neighbourhood. How expensive is the house?

This fuzzy logic is basic in the ability of humans to summarise information - an ability of paramount importance in the analysis of any complex concept, especially those which are manifest in the use of natural languages (43).

Uncertainty, when related to the 'fuzziness' of possibility theory, is apparently being equated with imprecision as distinct from randomness. In retreating from precision researchers have found it natural to use what are called linguistic variables (44): that is, variables whose values are not numbers but words or sentences in a natural or artificial language. The motivation for the use of words or sentences rather than numbers in that linguistic characterisations are, in general, less specific than numeral ones. For example, in speaking of age, the statement 'John is young' is less precise than if to say, 'John is 25'. In this sense, the label 'young' may be regarded as a linguistic value of the variable Age; it plays the same role as the numerical value 25 but is less precise, and hence also less informative. Figure 4.6 illustrates the possibility distributions, U_{Age} (young), U_{Age} (close to middle age), U_{Age} (middle aged), of three fuzzy sets in the given range of possible ages of a population.

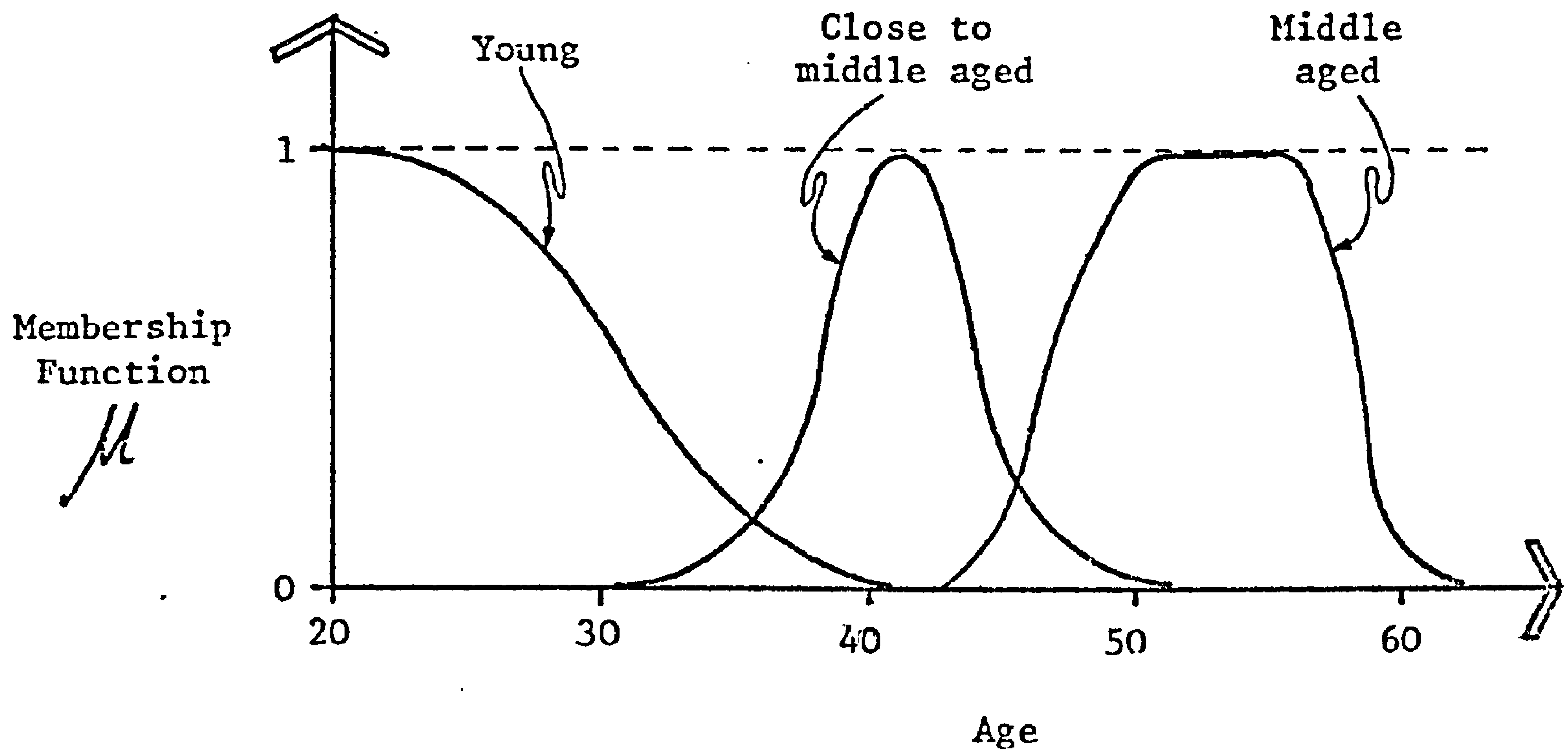


Figure 4.6: Characterisation of 'young', 'close to middle age' and 'middle-aged' as fuzzy sets in U. (After L A ZADEH "Quantitative Fuzzy Semantics" in Information Sci., Volume 3, 1971, p163)

Although the linguistic approach of possibility theory is orthogonal to the rigourous, quantitative approaches which reflect what have become the prevailing attitudes in scientific research, it addresses uncertainty in a way in which probability theory never can; as imprecision. The substantive differences between this approach and the conventional quantitative techniques raise many issues and problems which are novel in nature and hence require a great deal of additional study and experimentation. (For an excellent introduction to the current theory of fuzzy sets, see Kaufmann (45)).

4.2.4 Comment

4.2.4.1 The nature of uncertainty in cost generation

Uncertainty in the cost generation process has been identified as emanating from two sources:

(i) within the estimating process various assumptions are made about labour output, material use, plant efficiency, and how unit costs are distorted by loading, etc.

(ii) within the cost analysis very general principles are applied subjectively.

The uncertainty can therefore be traced quite definitely to those assumptions and judgements of human beings which impact upon the process. The vast majority of the uncertainty will lie in what decisions the human beings take: whether labour output is taken as good or bad; whether the bid is reduced slightly to gain continuity of work; whether a coping stone is included in the cost analysis as roof or as wall; etc. It follows that the nature of the uncertainty equates with how such judgements are made: with human behaviour.

One of the most important determinants of human behaviour is meaning (46), and meaning has two very important properties:

(i) it is structured by the context of the situation (47), so the meaning of 'table' will change depending on whether the person is about to eat a meal, examine some facts, play snooker, make a proposal, etc.

(ii) it is not always absolute (48); so that in a particular context, 'table' is a name for a class of objects whose boundaries are not sharply defined (bench, desk, trestle, etc.).

It is suggested that like all systems whose behaviour is influenced strongly by human judgement, perception or emotion, the nature of the uncertainty in cost generation can largely be equated with the nature of meaning, notably:

(i) it too is structured

(ii) it too is imprecise

4.2.4.2 A comparison of alternatives

It is folly to compare alternatives, based only on past successes in other fields. The aim, rather, should be to attend the characteristics of the object problem and make a comparison of alternatives in respect to those characteristics. In this case the relevant characteristics are:

(i) the uncertainty is structured

(ii) the uncertainty is imprecise

Hillier and Leaman (49) comment that "structure is the enemy of statistical stability". They mean by this that in a statistical analysis of a system, the causal aspects of the system which cannot be described are taken to be statistically stable, or random. When such causal effects are not random but merely outwith current knowledge, then they will interfere with the statistical stability - manifest in an unacceptably large standard deviation. The task of science has been to determine and relate all structure that produces non-randomness in a system, such that what remains is random and therefore epiphenomenal. There are, indeed, those who maintain that this stage has already been reached in quantum physics. The rationale is based on the fact that the determinism postulated in classical physics required that it be possible, at least in principle, to ascertain the position and momentum at any given instant of all the particles in the universe. This is a condition that microscopic particles do not satisfy (50). It can still be argued, however, that this reasoning does not logically preclude their falling into some deterministic pattern (51). Even so, the fact remains that such a pattern has not yet been found. Until it is found, the view that the fundamental laws of physics are not causal but only statistical, would appear to hold the field.

A similar argument can be applied to the uncertainty in cost generation. A lack of any meaningful evidence demonstrating the existence of systematic relationships between the dispersion of bids and any possible causal variables strongly encourages the assumption that bids can be theoretically treated as being drawn at random from a distribution of possible bids (52). It can be argued however that this inability to evidence causal variables may well be due to the immense complexity of systems influenced by human judgements, emotions and perception. Certainly the system is structured by the many human decisions taken throughout the process and is therefore, at least intuitively, not random. But the toss of a coin, characterised as an occurence of chance, is also structured by the force of the flick, the resistance of the air, etc. Clearly the situation is something more than a simple dichotomy between order and disorder.

The significant property of uncertainty in the cost generation process is imprecision.

In classical mathematics, the substance of probability theory, it is understood that there are only two acceptable situations for an element: being a member or not being a member of a subset. Any formal logic, Boolean logic, rests on this base: membership or non-membership in a subset of a reference set. The merit of L A Zadeh has been to attempt to leave this impasse by introducing the notion of weighted membership. An element may then belong more or less to a subset, and, from there, introducing a fundamental concept, that of a fuzzy subset.

A basic tenet has been that the uncertainty intrinsic in cost generation is a mixture of probabalistic and possibilistic constituents. An important aspect of the connection between probabilities and possibilities relates to the fact that they are independent characterisations of uncertainty in the sense that from the knowledge of the possibility distribution of a variable one cannot deduce its probability distribution, and vice-versa. Needless to say, the inability of conventional statistical techniques to deal with imprecise data, in an imprecise way, would not matter much if the predominance of fuzziness were a rare phenomenon. In reality, the opposite is the case in cost generation; for upon fundamental examination it becomes clear that much of the uncertainty can be traced directly to human decision-making and cognition.

It transpires that while the argument for or against probabalistic and possibilistic treatments of uncertainty is still balanced in terms of the interpretation of order or structure in cost generation, the absolute inability of probabalistic techniques to deal with imprecision directs choice between the two alternatives quite definitely. Given that an imprecise treatment equates most closely with human decision-making and that there is strong practical evidence to suggest that cost generation is significantly structured, the continued commitment of research endeavour wholly towards a probabalistic treatment of cost uncertainty reflects a substantial imbalance. This thesis is an attempt to initiate the redressing of that imbalance by adopting a possibilistic approach to cost uncertainty.

An example of how such an approach might be applied to cost generation is expounded in Appendix III, but the novelty of the technique prevents its detailed incorporation within the thesis generally. Acceptance of the uncertainty in cost generation as characterising imprecision, rather than randomness, does however impose quite severe limitations on the use of cost data, and therefore the form of any costing function; most notably

(i) the process must handle imprecise and inherently inaccurate data.

(ii) the 'meaning' of data must be governed by the context of the situation - a syntactic rule.

(iii) the relationship of 'meaning' with context must be variable - a semantic rule.

Of course these restrictions devolve from the properties of meaning already identified, and would apply equally to the formulation of, say, a language - wherein most applications of possibility theory have so far been made.

4.3 Summary

The cost generation process has been shown to constitute two sequential phases:

(i) phase one is tender estimation which translates the operational costs of the contractor into a bill of quantities in which even the tender price is based on variable and inherently inaccurate assumptions about labour output, material use, plant efficiency, etc., and in which unit costs may be distorted by loading as part of tender strategy, firm policy, or just fundamentally inaccurate cost data.

(ii) phase two is cost analysis in which, though patently more formalised than the estimating process, the allocation of each bill of quantities item to a functional element is still based on an individual's interpretation of very general principles.

The cost data emanating from such a generative process is clearly uncertain, and shown to be quite significantly variable.

Two alternative interpretations of uncertainty have been considered and related to the cost generation process described.

(i) A probabalistic approach which has proved highly successful in other fields, but which lacks any means of dealing with imprecise data. Though in theory there are strong indications that cost generation can be equated with randomness, intuitively at least, the process is structured by the many human decisions - a quality which complicates the calculus of probability.

(ii) A possibilistic approach based on the concepts of fuzzy set theory. This treatment equates uncertainty with imprecision, and therefore relates to the modes of human decision-making and cognition in a fundamental way. Although an understanding of possibility theory is quite fragmentary at this juncture, it is very likely that, in time, fuzzy sets will become an important area of study and research in artificial intelligence, psychology and all fields related to human decision-making; as construction cost generation most surely is.

An example of how a possibilistic approach might be applied to cost generation is given in Appendix III, and at a more general level, several quite severe constraints are placed on the costing function.

(i) the process must handle imprecise and inherently inaccurate data.

(ii) the 'meaning' of data must be governed by the context of the situation.

(iii) the relationship of 'meaning' with context must be variable.

The severity of the constraints goes some way towards explaining the paucity of success in the modelling of cost relationships, as evidenced in Chapter 3 of this thesis. For example, if costs are context dependent then the single rate costs used by the vast majority of existing models to relate to all contexts, are inappropriate. Similarly, the many cost models which assume absolute/static cost relationships are over simplifying the problem and will rapidly become obsolete.

4.4 Conclusions from Part One; A Mandate for Part Two

This chapter presents a list of criteria on which, it is suggested, the full potential of any alternative costing function might be judged. The preferred characteristics are those identified already as providing the necessary external properties to interface with design and construction.

(a) From chapter three:

1. does it minimise conflict?
2. does it assist in solution generation?
3. does it relate a project to other comparable projects?
4. does it link the user to a central data base?
5. is it quick?
6. is it adaptable?
7. is it dynamic?

(b) From chapter four:

1. does the process handle imprecise and inherently inaccurate data?
2. is the 'meaning' of data governed by the context of the situation?
3. is the relationship between 'meaning' and 'context' variable?

The list of criteria, while focussing attention upon salient characteristics, fails to provide a definitive specification of the most desirable costing function, and thus exposes them to wide ranging interpretation, possibly. It remains to test the latitude of possible interpretations by investigating the mechanics of a particular solution, which achieves a high rating in all criteria.

Such is the mandate for Part Two of this thesis.

REFERENCES

1 POWELL C G
"An Economic History of the British Building Industry 1815-1979", Architectural Press, 1980.

2 FERRY D J and BRANDON P S
"Cost Planning of Buildings", Fourth Edition, Granada, 1980, p.32.

3 RICS and NFBTE
"Report on the Joint Working Party on Measurement Conventions", RICS, 1972.

4 BINDSLEV B
"CBC" in Architects Journal, 30 December 1964, pp.1571-1576.

5 RICS and NFBTE
"Standard Method of Measurement of Building Work", Sixth Edition, RICS, 1979.

6 HILL I
"SMM - Its Past and Future", Building, 27 July 1973, p98.

7 BCIS
"Section G: The Standard Form of Cost Analysis", RICS.

8 SHAW D T
"Do Builders Estimate? Or Do They Price?", Surveying Technician, Vol. 2, August 1973, pp.16-18.

9 SKINNER D and JEPSON B
"The Contractor's Use of Bills", CQS, September 1980, p.67.

10 JAGGER D M
"Cost Data Bases and their Generation", 'Building Cost Techniques: new directions', P S Brandon (Ed.), Spons, 1982, pp.90-106.

11 FORBES W S
"Some Aspects of the Measurement of Productivity in the Building Industry", PACE Journal, April 1066, pp13-16.

12 WAINWRIGHT W H and WOOD A A B
"Practical Builders Estimating", Fourth Edition, Hutchinson, 1981.

13 SHAW W T
Op. Cit.

14 HARRIS F C
"Controlling Costs on Site", BT and M, November 1976, pp5-8.

15 LIVERPOOL AND DISTRICT JOINT COMMITTEE for the Building Industry
"Working Rules and General Information", Revised to 6 October 1975.

16 PROPERTY SERVICES AGENCY
"Construction Cost Data Base", Vol. 2, PSA, 1980, p.62.

17 AZU N O M
"Preliminaries in Bills of Quantities for Building Works", The Quantity Surveyor, May 1977, pp.185-188.

18 BCIS
"Detailed Form of Cost Analysis", RICS, 1969.

19 FERRY D J and BRANDON P S
Op. Cit., p.176.

20 ANON
"Application of Data Co-ordination to Drawings, Specifications and Bills of Quantities", Architects Journal, 26 August 1970, pp.489-503.

21 SKITMORE M
"Why Do Tenders Vary?", CQS, December 1981, pp.128-129.

22 CIOB
"Code of Estimating Practice", Fourth Edition, CIOB, 1979.

23 BEESTON D T
"Estimating Market Directions", 'Building Cost Techniques: new directions", P S Brandon (Ed.), Spons, 1982, pp.265-277.

24 ASHWORTH A et al
"An analysis of the accuracy of some builders estimating", The Quantity Surveyor, April 1980, Vol. 36, No. 4, pp.65-70.

25 BEESTON D T
"One Statisticians View of Estimating", Building Economist, Vol. 14(3), 1975, pp.139-145.

26 FLANAGAN R
"Tender Price and Times Prediction", unpublished PhD thesis, University of Aston, 1980.

27 PROPERTY SERVICES AGENCY
Op. Cit., p73.

28 BEESTON D T
Op. Cit., 1982.

29 SKITMORE M
"A Bidding Model", 'Building Cost Techniques: new directions', P S Brandon (Ed.), Spons, 1982, pp.278-289.

30 SPOONER J E
"Probabalistic Estimating", ASCE Journal of Construction Division, March 1974, pp65-77.

31 BELLMAN R E and ZADEH L A
"Decision Making in a Fuzzy Environment", Management Science, Vol.17(4), December 1970.

32 McCAFFER R
"Contractor's Bidding Behaviour and Tender Price Prediction", unpublished PhD thesis, Loughborough, University of Technology, 1976.

33 WILSON A J
"Experiments in Probabalistic Cost Modelling", 'Building Cost Techniques: new directions', P S Brandon (Ed.), Spons, 1982, pp.169-180.

34 SKITMORE M
Op. Cit., 1982.

35 JOHNSTON R H
"Optimisation of the Selective Competitive Tendering System by the Construction Client", Transport and Road Research Laboratory Report 855, DOE, 1978.

36 AYER A J
"Chance", 'Risk and Chance', J Dowie and P Lefrere (Eds.), Open University Press, 1980, pp.33-51.

37 ZADEH L A
"Fuzzy Sets", Information Control, Vol. 8, 1965, pp.338-353.

38 ZADEH L A
"Possibility Theory and Soft Data Analysis", Memorandum No. UCB/ERL M79/66, University of California, 27 August 1979.

39 HEYTING A
"Intuitionism: an introduction", North-Holland, 1966.

40 BORKOWSKI L
"Jan Lukasiewicz: selected works", North-Holland, 1970.

41 ZADEH L A
"Fuzzy Sets as a Basis for a Theory of Possibility", Fuzzy Sets and Systems, Vol. 1(1), 1978, pp.3-28.

42 ZADEH L A et al
"Fuzzy Sets and their Applications to Cognitive and Decision Processes", Academic Press, 1975.

43 ZADEH L A
"Outline of a New Approach to the Analysis of Complex Systems and Decision Processes", 'IEEE Transactions on Systems, Man and Cybernetics', Vol. SMC-3, No. 1, January 1973, pp.28-44.

44 ZADEH L A
"The Concept of a Linguistic Variable and its Application to Approximate Reasoning - Parts 1, 2 and 3", Information Sciences, Vol. 8, 1975, pp.199-249 and pp.301-357, and Vol. 9, 1975, pp.43-80.

45 KAUFMANN A
"Introduction to the Theory of Fuzzy Subsets", translated by D L Swanson, Academic Press, 1975.

46 OSGOOO C E et al
"The Measurement of Meaning", University of Illinois Press, 1967, p.10.

47 JORDAN N
"Themes from Speculative Psychology", Tavistock Pubs., 1968, pp.44-65.

48 ZADEH L A
"PRUF - A Meaning Representation Language for Natural Languages", Int. J. Man-Machine Studies, Vol. 10, 1978, pp.395-460.

49 HILLIER B
"The Architecture of Architecture", 'Models and Systems in Architecture and Building', D Hawkes (Ed.), Construction Press, 1975, pp.5-28.

50 BORK A
"Randomness and the Twentieth Century", 'Risk and Chance', J Dowie and P Lefrere (Eds.), Open University Press, 1980, pp.52-73.

51 POPPER K
"The Logic of Scientific Discovery", Hutchinson, 1968.

52 SKITMORE M
Op. Cit., 1982, p.281.

PART TWO: THE COSTING FUNCTION - ITS MECHANISMS

CHAPTER FIVE: A SPECIFIC INTERPRETATION OF THE PREFERRED COST FUNCTION CHARACTERISTICS

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5.1 An Introduction to Part Two

The set of preferred cost function characteristics proposed in Part One of this thesis indicate the criteria on which a cost function should best be judged. These criteria are not wholly disparate however suggesting that the 'optimum' performance will incur a degree of compromise between conflicting characteristics. The extent of this 'trade-off' between characteristics will be governed largely by the importance (or 'weight') attributed to each, and this ascription will vary from person to person. The situation is clearly equivalent to the expression of an isomorphous system as described in Chapter 2, Section 2.2: indeed it is a direct consequence of considering the costing function at a process level.

The aim of Part Two of this thesis is to detail how one (typical) person might interpret these characteristics, through the development of a tentative specification for the next-generation of costing function. Further, the practicability and validity - of both the set of characteristics which form its basis, and of the specification itself - is exemplified by ACE (Analysis of Construction Economics); a computer based cost simulation model.

Part Two switches emphasis from the overall process characteristics, to the particular mechanisms which collectively produce the necessary effect.

A primary objective for Part Two therefore is to provide a specification sufficiently detailed to determine an actual implementation, and this objective has engendered a quite exceptional brevity in the treatment of many tertiary subjects - most of which offer substantial potential for research within themselves. It is hoped, never-the-less, that more meticulous research will derive some, not insignificant benefit from this, inevitably blinkered, research. Particularly in a subject such as building economics, which only now is beginning to recognise some scientific basis, often there are substantial insights to be gained by making bold assumptions about the problem structure.

5.2 The Cost Function Characteristics

To 'interpret' means to convey the vital principles or meaning of something, and as such any interpretation will be moulded by the conceptions of the interpreter: by the frames and schema held in the mind and applied to suitable situations as they arise (see Chapter 3, Section 3.4.2). The more explicit the expression of these basic assumptions and preconceptions, the more rigorous - in a scientific sense - will be the interpretation. Thus, in describing how the cost function characteristics of Part One may be interpreted, it has been necessary to resolve a number of issues which might otherwise have been considered beyond the scope of this thesis.

To assist the reader, the most significant considerations are given in parenthesis with each section heading.

5.2.1(a1) Minimise Conflict (expert systems, representation)

Three sources of conflict are considered:

* the user/computer interface (a need for some form of computer program is determined in Sections 5.2.2, 5.2.4 and 5.2.5).
* the way data is presented to the user.
* the consistency of the data provided throughout the design process.

(i) The user/computer interface: computer programs have taken on many roles -

* the dumb servant (e.g. menial calculations)
* the typist (e.g. word processing, text manipulation)
* the draughtsman (e.g. graphical manipulation)
* the filing clerk (e.g. database management)

To replace the building economist however requires a very different type of role playing: that of the 'expert consultant'. The designer or design team has certain expectations of any 'expert consultant', expectations which are different fundamentally to other roles, and substantially more difficult to replicate. For example, 'consultants' have the following characteristics:

* their skill is based on past experience and is continuously being supplemented.
* there is a high degree of interaction, both evaluating and generating proposals.
* the information provided can be explained, and considered in terms of its wider implications.
* they are highly adaptable to unusual situations.
* they can proceed on partial information, and respond differently to context.

'Expert systems' have now been successfully implemented in a range of professional activities and offer a real opportunity closely to match the computer program and expert consultant (1). The intention obviously is to reduce the impact of replacing (or more realisticly partially replacing) the consultant by ensuring that the computer program exhibits similar characterisitcs.

The basic structure of an expert system is illustrated in Figure 5.1 and consists of a number of essential parts:

* a knowledge base
* a driver program
* a natural language front-end translator program
* an explanation capability
* a program to enable an expert to update the knowledge base

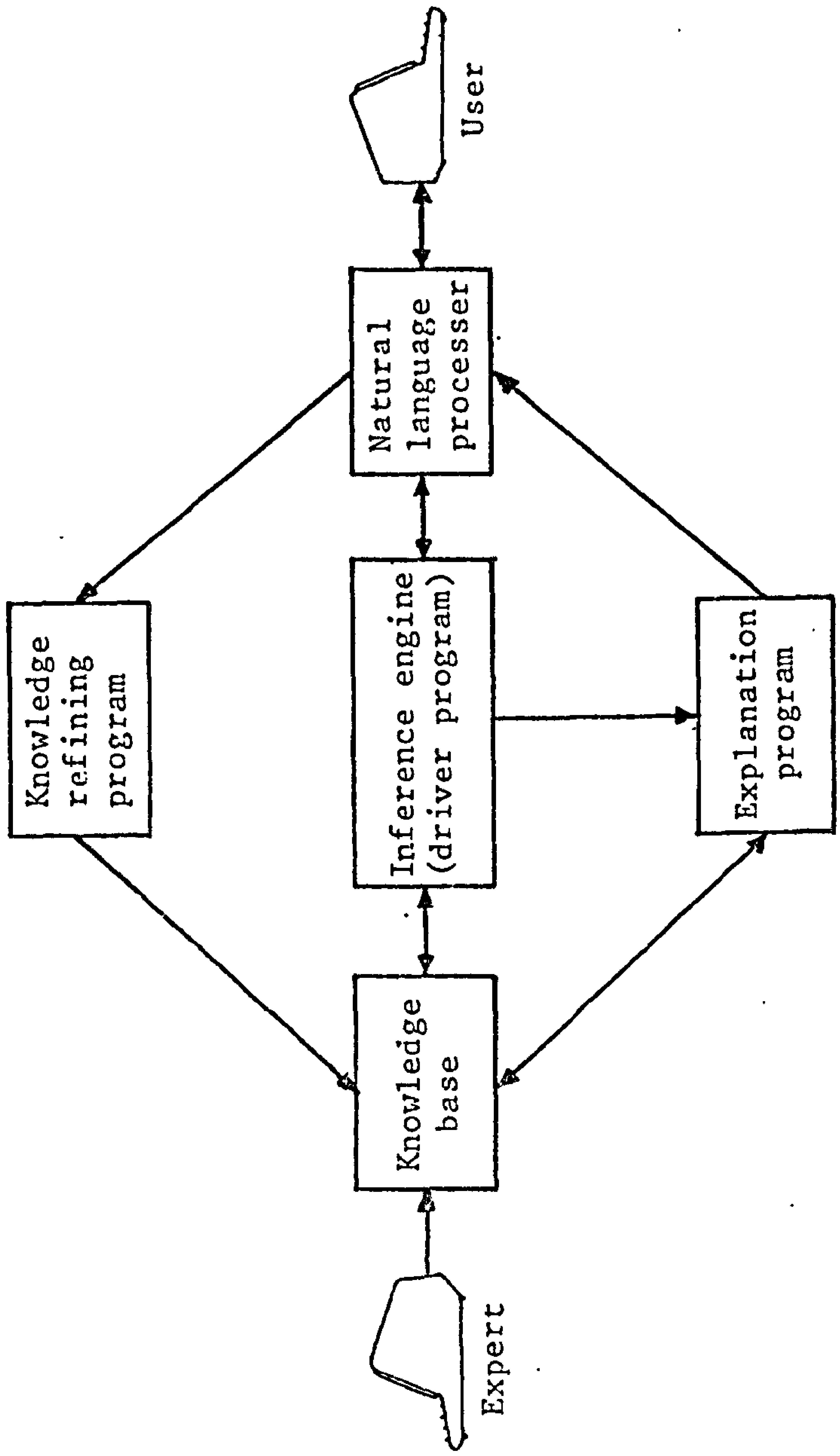


Figure 5.1: The basic structure of an expert system

It is apparent that the more 'expert-like' the system becomes the more useful it will be in the design environment. Unfortunately related research is still very much at a preliminary stage, and any attempt to produce a fully operational expert costing system at this juncture unquestionably would demand an inordinate commitment of resources. The important consideration for the next generation of cost model is to produce a knowledge-based system which would exhibit a limited similarity to the 'true' expert system of the future, while still offering the potential to graduate towards such a state.

Figure 5.2 illustrates how a knowledge based system might be implemented, while still allowing for future refinements to be made. What is important at present, is the choice of how the knowledge is to be represented.

Several methods of representing knowledge within a computer are currently used (a good review of them all may be found in Barr and Feigenbaum (2)):

* logic
* semantic methods
* production systems
* procedural representations
* semantic primitives

The representation which is recommended as having the most immediate promise for construction industry work in particular (3), and most widely used in expert systems generally, is the production system.

A production system consists of a number of rules, each rule being of the IF... THEN... type. These rules are sometimes referred to as 'situation-action' rules; that is, IF 'some situation occurs' THEN 'some action is performed' (see Figure 5.3 for an example of a production rule). The power of the technique lies in its ability to use the consequents of some rules as the antecedents of others thus allowing quite complex conditions to be chained together in a relatively simple way.

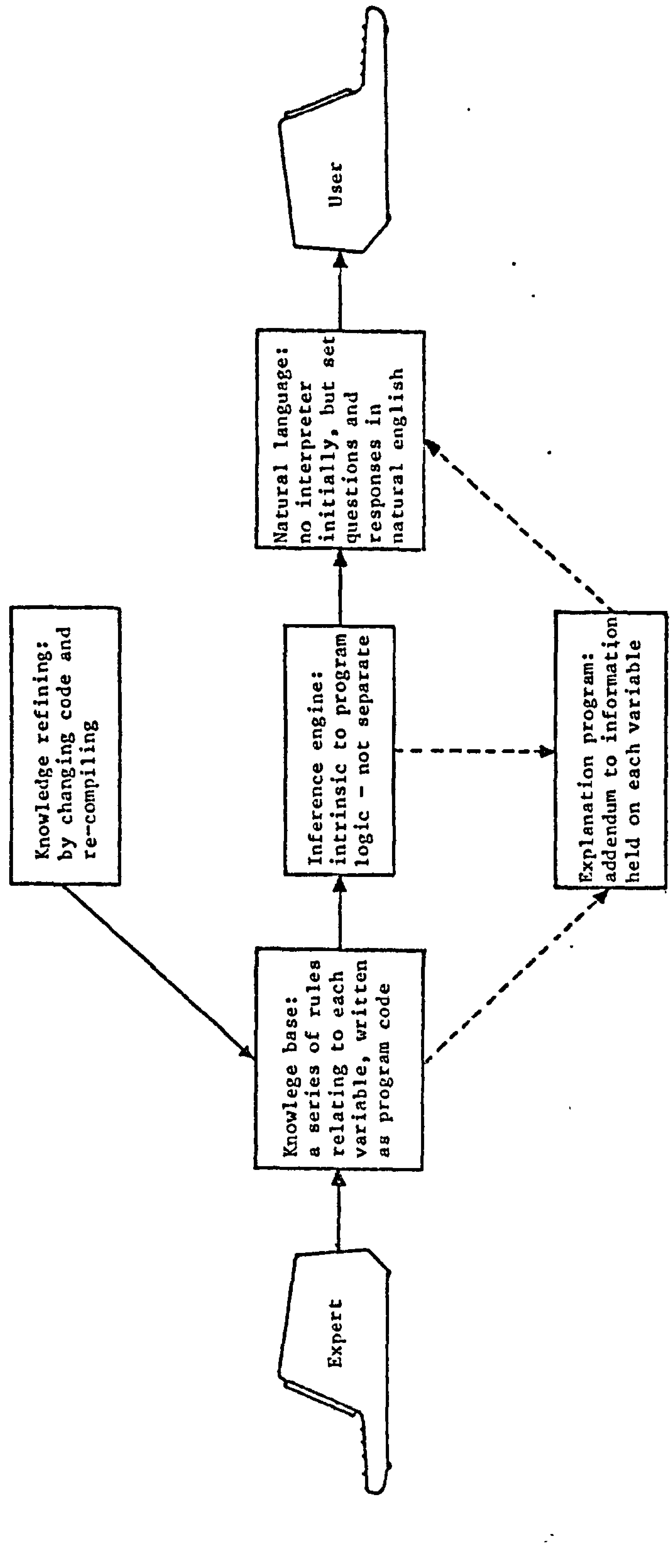


Figure 5.2: The proposal for an expert-like costing function

```
IF:          Request is for the gross floor area
       AND   gross floor area is unknown
       AND   no geometry has been input
       AND   user doesnt know gross floor area

THEN:        Request plan area
       AND   request number of storeys
       AND   gross floor area = plan area x number of storeys
```

Figure 5.3: An example of a production rule

The most suitable implementation of an expert-like costing function would appear to be as illustrated in Figure 5.2, using a production system knowledge representation.

(ii) The data representation: in many instances, data representation (i.e. the way information is communicated) is considered largely to be a function of the particular analysis techique which produces the information. Increasingly however computer-aided data manipulation provides for a whole range of different representations, assuming of course that:

(a) the information, in its raw state, is computer based; and
(b) there is enough data to provide a display (most pertinent in multi-variate representations).

Obviously the main gambit is to get a sufficiently munificent set of raw data onto the computer. Given this situation the choice of display technique is governed largely by the characteristics of human perception.

Research (4) has shown that both the channel capacity of the attention channel (the number of dimensions on which a person can register change at the same time) and the storage capacity of the short-term memory (the number of items thought about at any one time) are limited. In many cases, seven alternatives are the approximate limit of channel capacity for unidimensional information. Seven is small when considering a complex multi-dimensional problem, and fortunately there are a number of ways of increasing the effective channel capacity (based primarily on the somewhat intriguing fact that, up to a point, the number of items that can be stored in short-term memory is independent of the information content of the items (5)):

* provide for relative, rather than absolute, judgements through comparative displays.
* organise the display so that several judgements can be made in succession, rather than simultaneously.
* increase the number of dimensions perceivable (e.g. number of axis, terms, colours, line types, etc.).

The independence of data representation from data generation suggests that the display of information can be considered as a separate issue from actual cost generation. However, research already suggests that in the multi-dimensional problem context of design, communication will be enhanced by the use of graphs, colour, 3-dimensional plots, histograms, simplified charts, etc.

(iii) The consistency of the information throughout the design process: the need to maintain consistency throughout the design process provides two very stark requirements for the costing functions;

(a) the generative mechanism must produce the same output given the same input, run to run.

(b) the same costing function must be applied throughout the design - although, naturally, various abstractions of the technique are acceptable.

The former requirement means largely that stochastic techniques are unsuitable (see Appendix I, Section 3.2.1).

The latter requirement means that switching (or staging), from one technique to another as design proceeds, is less acceptable than having only one approach to costing throughout. Given that with plenty of time, labour resources and information the most popular technique for estimating cost is the approximate quantities approach (see Appendix II, Section 2), this would seem the most realistic target as a basis for the next generation of cost models, at least in the short term.

The problem of applying this technique at an early stage of design is considered in Section 5.2.9.

5.2.2(a2) Assist in solution generation (symbolic modelling, optimisation, simulation)

Perhaps the most logical target for any design aid is to prescribe, in absolute detail, the optimum solution for any given design problem. In many ways, however, the optimum solution in design is a Utopian ideal, and the rationality of prescription should be tempered by an appreciation of the inherent, subjectivity of much in the design process. 'Assistance' in solution generation then becomes a relatively informal activity of:

(i) predicting the cost consequences of alternative design solutions - in current scientific practice, the prediction of some future event invariably is entrusted to a process known as modelling (see Appendix I for a detailed description). The technique has proved remarkably successful in recent years, most overtly in man's conquest of space travel.

In a basic sense, all models have a certain relationship to what they represent, and how that relationship is expressed determines the form of the model. Appendix I notes that the advent of computer technology has directed model formulation towards the more readily manipulable, symbolic types. It would appear that the additional effort involved in formulating, interpreting, and understanding these more rigorous models is well justified despite the fact that many still suffer serious drawbacks.

(ii) Taking into account the full 'knock-on' affect of any design alternative - in another sense all models are also a simulation of reality, in that they replicate the responses of a particular system. With symbolic models, this replication may be effected in either of two ways:

* the use of concise mathematical symbols to describe the status of variables in the system and to describe the way in which variables change and interact. Predictions are made from these representations by means of mathematical procedures such as differential or integral calculus.
* a procedural approach which expresses the dynamic relationships that are hypothesised to exist in the real situation by means of a series of elementary operations on the appropriate variables. The prediction of outcomes is made actually by executing the procedural steps with appropriate initial data and parameters.

Building economics is not yet well understood, and this fact suggests that the latter approach might be a more suitable alternative for taking into account the full knock-on effect of any design proposal; since the former of the two alternatives demands a sound a priori knowledge of the system in reality.

(iii) Providing an automatic enhancement to coarse design proposals - the provision of some automatic enhancement to an otherwise coarse design proposal involves the generation of a detailed 'image' from general design information (see Section 5.2.9). It can also relate to a 'building-blocks' approach to design, where the designer is provided with a number of prescribed options for plan shape, building form, heating strategy, quality of finishes, etc., from which the computer can automatically generate all required data given a limited input of key values. Such an approach has proved particularly useful in the field of geometric modelling (6).

(iv) Directing subsequent proposals, through an explicit expression of their effect on particular objective performance attributes - this is an inherenet characteristic of optimisation. Optimisation, as described in Appendix I, Section 3.2.3, provides an ordered subset of those solutions which best satisfy the specific performance objectives. The approach subsumes simulation and generation but, as Appendix I, Section 4 goes on to state, there is a trade-off between the degree of formalised optimisation (using differential calculus, linear prlgramming, geometric programming, etc.) and the definition of the performance objectives: as an optimisation process becomes more formalised, so the expression of performance objectives needs to be increasingly definitive. As both building economics and building design are poorly defined, it would be unreasonable to expect the objectives of either process to be expressed absolutely. This tends to suggest that a formal optimisation process is untenable and, rather, that the search for optimum decisions should be expedited through the use of a simulation model, supplemented by heuristics or some form of informal 'hill-climbing', or random search procedure.

Heuristics can be thought of as 'rules of thumb' and tend to accrue over many years of experience. Of considerable assistance in developing heuristics are parametric studies. A parametric is essentially a slice through the solution space which reveals how two variables alter relative to one another, and thereby gives some indication as to the 'terrain' immediately surrounding a particular point in the solution space. The search then proceeds up-hill to the 'mountain peak' which represents the optimum. To continue the analogy for building design, 'the search is for the peak of a range of mountains in multi-dimensional space, of nearly equal height on a foggy day, under conditions where landslides and earthquakes keep shifting the terrain and directed by a group of people who each have their own altimeters giving totally different readings!'.

To summarise, it is unlikely that absolute optimisation, in the mathematical sense, is possible in design. Rather, the problem structure suggests a less formal approach involving an iterative use of some procedural-type simulation model, supplemented by an ability to produce parametrics or 3-dimensional cost-terrain maps which focus attention on the most effective design alternatives; along with generative facilities, which increase the rate of iteraction.

5.2.3(a3) Relate to other comparable projects (statistical analysis)

Projects can be compared on two levels:

(i) the general

(ii) the particular

For a general comparison of data there is much to commend the use of statistical analyses. In applying these techniques to a 'family' of data, the most powerful expression of relationship is the frequency distribution. Transformation of this distribution into a 'standard' form (such as the 'normal' distribution) along with the associated standard deviation, means that any proposed project can be located in the range of probable costs and its relationship to other members determined. Confidence in such a prediction is increased the larger the number of data included in the frequency distribution.

A useful source of such information is the Building Cost Information Service which has a large number of historical cost analyses avaiable (7). In the United States of America a computer-based cost database, known as ORR (8), already provides comparative frequency distributions to subscribers who interrogate the database interactively. As well as showing where a predicted project cost lies in relation to other, similar projects it is possible to compare the predicted cost with what might be termed as 'expected' cost (9). In this respect a multi-variate clustering package (10) can interrogate a database of cost analyses and produce a small group of directly comparable projects from which an expected cost can simply be interpolated.

For particular comparisons, the costing function should obviously be capable of generating data on specific deviants from the proposed project. This will have implications both for the control structure of the costing function (see also Section 5.2.7) and for the way in which alternatives are generated. It is likely, for example, that the control structure will need to be able to trace back through the sequence of decision-making to the point where a particular change is to be initiated. That change may then be to:

(i) propose a new design alternative
(ii) return to a previous design alternative
(iii) consider the implications of several alternatives

Thus each variable should have associated with it a record of previous values, and whether the current value was input by the user or generated by the computer (i.e. if the current value is to apply to future proposals).

Relating a project to other projects generally then involves the use of statistical analysis techniques and some large, computer-based database of historical costs - such as that proposed by BCIS. While this can be considered as somewhat distinct from, and peripheral to, the costing function, the needs of a particular comparison are more immediate and call for:

(i) a control structure which allows back tracking and iteration.
(ii) a series of flags associated with each variable to indicate its previous values, and how the current value was determined.

5.2.4(a4) Link to a database (information technology, integrated design, CAAD)

The justification of a need to link the costing function to some central database was primarily ascribed to two factors:

(i) design is multi-person, which tends to create an unacceptably high proportion of redundant information.

(ii) the pace and diversity of technological progress demands an even greater expansion of design bureaucracy.

The solutions proposed invariably involve some form of computer-based database management system (DBMS). Naturally, keen exponents of such an approach are those involved in the development of computer-based design aids already, for whom the cost of data preparation and entry - especially of geometric data - often exceeds the value of any anticipated benefits (11). In consequence, there has emerged in recent years a radical and ambitious new concept in computer-aided architectural design, that of the integrated design system (12).

Two alternative strategies for integrated design are commonly proposed:

(i) the comprehensive approach - which is one demanding an all-or-nothing commitment: a system which will function effectively only if all components exist, or are known to exist, and are included to some extent from the outset.

(ii) the ad hoc approach - which is any system which fails to attain this quality of absoluteness.

The distinction is confusing because it is based on a notion of 'totality' (13), and will naturally encourage the use of an 'ad hoc' approach while the only apparent alternative is so very expensive in terms both of equipment, and of expertise. But not only have the attempts to produce a total system (such as BILD (14), ARK-2 (15), etc.) largely failed to make any impression on general practice, even the 'ad hoc' systems - as they become larger and more sophisticated - tend to fail without some form of distinct data management system (16). This need for a distinct data management system suggests that a more useful differentiation between alternative approaches might be:

(i) the data independence - in which the applications programs and terminal activities are independent from the growth of data types and changes in the data representation.

(ii) the data integration - in which the data of a particular system and the system itself are cast intrinsicly together.

In this categorisaton then, most current systems - comprehensive or ad hoc - fit the description of a data integrated approach. Their failure can therefore be attributed, at least in part, to the fact that data management and the manipulation of the data structure are exacerbated quite considerably if data is integral to the system. Rosental et al (17) further suggest that by integrating the data (what they term a 'function-oriented' approach as opposed to a 'data-oriented' or data independent approach) the system is made less general, because the data requirements of each individual organisation is bespoke.

The obvious need for flexibility would seem to favour an approach in which the data is independent of the system, and this places considerable emphasis on the selection of a suitable database system. The database management sytems currently available roughly may be grouped according to the principles which govern how each item is linked within the data structure:

(i) the hierarchical structure - where each item is linked to a single parent/superior, and many child/subordinate items (see Figure 5.4 (a)). The inherent limitation of the approach is that it assumes a one-to-many relationship which does not apply in many situations, causing difficulties in adding, deleting and updating the database (18).

(ii) The network structure - where the data is structured as a network, and any node in the network may have any number of parents or children (see Figure 5.4 (b)).

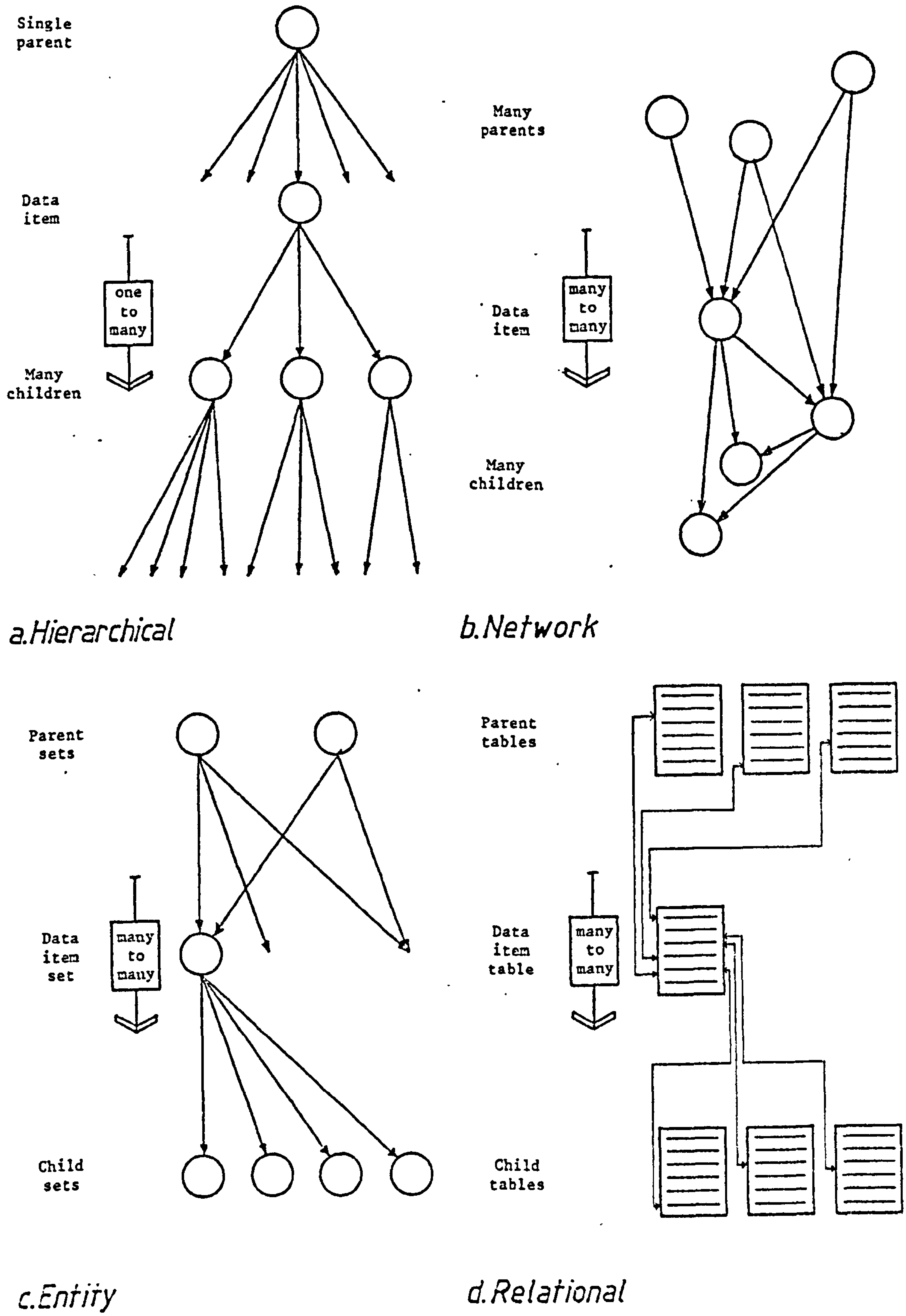


Figure 5.4: Database structure types

One of the major disadvantages is that the paths which exist through the network must be specified at the outset and this may place limitations the database users, making them data dependent (19).

(iii) The entity set - which is based on set theory (see Figure 5.4 (c)), achieves a high degree of data independence but its viewing of particular values may not be natural to many people (20).

(iv) The relational structure - all information in a relational database is represented by values in tables with even the table names appearing as character strings in at least one table (see Figure 5.4 (d)). Addressing data by value rather than position boosts the productivity and achieves a high level of data independence (21).

Clearly the choice of database structure will be determined largely by the following:

* the number of many-to-many relationships
* the degree of data independence required
* the level of user interaction (i.e. the importance of natural semantics)
* the computing environment - not all languages have a relational processing capacity (Cobol, for example (22)).

Figure 5.5 illustrates how the representation of a 'real world' expression is transformed into a series of physical addresses within the computer. There are two forms of data description possible:

(i) as entities and attributes in a conceptual model

(ii) as records and data items in a logical model

The two are not exactly equivalent (one entity does not necessarily correspond to one record), but they may be considered as alternative views of the same thing; the entity view generally being adopted by systems analysts. An entity is anything which has

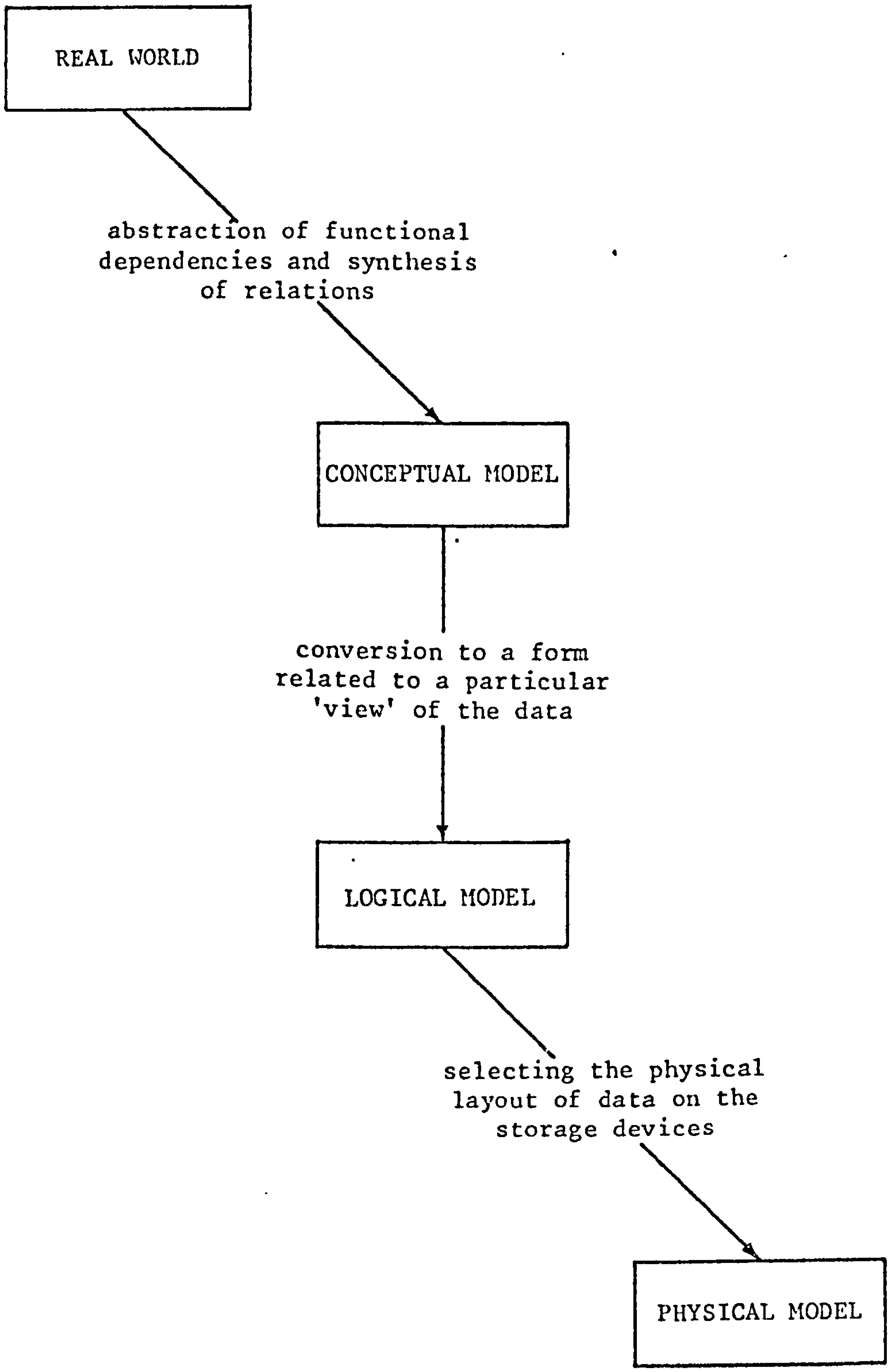


Figure 5.5: Transformation of a 'real world' expression of data into a series of physical addresses within the computer

been selected to, and can, be distinctly described. Each entity type is described by a group of attributes, one or more of which are 'key' attributes, in that to uniquely identify an occurrence of the entity type only the key attributes need be determined.

For example, Figure 5.6 shows two entity types, 'window' and 'paint'. Obviously the paint entity is related to the attribute 'colour'. Similarly each attribute in window is related to the key attribute/attributes, 'aspect' and 'window number': they are said to be functionally dependent upon the key.

A transformation from the real world to the conceptual model can now be described as being a process of analysing the real world data into a series of entities associated by relationships, which can further be manipulated into a 'third normal form' - the conceptual model. The third normal form is a state in which for each entity:

(i) there are no repeating groups of attributes,
(ii) non-key attributes are functionally dependent upon the whole of the key, and
(iii) all non-key attributes are mutually independent.

Appendix IV details the derivation of the global conceptual model for the costing function, which is reproduced in Figure 5.7.

The number of many-to-many relationships apparent in the global conceptual model, allied to the need for data independence and an efficient user interaction strongly suggests that the most effective form of data structure will be the 'relational' representation: i.e. that the link between the costing function and the cost data, will be through some abstract interface with a relational database management system.

5.2.5(a5) Be quick (computer hardware)

Speed and the computer have become almost synonomous.

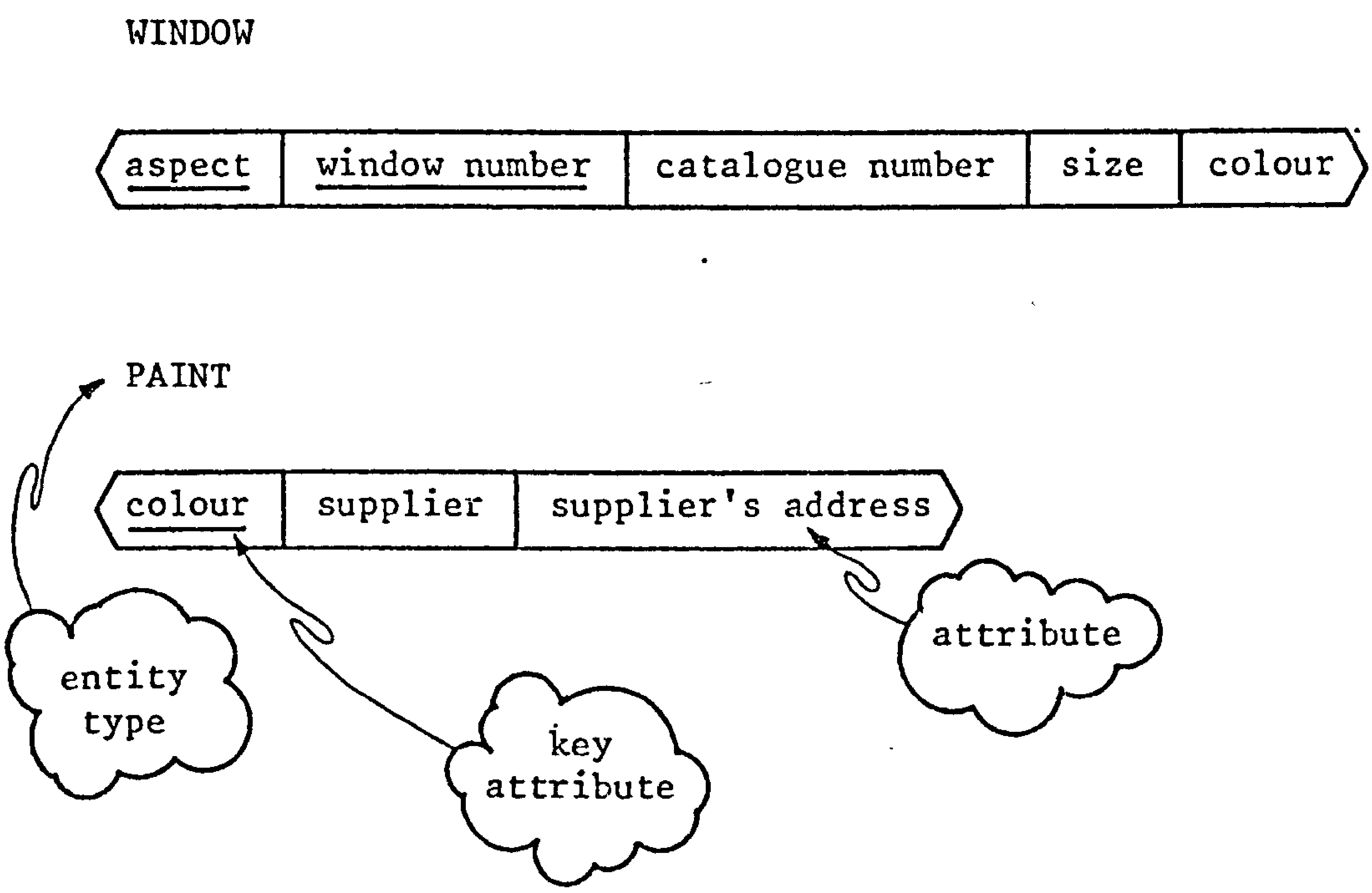


Figure 5.6: Two example entity types; 'window' and 'paint'

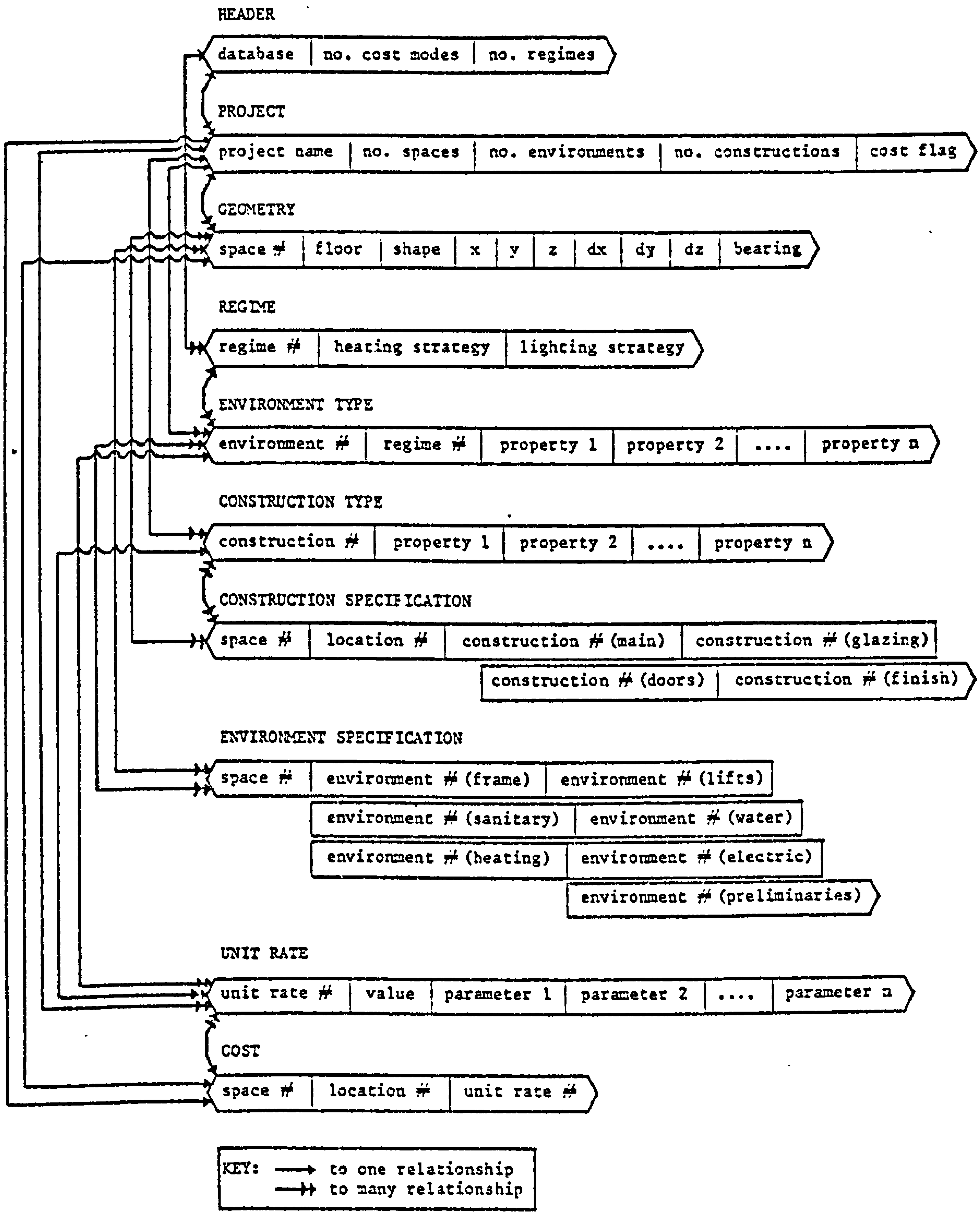


Figure 5.7: The global conceptual model for the costing function

Current advances in semi-conductor technology mean that a single processor can deliver up to 30-50 million instructions per second (23); with experimental chips made from Gallium Arsenide already switching circuits faster again by a factor of 10, and probably ready for commercial use by the end of this decade. This increase promises to jump the current standard 32-64K bit chips into 1 megabit chips, producing a concomitant power increase in mini and micro configurations for less and less cost. Already, single-chip processors based on the Intel 8086, Zilog Z8000 or Motorola's MACS can provide upto 4 megabytes of main memory and a virtual address space of about 16 megabytes, which can support quite large CAAD programs (1 megabyte of address space is sufficient for about 200,000 words of prose).

There are, however, certain limiting factors:

(i) Mass memory is becoming increasingly important, but is at present incredibly slow in comparison to main memory because of the delay involved in reading a disc mechanically. Bubble memories appear to offer only a partial solution, and the storage medium of the future promises to be based on laser technology which, though very quick and offering online storage of perhaps 2 terabytes (2 million, million bytes), is still much slower than the semi-conductor (24).

(ii) There is a movement towards an integrated computer environment consisting perhaps of several hundred nodes, tied together by a high-speed communications network (25). Again, current communication times typically can be as slow as 10-20 megabits per second.

(iii) While the technological breakthrough which promises the 1 megabit chips has occured in the semi-conductor field already, a similar breakthrough remains to be made in chip design methods. At the moment it can take one person a year to design 1000 circuits on a chip, meaning therefore that a 1 million circuit chip would take 1000 person years: with traditional 'colouring' methods, the task is just too complex.

There can be little doubt that the speed of the computer is inordinately fast, and that faster processors (CPUs) still remain to be developed. However, the CPU must now be approaching its power limit, and the historical reliance on simply increasing CPU size to overcome all ills is beginning to fail. It is particularly cautionary then, to remember the tale of 'tortoise and hare', for speed/ power is not the only factor involved:

* the provision of a 'background' facility (see also Section 5.2.7) can have the affect of reducing peaks and filling troughs in a demand profile which will reduce overall the power requirements placed on the CPU.
* current software has not yet succeeded in replicating the processing efficiency of a human mind, with its capacity to aggregate information. In simple terms this means that although a computer may have more processing power than the human, it must travel a less efficient (and thereby longer) route so as to reach the same goal.

Whatever the balance between the computer and the human in terms of power, load and efficiency, such differences pale into insignificance in the shadow of a manual system which involves preparing drawings, posting these to the quantity surveyor, and waiting possibly days and weeks for a single cost estimate. The computers immediate and dedicated attention invariably will provide the user with a quicker response than any alternative.

5.2.6(a6) Be adaptable (software design methodology, computing environment, programming language)

The need for a computer-based costing function is determined in Section 5.2.2, Section 5.2.4 and Section 5.2.5. The adaptability of any computer-based function is influenced substantially by the following:

(i) The computing environment in which the software is developed

* the software design methodology
* the tools available to support and manage software development

(ii) The programming language embodied within the software

* how reliable it is
* how easy it is to maintain

Unfortunately both factors are currently the subject of considerable controversy in respect to how each is expected to develop in the future, and it would be unreasonable therefore to credit a prediction at this time as anything more than speculative. General trends do seem to be emerging however, and these begin to suggest that particular features are being favoured.

(i) The software design methodology. The relationship between software design methodologies and programming languages is a most important one: this applies whether or not the programming language is viewed as a component of a software development facility. It is apparent that some languages are better suited than others to certain design methodologies. Older languages, such as FORTRAN, were not designed to support specific design methodologies. For example, the absence of suitable high-level control structures in FORTRAN makes it difficult systematically to design algorithms in a 'top-down' fashion where, conversely, Pascal was designed with the explicit goal of supporting top-down design and structured programming (26). (For a useful description of 'structured programming' see Bates (27)).

The developing trends in languages show that the idea of a language supporting a particular design methodology is increasingly becoming accepted (28).

Research in software design methodologies has focused generally on top-down design which, when applied to small programs (very loosely defined as those programs having less than several thousand lines of coding), is named stepwise refinement.

'Stepwise refinement' can be illustrated as a process of writing and re-writing a program. At each step of refinement, abstract declarations and statements can be left in the code as comments for the purpose of documentation. The process continues until eventually the entire text is legal program.

Although stepwise refinement is an effective methodology for 'programming in the small', it fails when applied to large programs. One reason is that it does not favour the recognition of commonalities between parts. Programmers are not encouraged to represent common parts by a unique abstraction, to be refined just once and invoked whenever necessary. Rather, each part is separately refined and in consequence the ability to read and to modify programs can be hampered for programs of substantial size.

Alternatively, the concept of information hiding (29) dictates that the designer decompose a system into small-size programs (modules) and distinguish clearly what a module does (what the module exports for use by other modules) from how it does it (its internal structure).

'Information hiding' then, is a technique for decomposing systems into modules, each module hiding a 'secret' - often the format of a particular data structure (record, file, etc.) or the mechanics of some algorithm. The module provides access functions that can be used to inquire or update the information contained in the data structure and thus users of the module (i.e. other modules) may access, through function calls, the information that the module is willing to provide; but they cannot access the information directly (by directly manipulating the data structure, or by using global variables). This has the obvious advantage of promoting the integrity of the program during subsequent updates; as each module is discrete and can be separately considered.

(ii) The tools available to support and manage software development. Although tools also are employed for programming in the small, their use becomes essential in a 'programming in the large' type environment (30).

The need for support tools was recognised very early in the programming era. In fact, assemblers were once viewed as helpful tools in programming the computer (in machine language). At present, a variety of development tools are often provided to establish friendly programming environments even on very small, personal computers (the programming language itself, for example). On large systems however a programming language by itself is not sufficient and there have been significant improvements in the productivity of programmers able to utilise basic tools (31); for example,

* the text editor - used to enter and correct programs (and other types of document) in the computer
* the macro processor - a simple translator used to overcome language deficiencies (ease of reading, etc.) or to supplement a language with certain symbolic constructs. For example, RATFOR (32) is a 'structured' FORTRAN language based on this scheme.

* the interpreter/compiler - an interpreter is used to run a source program and can produce better error diagnostics and debugging but takes longer to process than a compiler.
* the file system - a file system can be used to share data and/or programs either in source or in object format. The programmer can thus keep libraries of program components on mass storage. The system may provide help in administering such components by updating version numbers, creation dates, and so on. It is also possible to restrict access to the components to a specified set of authorised users.
* the linker - a linker takes several independently compiled modules and merges them into one.
* the program verifier - automatically, or with the help of the user, proves the correctness of a program with respect to a specificaton.
* the dynamic frequency analyser - which can run a program with typical data and determine which portions of the program are executed most often and therefore most in need of time optimisation.
* the source program optimiser - which can detect and transform inefficient code into a more efficient one.
* the source program control - which can maintain the different versions of a program, their relationships, and their dependencies (33).

Perhaps the main purpose of these tools is that they effectively create a separate, visible, uniform interface environment for almost any programming development project regardless of its intended target computer, or the size of that computer(s) (34) (see Figure 5.8). The distinct nature of the development process produces very flexible and reliable code (35).

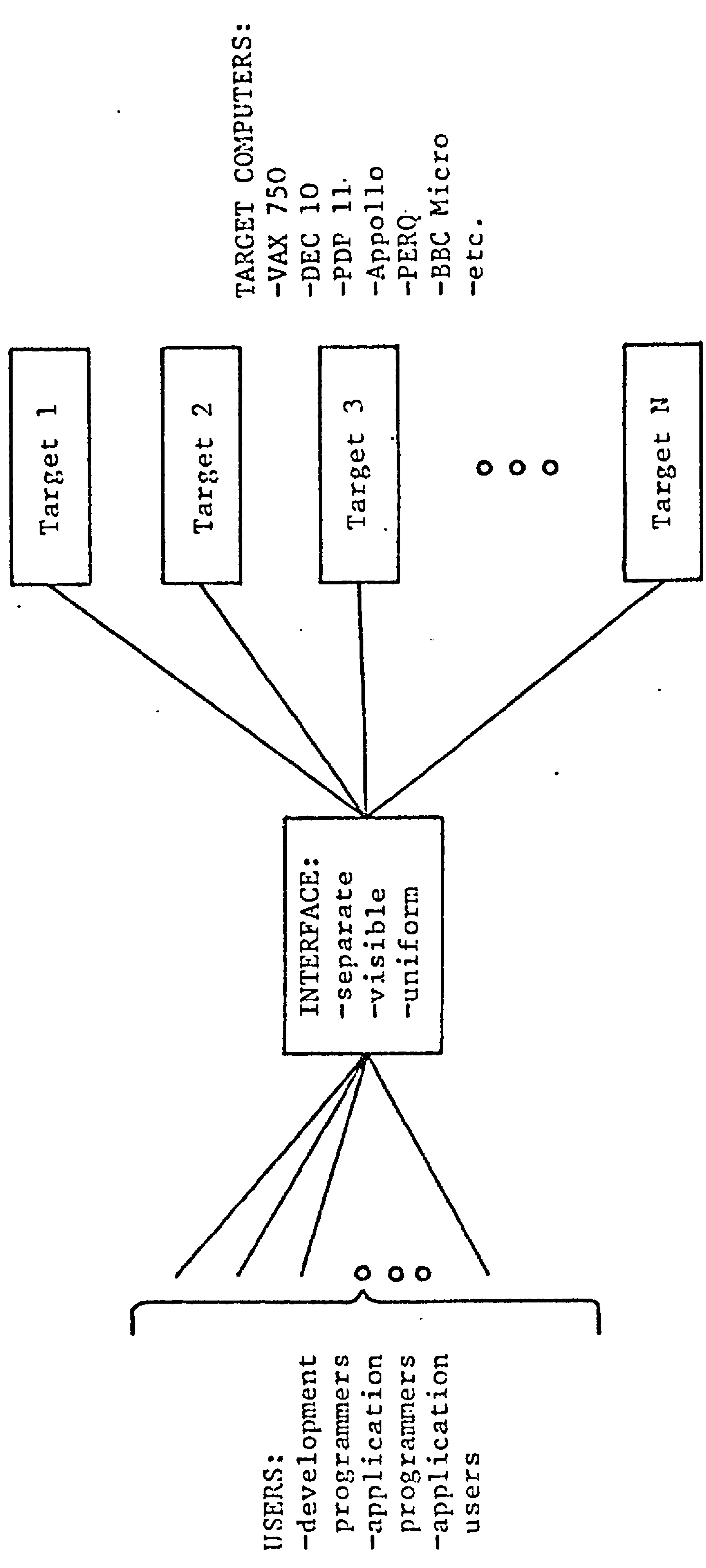


Figure 5.8: The structure of an effective development environment (After T A DOLOTTA et al "The Programmer's Workbench" in The Bell System Technical Journal, Vol 57, No 6, July-August, 1978, p2179)

(iii) Language reliability. The goal of software reliability is promoted by the following two programming language qualities.

(a) how writable it is - a hard-to-quantify property which, basically, refers to the possibility of expressing a program in a way that is natural for the problem: i.e. the programmer should not be distracted by details and 'tricks' of the language such as addressing mechanisms, index registers, etc. The rational conclusion is that programming languages will approach natural languages, and a program would then simply be a logical series of requirements describing what the user wants, not prescribing how they are to be achieved (36). This appears to be borne out by experiences in the use of, say, PROLOG (37) (the name stands for PROgramming in LOGic), described as remarkably simple, and quite easy to understand without any specialist knowledge of either logic or computers (38). Certainly, despite its subject criterion, it is usual to agree that higher-level languages are more writable than lower-level (e.g. assembler) languages.

(b) how readable it is - it should be possible to follow the logic of the program, and to discover the presence of errors, by examining the program. The readability of a program is also a subjective criterion that depends a great deal on matters of taste and style. However, the simpler the language is and the more naturally it allows algorithms to be expressed, the easier it is to understand what a program does by examining just the code. For example, the 'goto' statement is generally accepted as harmful because it can make it impossible to read a program in one top-to-bottom pass and to understand it: the reader must jump around in the program in search of the targets of the 'goto' statements (39).

If a program is to be adapted or modified, it must first be understood. Obviously that understanding will be affected substantially by how well the original coding was written and how easily it is then read.

(iv) Language maintainability. For a program to be maintainable the programming language must be both readable and modifiable. Like readability (discussed above), modifiability is somewhat subjective. It is possible, however, to identify features that make a program 'more' modifiable. Typically, the choice of an appropriate name for a constant promotes the readability of a program ('pi' instead of 3.14) and, moreover, a future need to change the value would necessitate a change only in the definition of the constant, rather than every use of the constant.

To summarise the particular features which appear to promote adaptable software, the following specification is proposed:

* a top-down methodology be employed
* a distinct, development environment be created through an operating system which is readily portably and supports a good number of software development 'tools'
* the programming language should:

(a) be sufficiently high level and yet simple

(b) exhibit the fundamental precepts of structured programming, information hiding and data abstraction

5.2.7 Be dynamic (interactive computing, control structure)

The need for a dynamic costing function evolves from an appreciation of both the circularity in a design process, and the temporal variability in any particular design problem. The problem/solution (illustrated in Figure 5.9) involves the 'control' of the costing function; or more specifically, the interface between effective control (the user environment) and actual control (the machine environment).

(i) The user environment - the significant components are:

* The user's model - the conceptual model formed by the user of the information he/she manipulates and of the processes he/she applies to this information. The model enables the user to visualise, even without necessarily a knowledge of computing, what the program is doing and thereby to anticipate the effect of various actions and to devise his/her own strategies for operating the program. Without this model the user can do little more than blindly follow instructions, much as an inexperienced chef would follow a recipe.

  A user's model can thus be represented as a set of objects together with a set of actions which the user can apply to the objects. Each object (whether it be intrinsic to the application or its purpose be to assist in the control of the program) is an item of information over which the user has some control. Actions are the operations the user can apply to the objects: the complete set of actions thus defines the functional capability of the program.

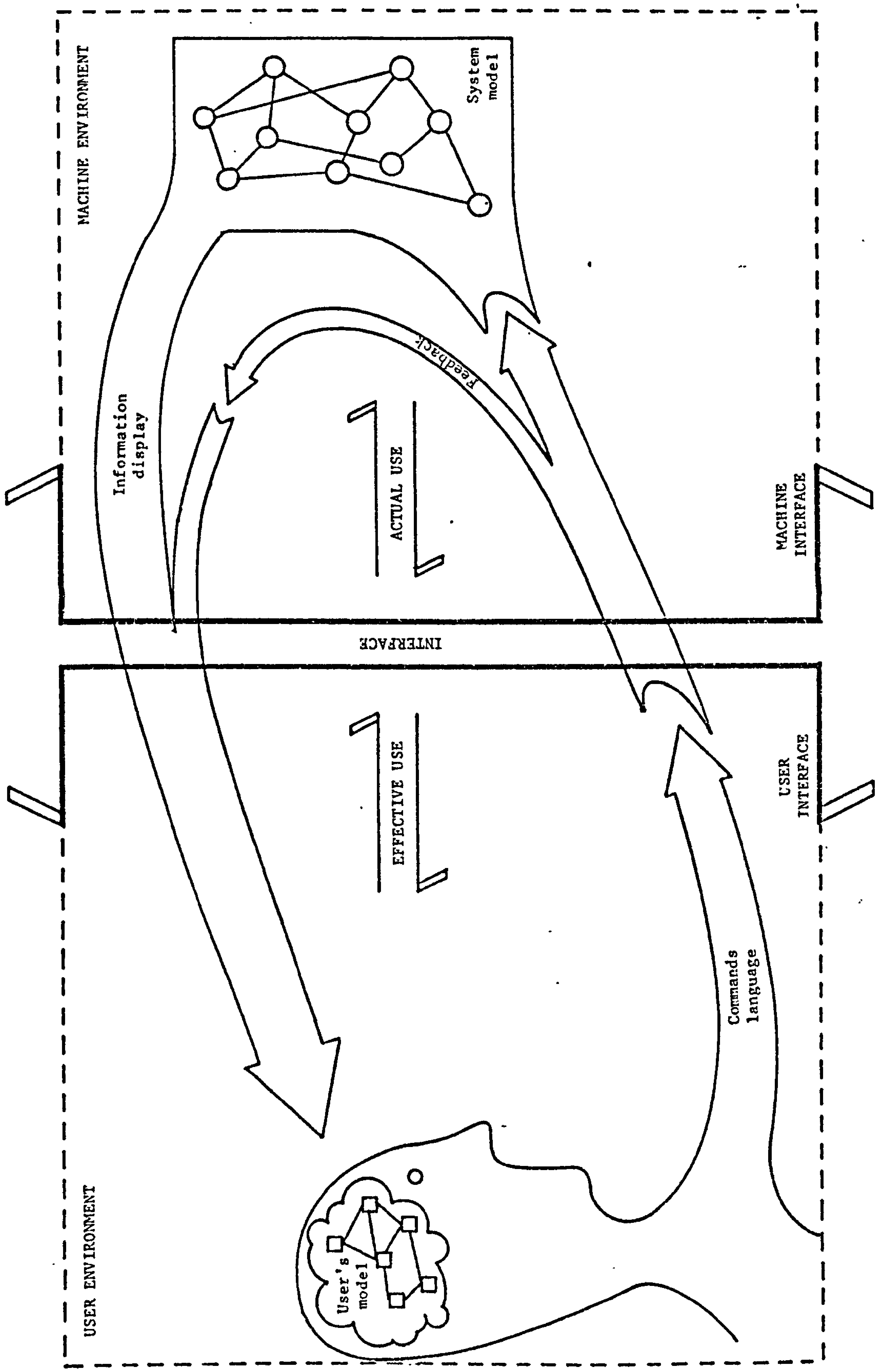


Figure 5.9: The primary components of an interface between the user environment and the machine environment

* A command language - a system of commands with which the user manipulates the system model. Constituent commands will not only relate to one another in a systematic way (i.e. have a syntax), but also have a meaning attached to each syntactic construct (i.e. semantics). The command language may be viewed as a concrete representations of the user's model since it defines in an abstract form the operations a user can apply (actions) and the operands to which he/she can apply them (objects).

* Feedback - indicates to the user how the program has interpreted his/her commands, but says little about their real effect. The purpose of feedback is:
  (a) to inform the user whether the command has been accepted, what stage of executing the command has reached, and whether an error condition has arisen.
  (b) to indicate that a particular option has been selected.
  (c) unrelated to either of the above; curser feedback, character echoing, etc.

* Information display - shows the state of the information being manipulated. Data that would otherwise have been printed out in numerical form can, with the aid of a display, be plotted as a graph, network, overlay, etc.

These four components provide a useful scenario of focus points, for consideration when designing the user interface.

Using this scenario, Table 5.1, effects a comparison between the various forms of user interface, and it is apparent that the two most important variables are:

FORM OF INTERFACE	INITIATOR	DESCRIPTION	ADVANTAGES	DISADVANTAGES	COMMENTS
1.Command driven	user	Involves the user inputing a command to the computer system which takes some action depending on the command. The command may be a query, the initiation of some sub-system or it may call up a sequence of other commands.	The most common form at present. Suits straight-forward text input and output. Command may be implicit (eg. the user simply inputs parameters), or simplified through the use of mnumonics. Can easily supplement generally concise messages with a fuller, more explanatory version for naive users.	The user is forced to learn a whole sequence of dialogue responses, and through this the syntax and semantics of the language - the learning period can be lengthy but may be justified if the user is to make extensive use of the program. Mnumonics can be particularly difficult for naive users.	Gives the user a genuine sense of control, but is orientated considerably towards an experienced user of the system.
2.Natural language	user	The user inputs commands in English (or some other particular language) and the program responds in the same manner.	The logical forerunner to verbal input/output facilities. Obvious advantages for the naive user, since nearly everyone can converse to some degree.	Natural dialogue is often too verbose for typing, and speech recognition is still some distance in the future. The speed of response of such systems is very slow, a large amount of processing being required to interpret the user's commands and to formulate replies.	Natural language interaction continues to be the focus of a great deal of research, but for most applications at this time it is too inefficient to be a practical alternative.
3.Forms based	user	The user calls up an image of a form and fills it in by typing in the appropriate screen locations.	Logical solution to a problem which only involves the automation of manual paperwork system, based on standard forms.	Rely on terminals with a cursor that can move anywhere on the screen. Not applicable to problems which are not based on standard forms.	Still needs some other interface so that the user can request a particular form. Unlikely to be of use in cost estimating.
4.Menu system	computer	User selects one of a number of possibilities from a menu displayed on the screen.	Helps the user to understand the full range of alternatives open to him/ her, at the same time it protects him/ her from making an invalid selection, since only valid selections are included in the menu. A menu is easilly changed.	There must be sufficiently few choices to be displayed at the same time. With cathode-ray tubes (crt), unless the screen is cleared, several menus can soon clutter-up the display.	This type of menu-driven command language is in many respects the most effective for general graphical interaction.
5.Question answer	computer	The computer prints messages to the user who responds with the answer. The range of acceptable answers to each prompt is generally quite limited and if an answer lies outside of the acceptable range, the program must ask the question again, perhaps indicating what kind of answer it expects.	It is possible for the question asked to depend upon the user's responses to previous questions and this allows quite complex dialogues to take place without the need for user training.	May require a sophisticated pattern matching system to interpret user responses. Often need a number of responses to achieve even the simplest operation.	This type of interface would be used in preference to a menu-system in situations where some overall picture of the user's requirements has to be built up by considering responses to a number of queries.

Table 5.1: A comparison of alternative forms of interface

(a) the user's model which - as it becomes better formulated and more comprehensive - switches requirements from a computer initiated (where the computer prompts the user for a reply to a specific question) to a user initiated interface (where the user is in charge of the man/machine dialogue).

(b) the command language which as the interaction becomes increasingly prescribed, switches emphasis from a dialogue to a standard form or menu.

Unfortunately this fails to distinguish any clear preference in the context of a costing function, where users could as well be experienced as naive, and where interaction can fluctuate many times between dialogue and standard graphics.

The need to fluctuate between dialogue and graphics is solved traditionally using two logically separate channels, one for graphics input and output, and the other for normal text. This, to a large degree, is a symptom of hardware constraints which no longer apply (e.g. cathode-ray tube technology) and future systems can expect to use several 'windows' all from a single channel. (Windows are rectangular regions of the screen whose positions and dimensions may be set by the user, who can therefore rearrange the screen area so as to present the information in the most convenient way for himself).

The need to accomodate both expert and novice users, however, demands a wholly more-resolute approach. On the one hand a system might anticipate an experienced user, provide powerful control facilities and hope that some form of 'expert system', tutorial, or documentation will dampen the learning curve. On the other hand a system might anticipate naive users, and develop a more powerful control mechanism subsequently, guided by the feedback from the users themselves. The arguements in favour of both sides are equally strong (or weak), and the final choice may well rest on the degree to which the system model can be considered absolute. For if a system designer has confidence that the fundamental principles which underly the system model are valid, he/she is less likely to, or to need to, cater for novice users because sufficient incentive to learn about the system will already exist. It is debatable however whether the principles which underly a costing function based around current contracting practice could ever be considered absolute or even fundamental. In the current situation, certainly, a significant function of the cost model is that it be educational, and this indicates a computer initiated man/machine dialogue.

Current thinking on man/machine interfaces suggest separating all input and output into a discrete 'interface module'. This, apart from making the underlying software more portable, helps solve the dilemma by making it possible to have several interfaces (naive, expert, etc.) to the same piece of software.

(ii) The machine environment - traditionally there was no problem to the machine interface, as there was only one solution: each new command would not be processed until its predecessor was finished completely. This meant, among other things, that all requests were given equal priority, that any results displayed were consistent with the current state of the system and consequently, that output had to wait until the system was completeley resolved.

Recent developments in particular operating systems, notably UNIX (40) permit the 'parallel' execution of commands or groups of commands and thereby have the potential to differentiate task priority; and as Bijl et al (41) state:

> "In effect, this structure has replaced the always up-to-date but not instantly available results provided by current systems by always available but not instantly up-to-date results".

Rosenthal (42) has proposed a program structure which utilises this alternative machine environment to provide a smoother, and reduced demand profile for the system. It consists of the following components (see also Figure 5.10):

* a command processor which accepts user commands and categorises them in respect to their priority.
* an output processor which can read-only the solution database, and display the output requested.
* a change processor which accepts requests to up-date the solution database from user commands or other functions, makes the required change, and passes a notification of the change to:-
* a bucket-chain of function tasks. Each task in the chain reads the notification of change passed to it by the previous task, computes any effect that change may have on its own function, requests the change processor to make the necessary update to the database, and passes the original notification to the next task down the chain.

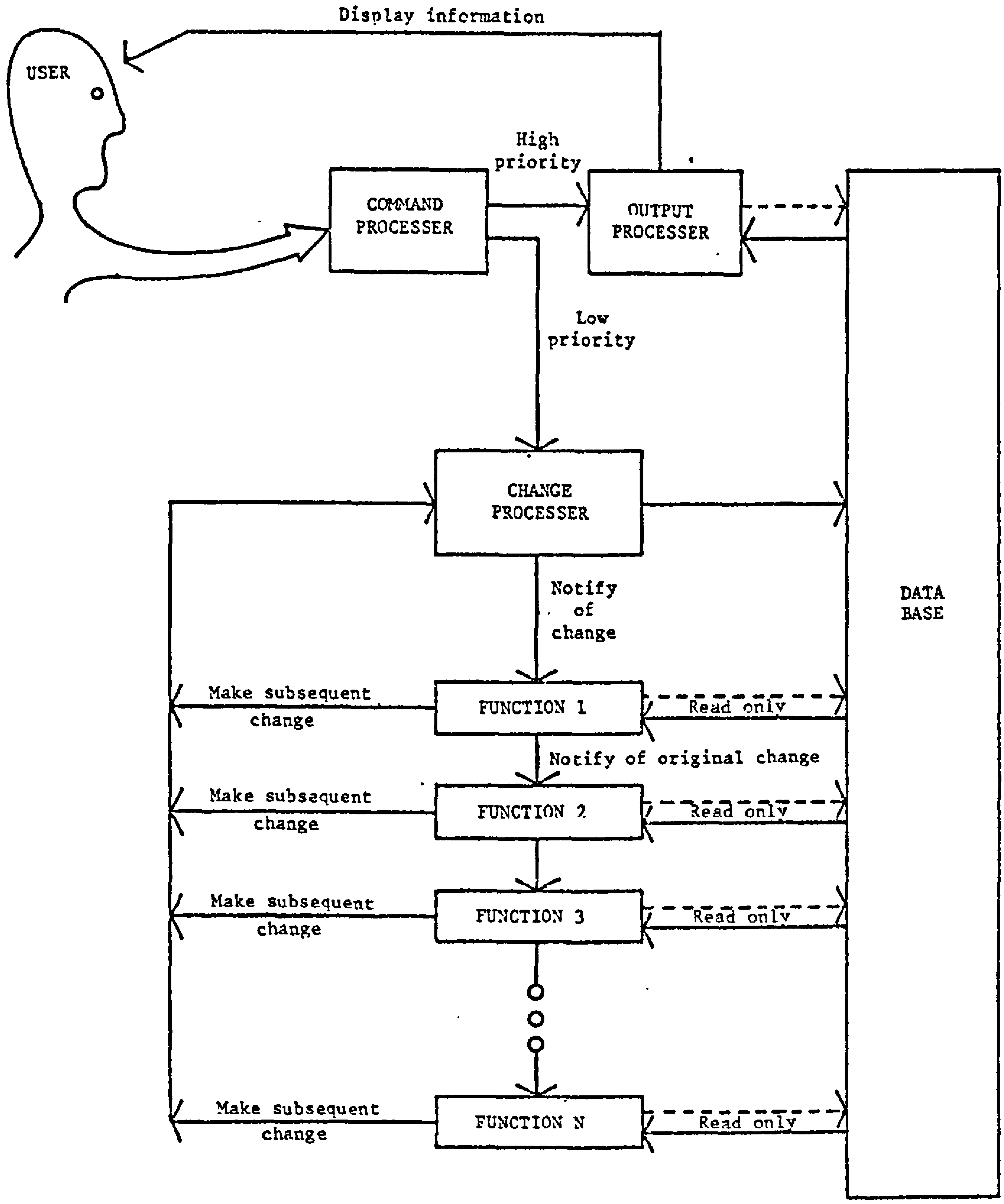


Figure 5.10: A bucket-chain program structure (After A BIJL et al, "Integrated CAAD Systems", Report DGR 470/12, EdCAAD Studies, March 1979, p 4.46)

The main implication of this alternative structure is that interaction (the time between a user initiating two contiguous commands) is decoupled from processing (the time taken to process a command). This means that a given program can run as effectively on a smaller machine, or, possibly more realistically, that a given machine can accomodate a larger interactive system.

The benefits of a 'parallel' processing environment are manifest, and witnessed by the fact the UNIX appears to be the best candidate for a de facto standard operating system for the new generation, 16-bit microprocessors; filling the role which CP/M has played for smaller machines (43).

5.2.8(b1) Manipulate imprecise data (fuzzy sets)

The need to manipulate imprecise and inherently inaccurate data is a direct reflection of the way cost data is generated: since cost generation is influenced considerably by human faculties, it is only natural that cost data should exhibit properties similar to any other human 'language'.

The processes involved in human reasoning are not clear however and the notion of 'fuzzy-sets' only recently has provided the means to depart from a conventional approach based on two-valued or multi-valued logic, where imprecision is taken to be probabalistic. This new-found notion of fuzzy knowledge and approximate reasoning is neither definitive nor complete, but attempts are being made to implement several computer based systems which have the capacity to process imprecise data. Currently, these implementations adopt either of two basic strategies:

(i) The system uses a conventional programming language (such as FORTRAN, Pascal, etc.) to produce an apparently 'fuzzy' procedure. The database management system AESOP (44), for example, incorporates a first approximation of fuzzy principles; entities which have certain characteristics, may be ordered according to a set of approximate requirements. A user may specify any number or combination of desirable properties (e.g. thickness, thermal capacity, sound reduction, etc. for brickwork) giving for each property a target value, or range of value, or combination of target value and value range. From this approximate specification is provided a list of constructions from the database, ordered in accordance with the selected general criteria - that is, one of:

* approximately equal to the target values
* the greater the values the better
* the lower the values the better

Different orderings may be obtained for different goal constructs. Alternatively the 'hedges' (see Appendix III, Section 3) such as VERY, may be used to help a user to distinguish very good from not so good constructions in the ordered list.

Clearly, there is only limited commitment to fuzziness incorporated in such a system but it does perhaps make a useful, acceptably small, first step. What is most important, is that it encourages the user to recognise imprecision without relying on probability theory: this makes it a very significant 'small step'.

(ii) The system uses a 'fuzzy' programming language to provide a wholly more realistic treatment of imprecise data. Unfortunately there are very few examples of such languages, currently. PRUF (45) has the following characterisitcs:

* the concept of a possibility distribution replaces that of two-valued logic as a foundation for the representation of meaning or value in the data.
* the truth-value of a proposition is defined as its compatibility with a reference proposition, so that given two propositions p and r, the 'truth' of p can be computed relative to r.
* quantifiers (like the truth-values) are allowed to be linguistic

The language incorporates many of the concepts developed in fuzzy sets and systems, and in addition to serving as a foundation for approximate reasoning, PRUF may be employed as a language for the representation of imprecise knowledge, and as a means of making fuzzy propositions expressed in a natural language more punctilious.

Even PRUF, however, is just a pointer towards an effective capacity to act on imprecise, incomplete or unreliable information. To implement a truly fuzzy system will require (46):

(a) a better system of linguistic modifiers than those that are available in natural languages, and

(b) special-purpose hardware that is orientated toward the storage and manipulation of fuzzy rather than non-fuzzy data.

Until such time as a more appropriate programming language is freely available, the computer-based costing function will need to make what first approximations of fuzzy principles it can.

The minimal commitment is considered to be a recognition that the data used is imprecise, not necessarily in a probabalisitc sense.

This impacts almost entirely upon the data preparation/ data selection procedures adopted. Once a value has been chosen (although in reality this is the label for some fuzzy set of possible values - again see Appendix III), there is little alternative but to treat it as a precise numerical value: simply to use what tools are available and to therefore treat the imprecision as, say, random, would be tantamount to using a hammer to drive a screw - positively a retrograde step.

5.2.9(b2) Vary the 'meaning' of data with context (image projection)

To vary the meaning, or value, of data with context makes two fundamental demands:

(i) that there be some way of recognising the context, and variations there-in

(ii) that there be some rules, or legend which links the value of each data item to the immediate context.

The 'context' in cost generation is the proposed project design, and the 'rules' which relate the unit rates to this context are those which comprise each quantity surveyors 'experience' - rules of thumb, heuristics, etc. (see Chapter 4, Section 4.2.1). To produce a cost estimate therefore requires:

(i) a mechanism which can generate a detailed project design from possibly incomplete information. This requirement is allied to the 'expert-systems' discussed in Section 5.2.1 but addresses a particular aspect only; the build-up of a general picture by a process based on deductive logic. The ability to infer, or to project, some detailed image from some less-detailed image is made possible because of the quality illustrated in Figure 5.11. The moment a project is initiated, there is a mandatory commitment to the range of minimum standards of performance and provisions as laid down in the Building Regulations, Codes of Practice, professional practices, etc. For example, Section E4 of the Building Regulations gives a maximum compartment area and volume; the Building Research Establishment Current Paper 35/76 sets out the minimum number of sanitary appliances to be provided, based on the number of people per floor; etc.

In addition to this implicit data, there are a large number of generally accepted 'ready-reckoners' such as steady state heat loss calculations, simple beam design based on span and load, etc. These very basic design aids provide the designer with a useful 'look-ahead' facility, and means that the information relating to a design at any particular point in time can be increased substantially. The final deficit is made-up by selecting the most likely default values, given the design as it exists. In this way, for example, if the building is a bank, then the iron-mongery is likely to be of a high quality; in a school, the finishes must be very durable; etc.

The process is patently analogous to the 'expert-like system' suggested in Section 5.2.1, and begs a similar solution.

(ii) A mechanism which selects a particular unit rate, given a particular project design. In this case the unit rate must simply be calculated as a function of selected project design characterisitcs. The unit

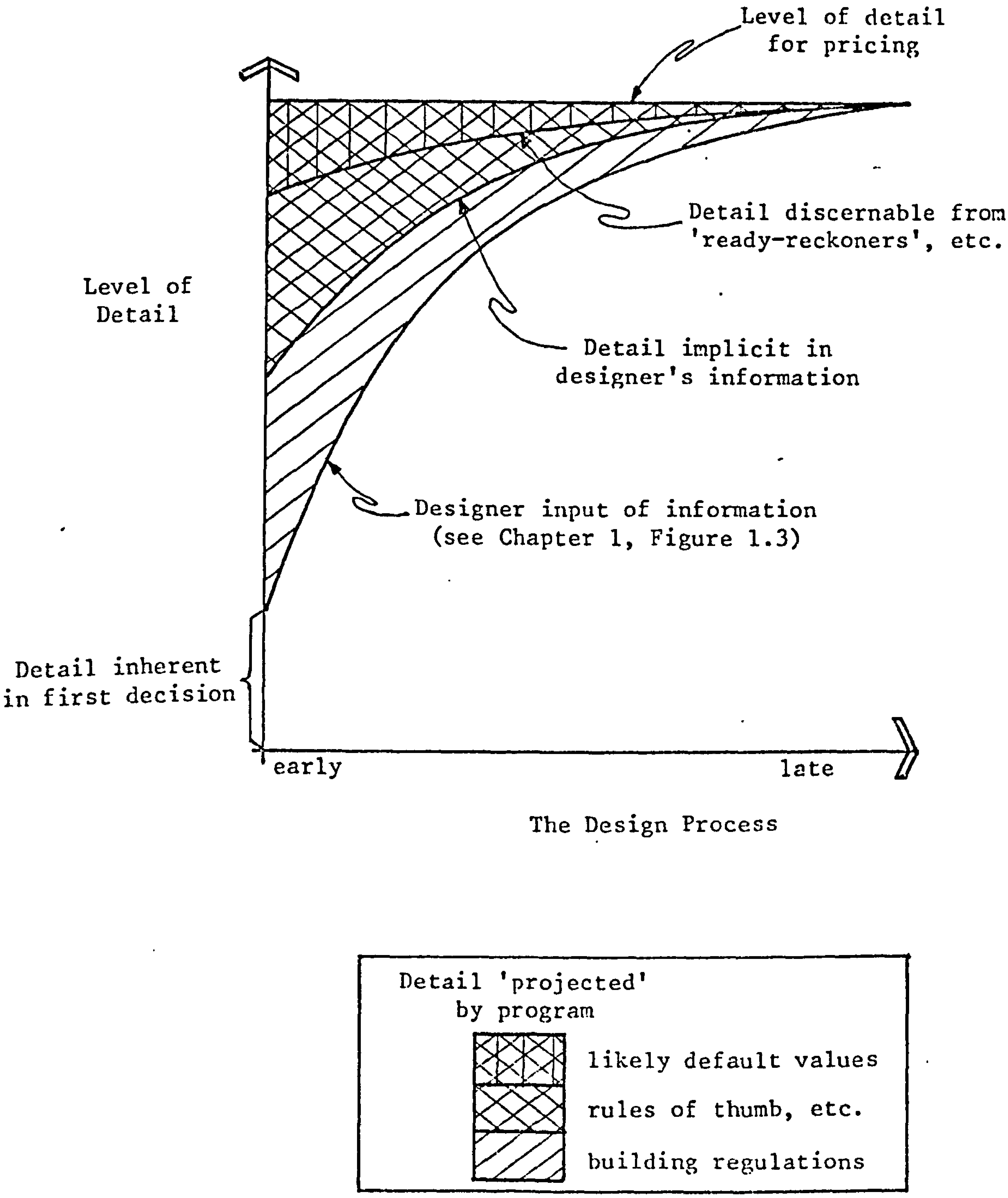


Figure 5.11: The capacity to project a detailed design image at all stages of the design process

rate per square metre of formwork to beams, for example, can be considered to be a function of the beam girth, its height above the floor, the total area of formwork required and the number of uses anticipated. If the project design is modified in any way, then the value of each unit rate must change accordingly, meaning that the mechanisms which determine a value for the unit rates must be re-invoked for each and every design alternative proposed.

5.2.10(b3) Vary the relationship of meaning to context (schema, frames)

To a large extent this requirement simply echoes those of Section 5.2.6. If the relationship between meaning and context is to change then the mechanisms identified in Section 5.2.9 must change also. Collectively, these mechanisms represent the schema, frame, or knowledge-base of a particular quantity surveyor and the transformation of each schema will demand an adaptable computing environment and programming language.

The solution proposed is as Section 5.2.6.

5.3 A Tentative Specification For The Next Generation of Cost Functions

The previous section, Section 5.2, made a number of specific proposals which are to be considered as the constituent conditions of a tentative specification. The conditions are grouped under four main headings and each is followed by its respective section number.

5.3.1 The Approach

* A distinct development environment is to be created through an operating system which is readily portable and supports a good number of software development tools (Section 5.2.6).
* A top-down software design methodology is to be employed (Section 5.2.6).

* The data used is to be recognised as inaccurate but treated as precise, rather than as random (Section 5.2.8).
* The knowledge-base implementation is to be as illustrated in Figure 5.2, where:
  - the knowledge base is a series of production rules relating to each variable, and written as program code.
  - knowledge refining is achieved by making changes to code and re-compiling.
  - the inference engine is intrinsic to the program logic, as a series of decision trees.
  - questions and answers are pre-defined in natural english.
  - explanations are given by making addendums to the information held on each variable (Section 5.2.1).
* The basic data input by the user is to be supplemented by including within the knowledge base previously defined, all information held in the form of Building Regulations, Codes of Practice, as 'ready-reckoners', etc. (Section 5.2.9).
* The costing function should link to a relational-type database management system, structured in accordance with the global conceptual model illustrated in Figure 5.7 (Section 5.2.4).

5.3.2 The Model Formulation

* The system is to be computer based (Section 5.2.5).
* The costing function is to be a simulation model formulated around a procedural approach (Section 5.2.2).
* The generative mechanism is to be non-stochastic (Section 5.2.1).
* The costing function is to be based on the approximate quantities technique (Section 5.2.1).
* Each alternative design proposal is to be separately costed with unit rates, etc. all calculated anew (Section 5.2.9).

5.3.3 The Computer Program

* The system is to utilise the 'parallel' processing environment offered by particular operating systems, to encourage portability to smaller machines (Section 5.2.7).
* The programming language is to be:
  - sufficiently high level and yet simple.
  - exhibit the fundamental precepts of structured programming, information hiding and data abstraction (Section 5.2.6).
* The control structure is to allow back tracking and iteration (Section 5.2.3).
* A series of flags are to be associated with each variable to indicate previous values, and how the current value was determined (Section 5.2.3).
* The dialogue is to be machine initiated (Section 5.2.7).
* The user interface is to use 'windowing' to present both menu and question/answer interfaces (Section 5.2.7).
* Output is to include user selected parametrics (Section 5.2.2).
* Data display is to be distinct from data generation; functioning from computer-based solution files and represented as a graph, colour chart, 3-D plot, etc. (Section 5.2.1).

5.3.4 Generally

* Data preparation should allow the user to declare 'approximate' values (Section 5.2.8).
* There should be a separate and distinct capacity to undertake a statistical analysis of historical cost data (Section 5.2.3).
* The user should be provided with a number of 'aggregate commands' or 'building blocks' (Section 5.2.2).

This specification determines in some detail the nature of future cost models. The following chapter, Chapter 6, will describe the program ACE (Analysis of Construction Economics): which successfully implements a significant proportion of the specification in a computer-based cost simulation model.

REFERENCES

1 MICHIE D (Ed.)
"Expert systems in the micro electronic age", Edinburgh University Press, 1979.

2 BARR A and FEIGENBAUM E A
"The Handbook of Artificial Intelligence: Vol. I", Pitman Books, 1981.

3 LANSDOWN J
"Expert Systems: their impact on the construction industry", RIBA Conference Fund, 1982.

4 MILLER G A
"The Magic Number Seven, Plus or Minus Two: some limits on our capacity for processing information", Psychological Review, Vol. 63, 1956, pp.81-97.

5 BARTLETT F C Sir
"Remembering", Cambridge University Press, 1961.

6 STEARN D and ROOS J
"VISTA: Visual Impact Simulation Technical Aid", ABACUS User Manual No. 31, December 1982.

7 BCIS
"Building Cost Information Service Manual", RICS.

8 ANON
"The ORR System of Construction Cost Management: An Overview", Cost System Engineers Inc.

9 ZAHRY M
"Capital Cost Prediction by Multi-Variate Analysis", MSc Thesis (unpublished), University of Strathclyde, 1982.

10 BRIDGES A
"MAGIC: Multi-Variate Analysis by Graphical Interactive Computing", ABACUS Occasional Paper No. 65, 1978.

11 ROSENTHAL D et al
"Integrated CAAD Systems", BOCAAD No. 33, August 1979, pp.30-46.

12 BIJL A et al
"Integrated CAAD Systems", EdCAAD Report No. 79/11, March 1979.

13 LANSDOWN J
"Waiting for the Revolution", Proceedings of CAD78, IPC Pubs., 1978, pp.54-61.

14 GENTLES J and GARDNER W
"BILD - Building Integrated Layout Design", ABACUS Occasional Paper No. 64, 1978.

15 LEE K
"The ARK-2 System", 'Computer Applications in Architecture', J S Gero, Applied Science, 1977, pp.312-342.

16 CLARKE J A
"ESP (Multi-Zone System)", ABACUS User Manual No. 30, 1982.

17 ROSENTHAL D et al
Op. Cit.

18 ARMITAGE B S
"Conceptual Schema for CAD", CAD Vol. 9, No. 3, July 1977, pp.194-198.

19 CODASYL
"Database Task Group Report", ACM, 1971.

20 SENKO M E et al
"Data Structures and Accessing in Database Systems", IBM System Journal, Vol. 12, No. 1, 1973, pp.30-93.

21 CODD E F
"A Relational Model of Data for Large Shared Data Books", Comm. ACM, Vol. 13, No. 6, June 1970, pp.377-387.

22 CODD E F
"Relational Database: A Practical Foundation for Productivity", 1981 ACM Turin Award Lecture, Comm. ACM, Vol. 25, No. 2, February 1982, pp.109-117.

23 CAHILL K
"Superchip Gives the Trilogy the Lead Over IBM", Computer Weekly, No. 863, 9 June 1983, P.29.

24 SCHOFIELD J et al
"Mass Storage", Practical Computing, Vol. 6, Issue 5, May 1983, pp.103-109.

25 METCALFE M R and BOGGS D R
"ETHERNET: Distributed Packet Switching for Local Computer Networks", Comms. ACM, Vol. 19, No. 7, July 1976.

26 ALAGIC S and ARBIB M A
"The Design of Well-Structured and Correct Programs", Springer-Verlag, 1978, p.10.

27 BATES D (Ed.)
"Infotech State of the Art Report on Structural Programming", Infotech, 1976.

28 GHEZZI C
"Programming Language Concepts", Willey and Sons, 1982, p.5.

29 PARNAS D L
"On the Criteria to be used in Decomposing Systems into Modules", Comms. ACM, Vol. 15, No. 12, December 1972, pp.1053-1058.

30 IVIE E L
"The Programmer's Workbench - a machine for software development", Comms. ACM, Vol. 20, No. 10, October 1977, pp.746-753.

31 BIANCHI M H and WOOD J L
"A User's Viewpoint on the Programmer's Workbench", Proceedings of 2nd International Conference on Software Engineering, October 1976, pp.193-199.

32 KERNIGHAN B W and PLAUGER P J
"Software Tools", Addison-Wesley Pubs., 1976.

33 ROCHKIND M J
"The Source Code Control System", IEEE Trans. on Software Engineering, SE-1, December 1975, pp.364-370.

34 DOLOTTA T A et al
"The Programmer's Workbench", Bell System Technical Journal, Vol. 57, No. 6, July-August 1978, pp.2177-2200.

35 LUDERER G W R et al
"The UNIX Operating System as a Base for Applications", associated papers by B C Wonsiewicz et al, A G Fraser, H D Rovegno, S P Pekarich and H Cowen and J C Kaufeld in Bell System Technical Journal, Vol. 57, No. 6, July-August 1978, pp.2201-2304.

36 BACKUS J
"ACM Turin Award Lecture", Comms. ACM, Vol. 21, No. 8, August 1978.

37 CLOCKSON W and MELLISH C
"Programming in Prolog", Springer-Verlag, 1981.

38 WARREN D
"Guest Private View: What is Prolog?", Computer Weekly, Vol. 615, 24 August 1978.

39 DIJKSTRA E W
"GOTO Statement Considered Harmful", Comms. ACM, Vol. 11, March 1968, pp.147-148.

40 KERNIGHAN B W and MASHEY J R
"The UNIX Programming Environment", Computer, Vol. 14, No. 4, April 1981, pp.12-24.

41 BIJL A et al
Op. Cit., pp. 4-44.

42 ROSENTHAL D
"Implementation Techniques for CAAD System - A Proposal", EdCAAD Report 77/11, September 1977.

43 EUUG
"European UNIX Users Group Newsletter", Vol. 2, No. 3, July 1982, pp.99-107.

44 PHILLIPS R J et al
"AESOP: An Architectural Relational Database", CAD, Vol. 11, No. 4, July 1979, pp.217-226.

45 ZADEH L A
"PRUF - A Meaning Representation Language for Natural Languages", Int. Journal, Man-Machine Studies, Vol. 10, 1978, pp.395-460.

46 ZADEH L A
Ibid., p.452.

CHAPTER SIX: A COMPUTER BASED COST SIMULATION MODEL - ACE

CHAPTER SIX: A COMPUTER BASED COST SIMULATION MODEL - ACE

6.1 Introduction

The specification proposed in Section 5.3 is quite detailed. Unfortunately, development of a system based on such a specification will be severely constrained by the limited resources available, in terms of the labour, hardware, software, etc. The actual implementation invariably will fail to satisfy every detail of the specification. To this extent, the practicability of the specification also can be only partially considered: it is hoped, however, that in its present form the ACE system represents a very substantial part.

The system described in this Chapter is ACE: version 2, its predecessor being a wholly different implementation. Like its successor however ACE: version 1 was only intended to be a partial solution - primary considerations then were:

(i) the scale of programming involved - this proved to be a not inconsiderable task, as each of the 200-plus variables and unit rates calculated in ACE produced a subroutine often of up to 200 lines of coding.

(ii) if response times would prove acceptable - the program gave excellent interactive responses. The caveat being that the host machine was a large main-frame computer, running a program which only matched a part of the total specification.

(iii) the impact of context on the cost relationships produced - a particular investigation was made of the relationship between building height and cost. A series of sample runs produced a cost estimate for each of the following combinations:

* constant gross floor area of 6000m^2; number of storeys varied from 1-30.
* constant plan area of 600m^2; number of storeys varied from 1-30.

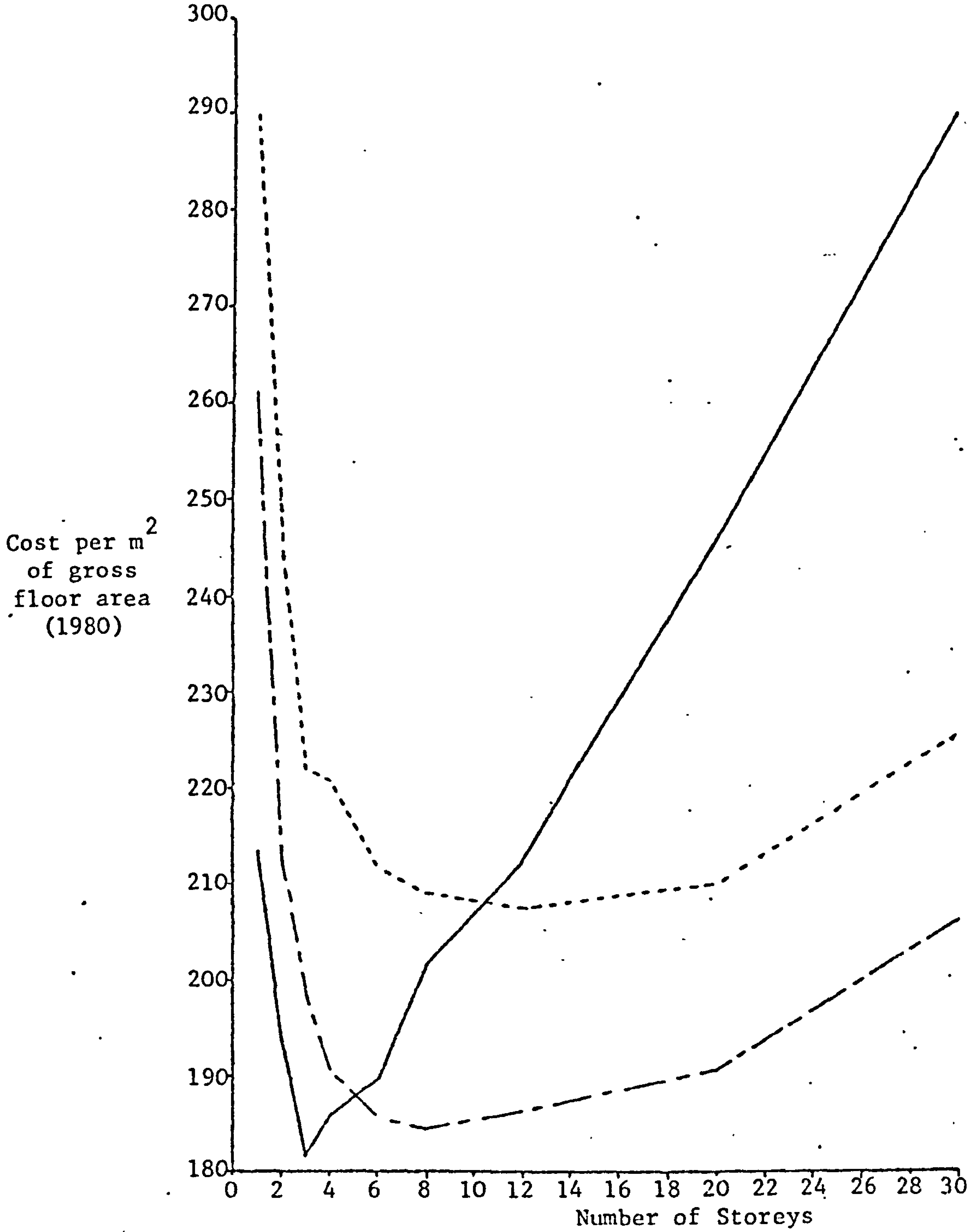
* constant plan area of 1200m2; number of storeys varied from 1-30.

The resultant cost relationships, illustrated in Figure 6.1, indicate a significant variation between each of the three contexts.

(iv) if some form of logical structure could be discerned - as the simulation model is based on a procedural approach, the actual logical structure remains implicit within the computer program. An investigation of this logic, by associating each variable and unit rate with those dependent upon it, revealed the structure to be extremely complex (see equivalent study of ACE: version 2 in Appendix VII):

* a large number of routines are recursive in that they are dependent upon other variables, in turn dependent upon the calling routine (see Figure 6.2(a)).
* the structure is dictated by the context in which each routine is called. That is, in different situations different modes of calculation might be selected which could produce a different set of dependencies (see Figure 6.2(b)), thus creating an animated logical structure.
* the large number of immediate dependencies (perhaps 6 per variable) and the depth of the overall structure (accentuated by the recursive nature of many dependencies) made the logical diagram unmanageably large, and difficult to reproduce on paper.

This chapter will describe ACE: version 2, concentrating on the overall structure of the program and making general observations relating to the individual processes which constitute the system as a whole. For a more pedantry account the reader is referred to Appendix VI, which gives an example run through the program, and to the ACE program documentation (1), currently in preparation. The documentation set will include the following supplementary details:



where: Constant gross floor area, 6000 m^2
Constant plan area, 600 m^2
Constant plan area, 1200 m^2

Figure 6.1: Selected relationships between cost per square metre of gross floor area and height, as output by ACE: version 1

```
Var 5.─┬dependent on Var.7─┬dependent on Var.5─┬dependent on Var.7  etc
       │                   │                   └────────── and on Var.26 etc
       │                   └────── and on Var.26┬dependent on Var.52 etc
       │                                        └───────── and on Var.53 etc
       └────── and on Var.26┬dependent on Var.52 dependent on Var.26 etc
                            └────── and on Var.53┬dependent on Var.26 etc
                                                 └──────── and on Var.52 etc
```

(a) The recursive nature of 'variable' dependencies

```
Variable 25 dependent on Variable 92
                  and if Variable 92 is greater than zero
                      on Variable 70
                      on Variable 71
                 else on Variable 82
                      on Variable 83
```

(b) The influence of context on 'variable' dependencies

Figure 6.2: The complexity of the ACE programs' logical structure: Two examples

(i) a description of how each and every variable and unit rate is calculated,

(ii) logical details of each process,

(iii) the system characteristics - run time, process sizes, portability checks, etc.

(iv) a guide to the computer implementation - the directories, necessary libraries, possible implementation problems, etc.

(v) an example run through the program.

Some of the many issues which relate to the possibility of validating a model of this type are introduced and discussed in Section 6.3.

The chapter concludes in retrospect, with a critique of the program and suggestions on how improvements might best be made to ACE: version 3.

6.2 The ACE System

Encouraged by the limited success of ACE: version 1, particularly in respect to the cost relationships produced, a more ambitious model was proposed which, in addition to the considerations of version 1:

(i) employed a sophisticated database management system

(ii) provided a more advanced programming environment

(iii) allowed a variety of display options

A very important contributory factor in the selection of these particular aspects for consideration, was the availability of a small 16-BIT mini-computer(the PDP 11/24), running a number of program development tools (the UNIX operating system), supporting two high level languages (FORTRAN and C), and offering at least two relational-type database management systems (INGRES (2) and FACT (3)). The combinations which make up the various options are shown in Table 6.1, together with a brief comparison of each alternative.

OPTION	COMPUTER	OPERATING SYSTEM	LANGUAGE	DATABASE SYSTEM
1	DEC 10	TOPS	RATFOR (structured FORTRAN)	ABACUS proprietry DBMS
2	PDP 11/24	UNIX	RATFOR	FACT
3	PDP 11/24	UNIX	C	INGRES
comments	As computers become increasingly more powerful the implementation of programs developed on a large main-frame, onto micro or mini-computers becomes less of a trauma. In a research environment where time is often at a premium, it is often of benefit to make use of the most powerful hardware available on the assumption that in the future much smaller, less expensive machines will give an equivalent performance.	The UNIX operating system offers significant advantages over TOPS: * it provides a far greater range of development tools (see however recent developments (4)) * it facilitates 'parallel' processing * it seems set to become the de facto standard operating system for 16-BIT machines	Both RATFOR and C are structured languages possessing equivalent features. RATFOR compiles directly into FORTRAN and will therefore be supported on a vast majority of computers. C is the language of UNIX and will be available wherever UNIX is supported. Unfortunately the FORTRAN compiler on the PDP is very inefficient.	ABACUS DBMS's are all hierarchical in structure and therefore less acceptable than other alternatives. FACT is a prototype system still very much under development; whereas INGRES is provided with full documentation and an interactive tutorial

Table 6.1: The various hardware/software options available

The advantages of UNIX and a relational database management system, promote the use of option 3 in preference to option 1; that which only has the clear advantage of providing a more powerful computer. Option 2 is most unacceptable.

In consequence, ACE: version 2 has been implemented on a PDP 11/24 operating UNIX, written in C, and using the INGRES database management system. For a description of the INGRES system, refer to Appendix V.

6.2.1 The general structure of ACE

The general operation of ACE, as illustrated in Figure 6.3, is intended to correspond to the notion of an integrated computer-aided architectural design system and, therefore, should be viewed as two distinct phases:

(i) Phase One: is the general preparation of the integrated project database from some standard database. Having created the project database (containing 'standard data' such as construction properties, various heating strategies, etc.) the user selects the analysis program to be used in Phase Two. A variety of programs would normally be available to the user, relating to structural analysis, environment simulation, draughting, visualisation, etc., of which the analysis of cost is but one option.

(ii) Phase Two: initiates the requisite appraisal program which reads from, and writes to the project database.

Thus, while at present the entire system is referred to as ACE, in a truly integrated computer-aided design environment those components relating to standard data preparation would be common processes, and the ACE system would reside wholly within Phase Two.

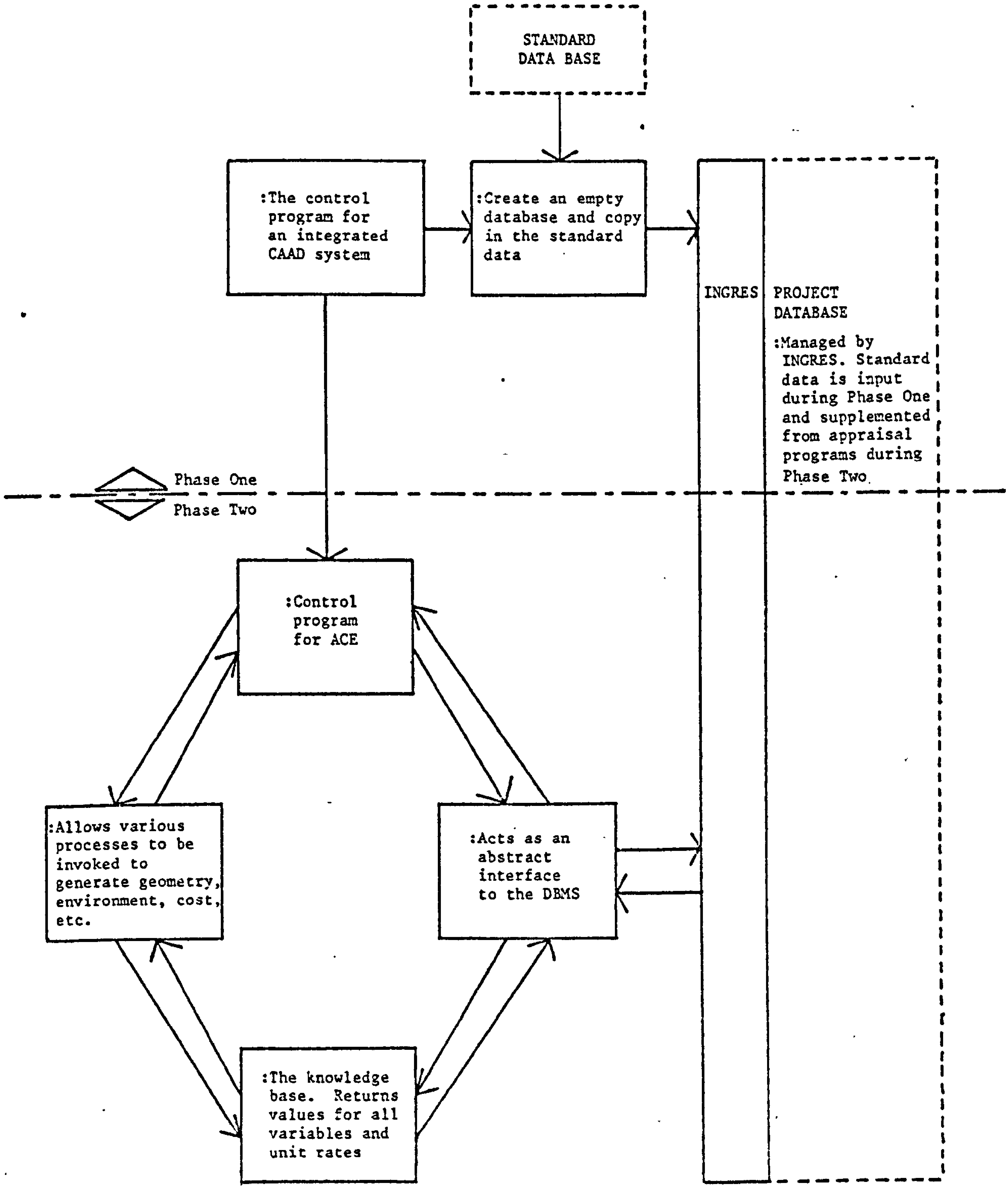


Figure 6.3: The general operation of ACE

Within Phase Two the general structure can be split into three levels, as illustrated in Figure 6.4:

(i) Level One: concerns the prediction of some detailed project to be costed (its geometry, environmental details, construction, etc.), and the representation of this in the project database.

(ii) Level Two: Provides the means by which the detailed representation can be generated, stored and later interrogated.

(iii) Level Three: allows the user to interrogate the solution files generated from Level Two by displaying individual parametric values, relationships, and/or aggregate values.

Each of these three levels is described in Sections 6.2.2.1, 6.2.2.2 and 6.2.2.3 respectively. See also Appendix VI.

6.2.2 Description of the ACE system

A description of the ACE system is illustrated in Figure 6.5, which summarises the various operations at each of the three program levels identified in Section 6.2.1.

6.2.2.1 Data input

The function of data input is to create the relevant project data within the project database. To this end, a user may:

(i) interact directly with the database using INGRES as a separate, stand-alone program.

(ii) create a properly formated data file using the editing facilities of the host computer. ACE would then transfer this data to the project database.

(iii) use other software to create a properly formated data file for transfer by ACE.

(iv) use ACE to create the necessary data file and to transfer same to the project database.

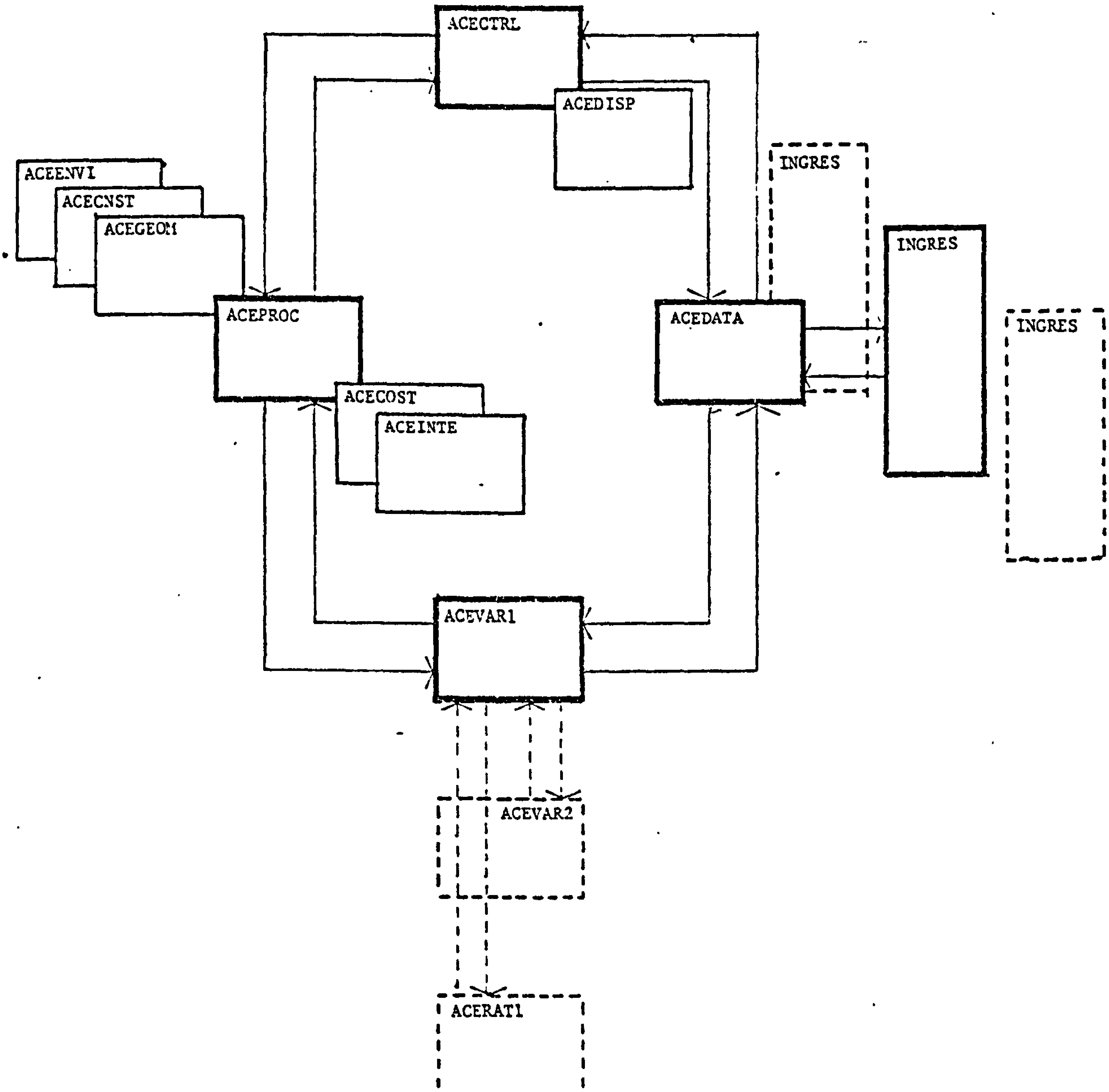


Figure 6.4: The 3-tier structure of ACE

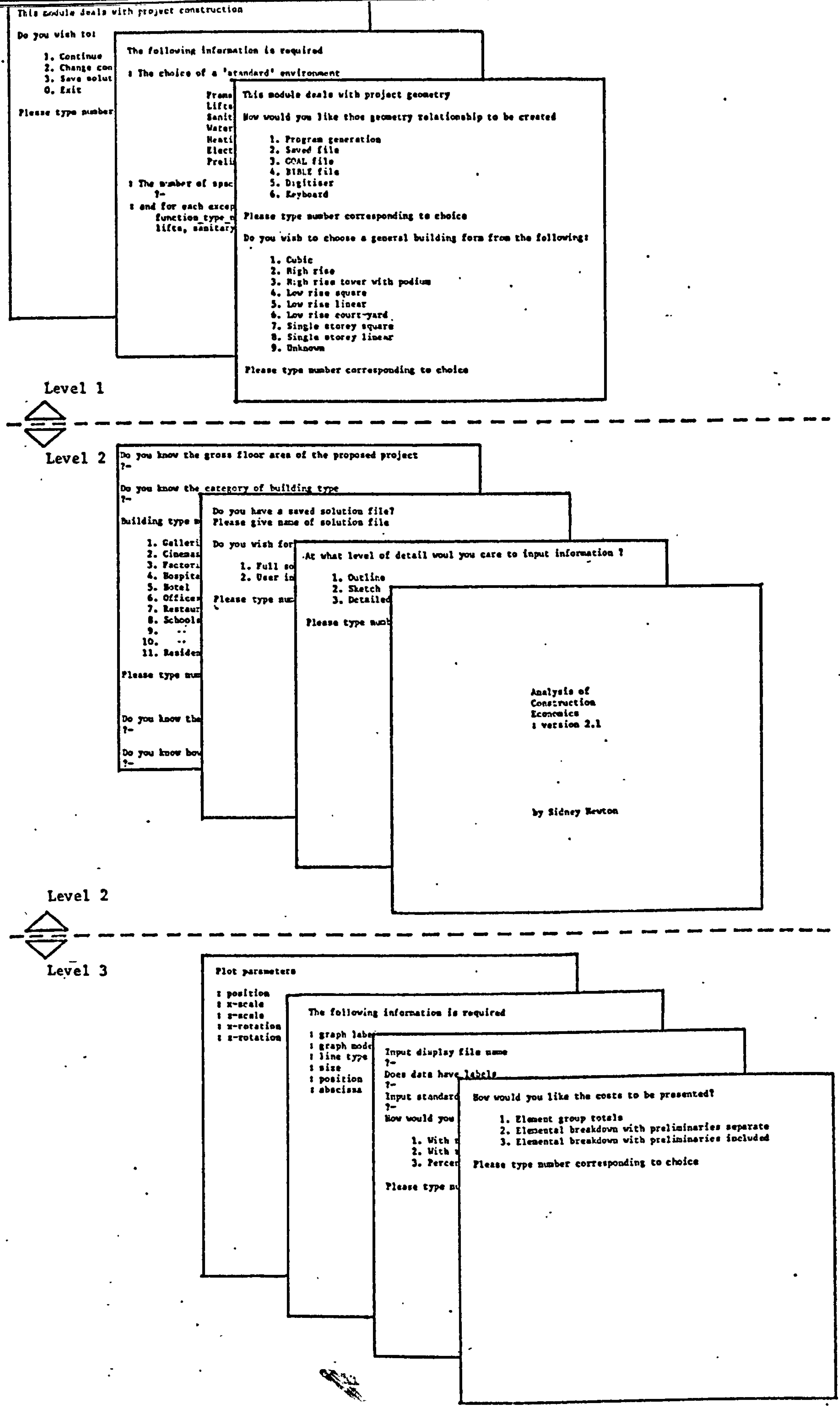


Figure 6.5: A synoptic description of the ACE structure

If the relevant data is to be produced interactively (using ACE) then the program will prompt the user for specific details as and when required. The program itself is directed to ask particular questions based on a tree-like decision structure defined in the program logic, which can also determine a course of action should such detail not be forthcoming.

At present the ACE system recognises three aspects of a project design in some detail:

(i) the process called ACEGEOM assists in generating the geometry data associated with each project design.
(ii) the process called ACECNST can associate a particular construction type with each roof, wall or floor within the proposed design solution.
(iii) the process called ACEENVI can associate a particular environmental specification with each space in the proposed design.

6.2.2.2 The simulation engine

The simulation engine, or infrastructure, of the ACE system is composed of four modules acting in parallel and communicating to one another directly.

(i) The control module: the main pupose of the control module, called ACECTRL, is to initialise the other modules which make up the complete structure. This procedure involves spawning-off replica processes, joined together by communication channels called 'pipes' and then replacing selected processes with a different module (this is standard UNIX procedure (5)). Other than this, ACECTRL acts solely as a 'clearing-house' which can either initialise particular processes in ACEPROC, or call-up the requisite data input routine within ACEDATA (see Figure 6.6).
(ii) The process module: ACEPROC, acts simply as a 'blank' which can be replaced by a variety of other processes, as determined by the user (see Figure 6.7).

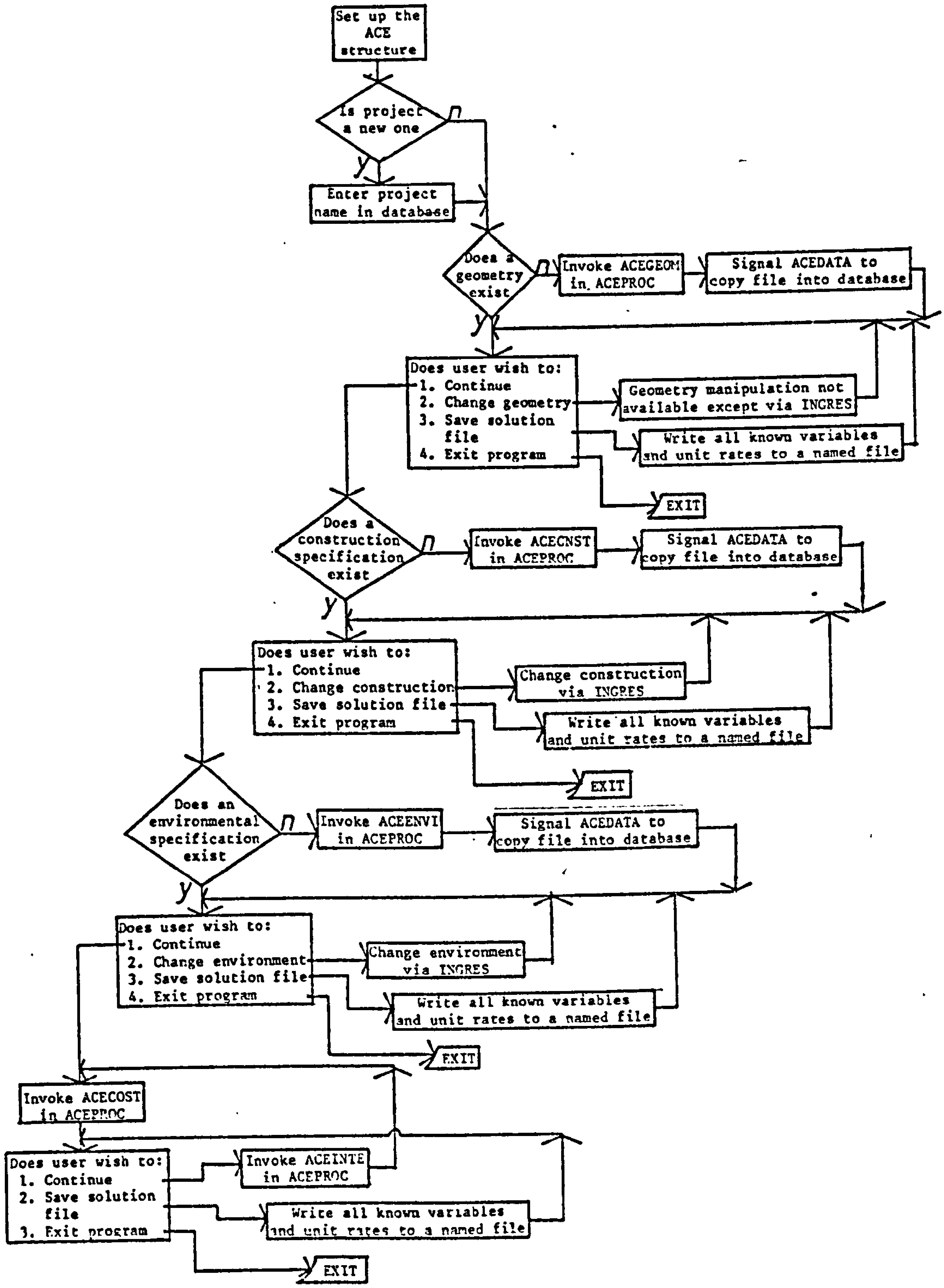


Figure 6.6: The control module logic structure

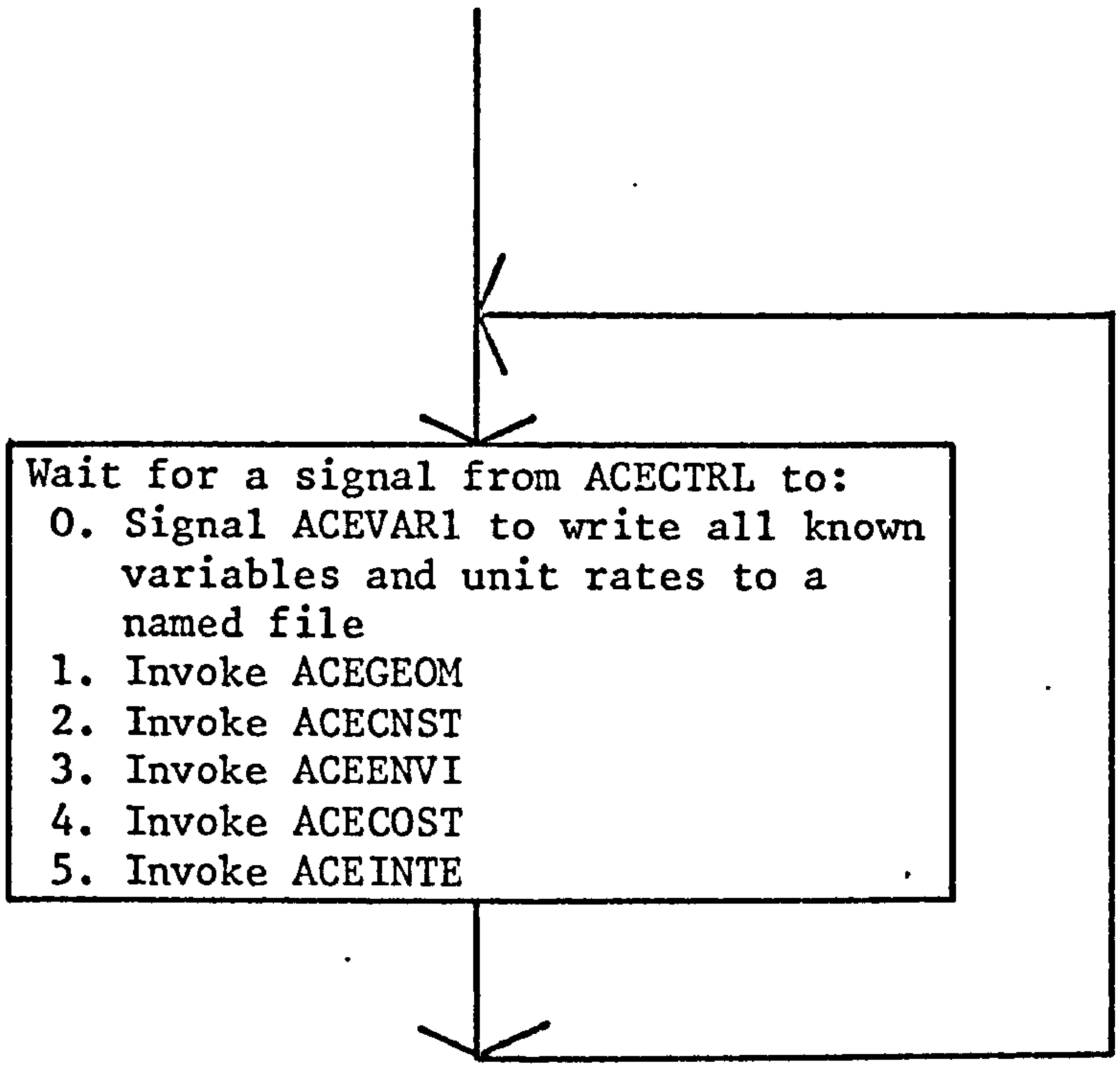


Figure 6.7: The process module logic structure.

(iii) The variables and unit rates module: in effect, this module represents the 'knowledge-base' of the system. Associated with each variable and unit rate are separate program routines which all follow the same basic pattern of logic as that illustrated in Figure 6.8. It is apparent that the basic rules can only be modified either by changing the existing rules, or by adding new ones, and recompiling the source code. There are 117 variables and a further 89 unit rates currently described in this way (for a complete list, with descriptions of each, see the ACE documentation (6) - an indication of there interdependency is given in Appendix VII). With each routine typically containing upto 200 lines of code, the total size of the process inevitably exceeds the maximum allowed on a PDP 11/24 (i.e. 64K). In consequence, a switching mechanism has been introduced which allows supplementary processes to be added to ACEVAR1. Each addendum is then linked directly to ACEVAR1, which processes all queries as illustrated in Figure 6.9.

(iv) The data module: ACEDATA, is intended to present an abstract interface between the ACE program and the database management system: it thereby enables a complete change to be achieved in the database management system without this being apparent to, nor affecting, the other ACE modules. In the present configuration ACE is linked to the relational database management system called INGRES (for a short technical description of the INGRES system, see Appendix V). Unfortunately, the module cannot anticipate the source of its next query, and must therefore continuously check each possible source in turn (i.e. the control module and the variables module) to ensure that the correct communications channel is chosen for output. Once a channel has been activated, the data module will undertake a particular function dependent upon the numerical code passed to it by the calling routine. The total structure is illustrated in Figure 6.10.

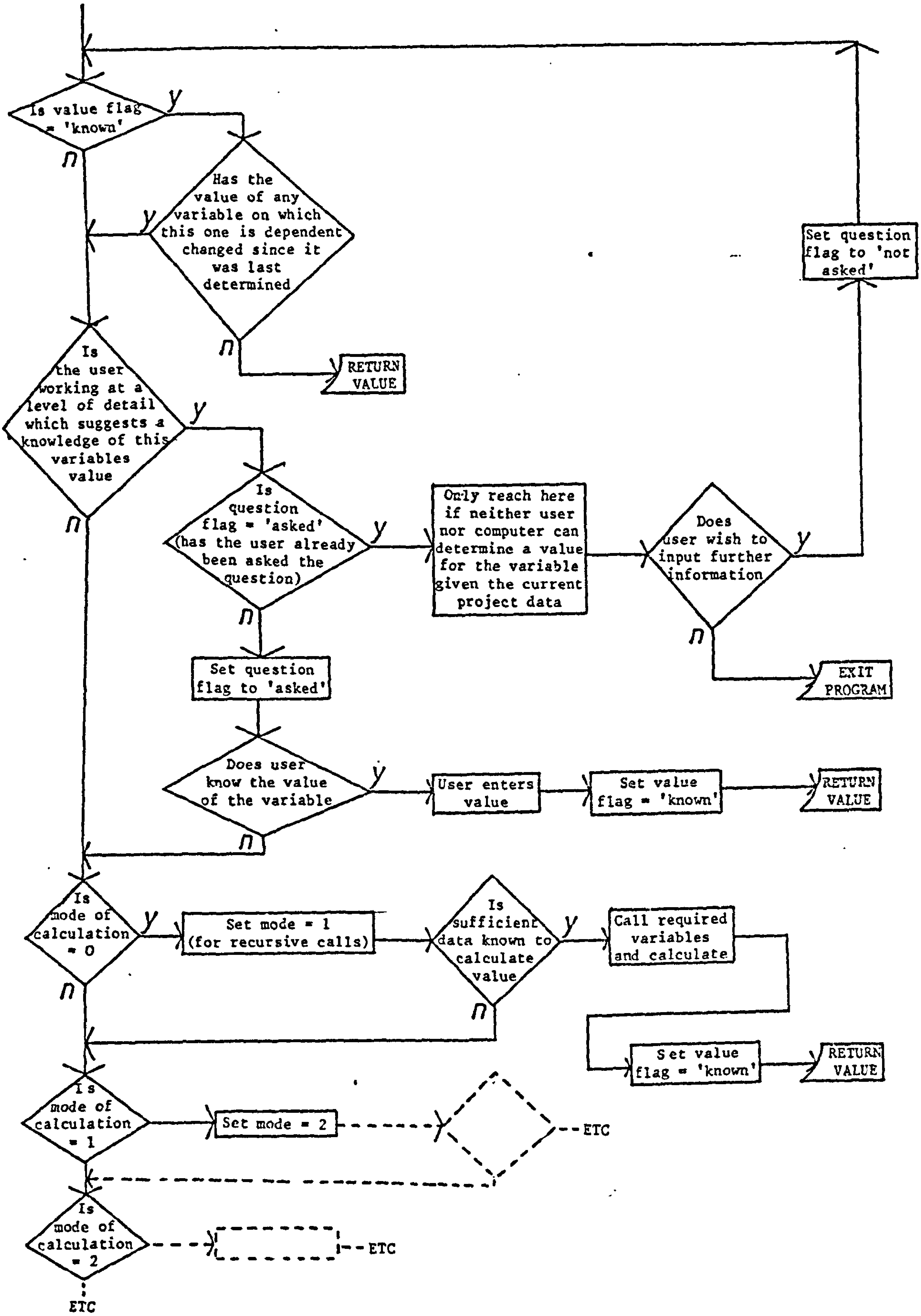


Figure 6.8: The variable and unit rate routines' logic structure

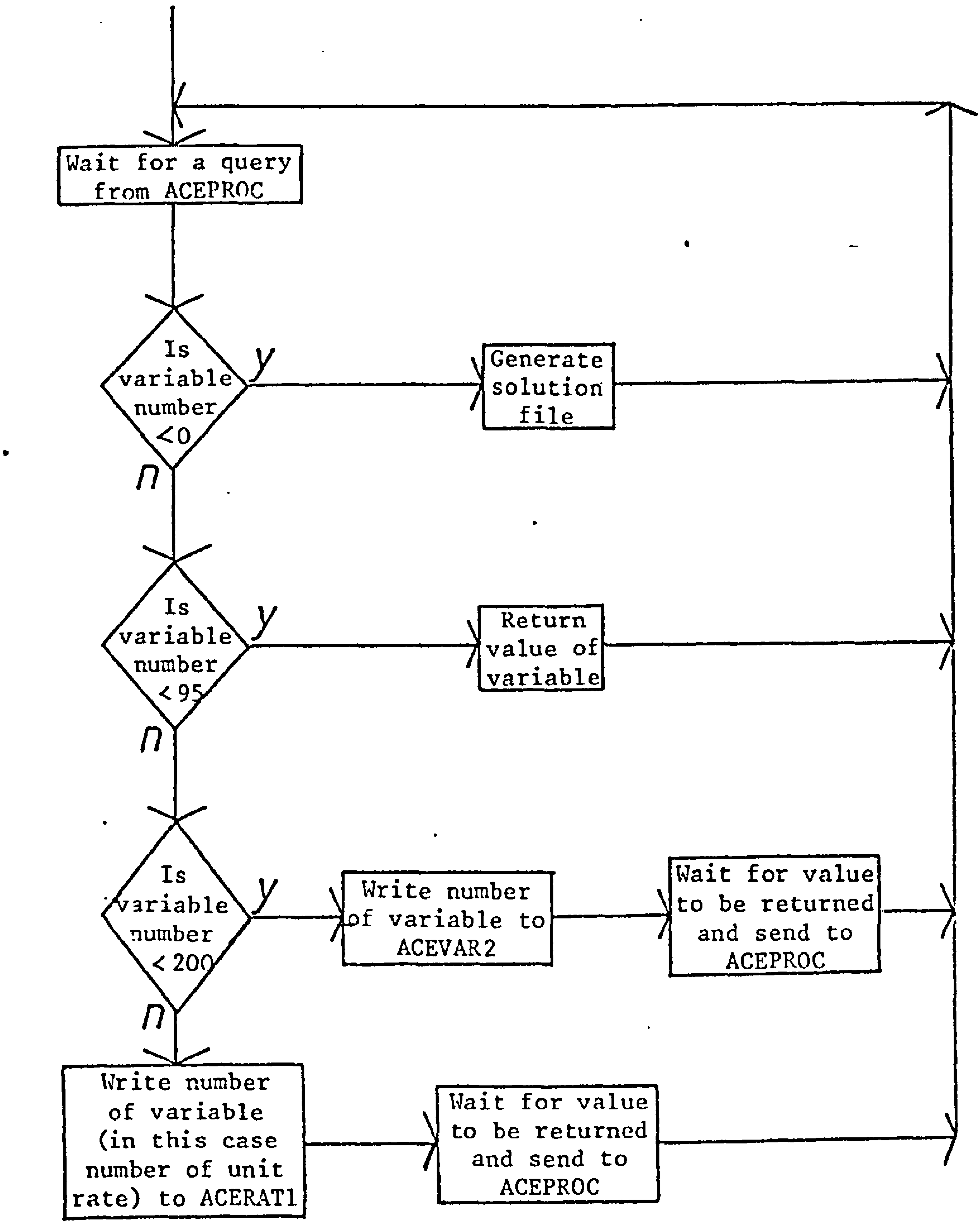


Figure 6.9: The variables module logic structure

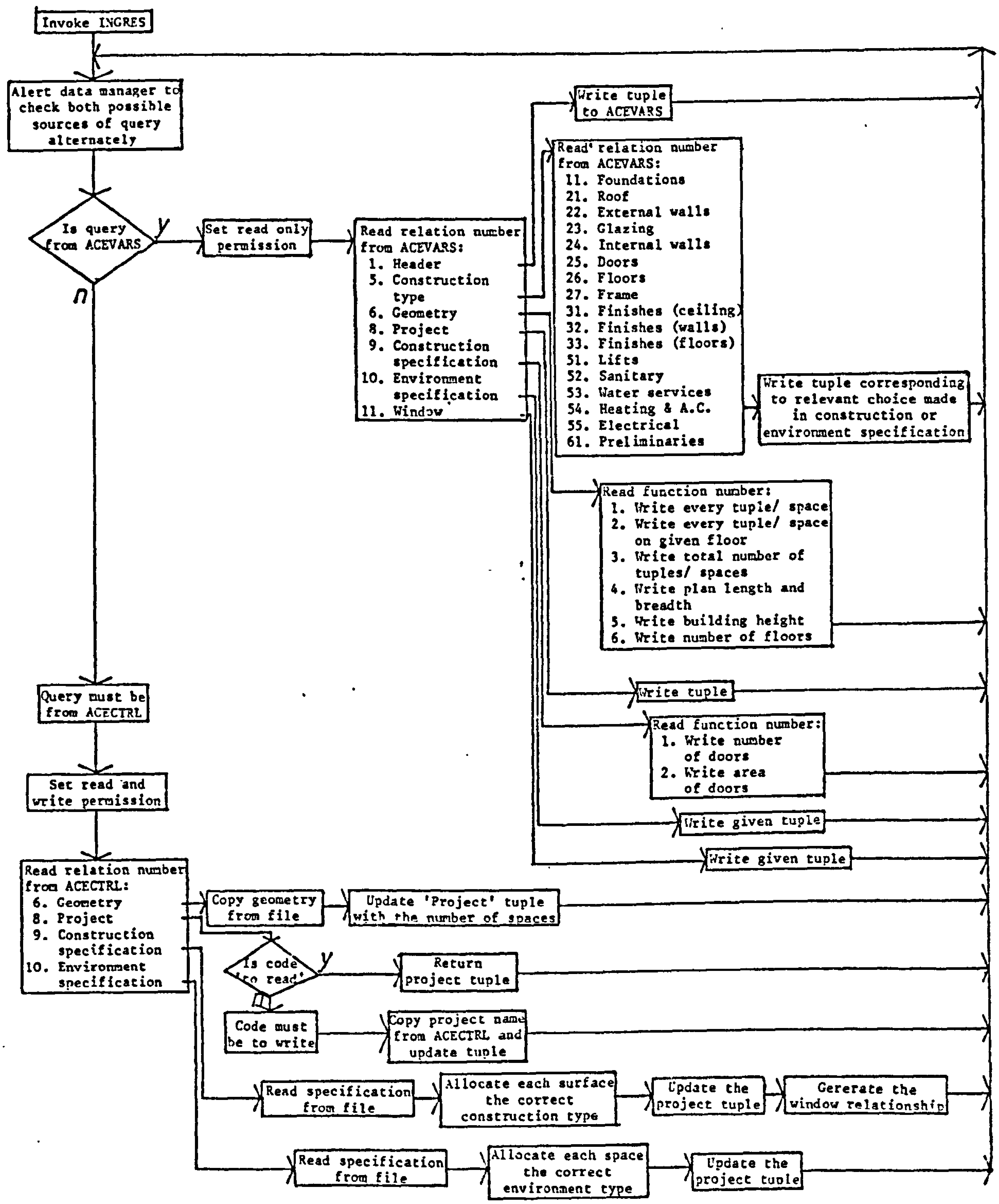


Figure 6.10: The data module logic structure

6.2.2.3 Output display

The output display is very important to any system because it largely determines a user's comprehension of the system; the more fluent the output the more readily it is understood. It is unfortunate then that the output of data from a computer program will all too often consist of large quantities of numerical data and cryptic messages.

Such a situation is not altogether without excuse, since the primary concern is to provide data which is correct: not necessarily packaged attractively. In a prototype such as ACE: version 2, effective output display is often sacrificed for a possibly more rigorous simulation engine, or improved data input facilities. As a result, the output display is perhaps the least well developed of the three levels.

There are currently three processes relating to output display:

(i) ACECOST simply applies a pre-selected mode of calculating the total cost, from the variables and unit rates contained in ACEVARS. In its current configuration ACE determines the total cost of a project based simply on a summation of elemental rates, which in turn derive from aggregates of unit rates. Because the overall total cost is an amalgam of more detailed rates, it can be broken down to provide a variety of expressions (see Figure 6.11).

At present the group element, and individual rates can each be expressed as:

* a total cost in themselves
* a percentage of some group total (such as overall total cost), or
* a cost per some unit of measurement (square metre of gross floor area, number of columns, etc.)

	TOTAL FOR ELEMENT		% OF TOTAL COST		COST/M2 GFA	
1.SUBSTRUCTURES	33957		1.57		4.24	
1.1.foundations		33957		1.57		4.24
2.SUPERSTRUCTURES	869279		40.14		108.66	
2.1.frame		82763		3.82		10.35
2.2.floors		166480		7.69		20.81
2.3.roof		37044		1.71		4.63
2.4.extl walls		288333		13.31		36.04
2.5.windows		97870		4.52		12.23
2.6.intl walls		21601		1.00		2.70
2.7.doors		7682		0.35		0.96
3.FINISH	114330		5.28		14.29	
5.SERVICES	910219		42.03		113.78	
5.1.sanitary		35182		1.62		4.40
5.2.water		96724		4.47		12.09
5.3.heating		329324		15.21		41.17
5.4.electric		448988		20.73		56.12
5.5.lift		167506		7.73		20.94
6.PRELIMINARIES	237954		10.99		29.74	
TOTAL	2165738.25		100.00		270.72	

Figure 6.11: Cost output from ACE

(ii) ACEINTE is little more than a facility to allow the user interactively to examine the current status of any chosen variable or unit rate. It is anticipated that this process will subsequently:

* interrogate also the solution files produced by ACE
* provide more synoptic data output, and
* prepare correctly formatted display files for ACEDISP

(iii) ACEDISP currently provides three display facilities:

* graphical display - with up to 6 line types, 3 grid types, choice of size and position, option to superimpose graphs, B-spline facility and fully automatic scaling (see Figure 6.12).
* 3-dimensional plot - on any scale, viewed from any point (see Figure 6.13).
* colour matrix - up to 50 user-defined colour grades, on a maximum grid of 200 x 30 (see Figure 6.14).

The display files however must first be created manually, which tends to relegate the programs utility, and sets it apart from the general ACE structure.

6.3 Validation of the ACE System

Some of the more fundamental issues relating to model validation generally are discussed in Section 3.3 of Appendix I. Therein, the validity of a model is said to be a test of its accuracy under a given experimental frame related to the purpose for which the model is intended. Since accuracy will rarely, if ever, attain an absolute value, the problem concerns 'acceptability' of the models accuracy.

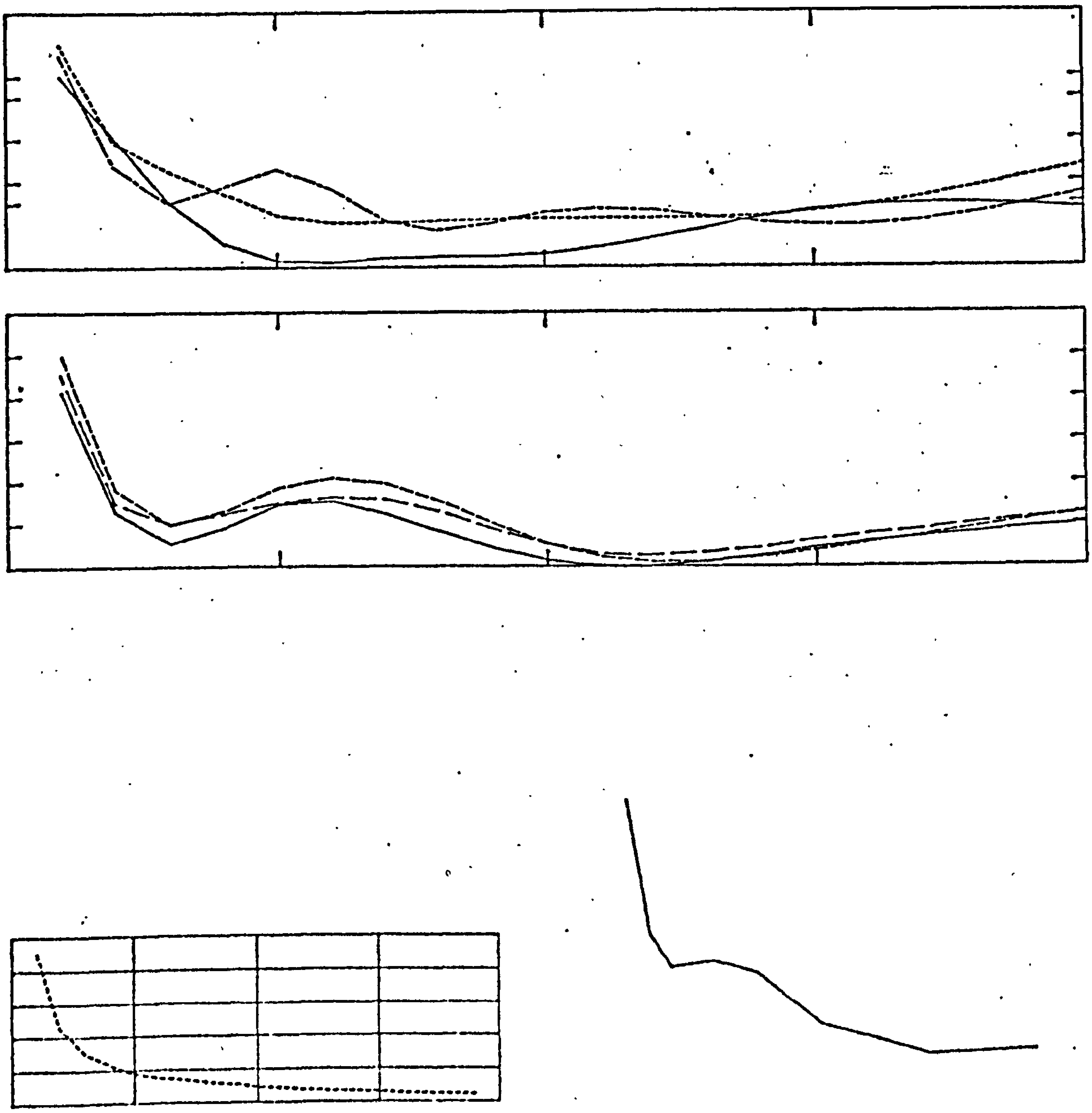


Figure 6.12: Some examples of graphs produced by ACE

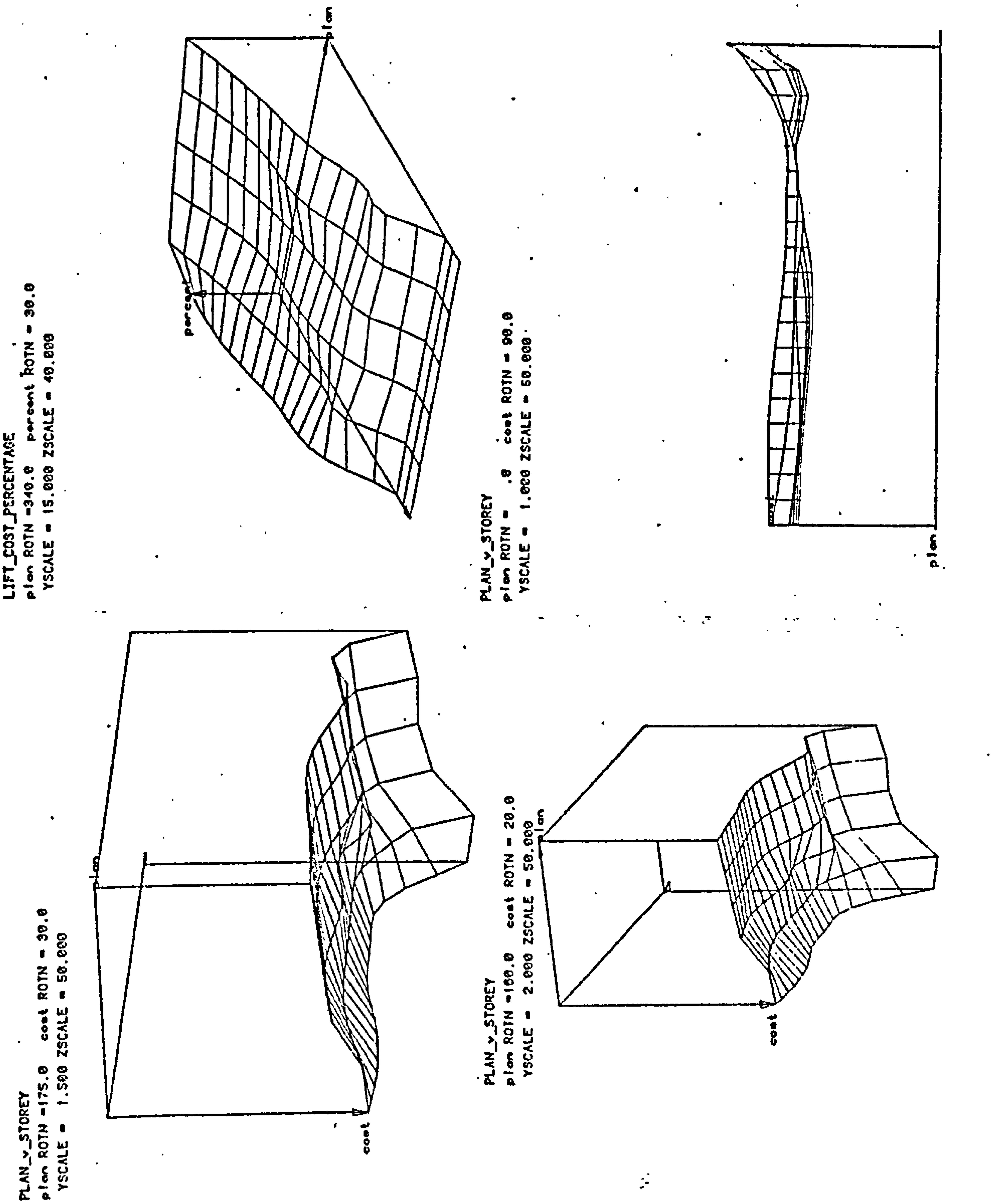


Figure 6.13: Some examples of 3-dimensional plots produced by ACE

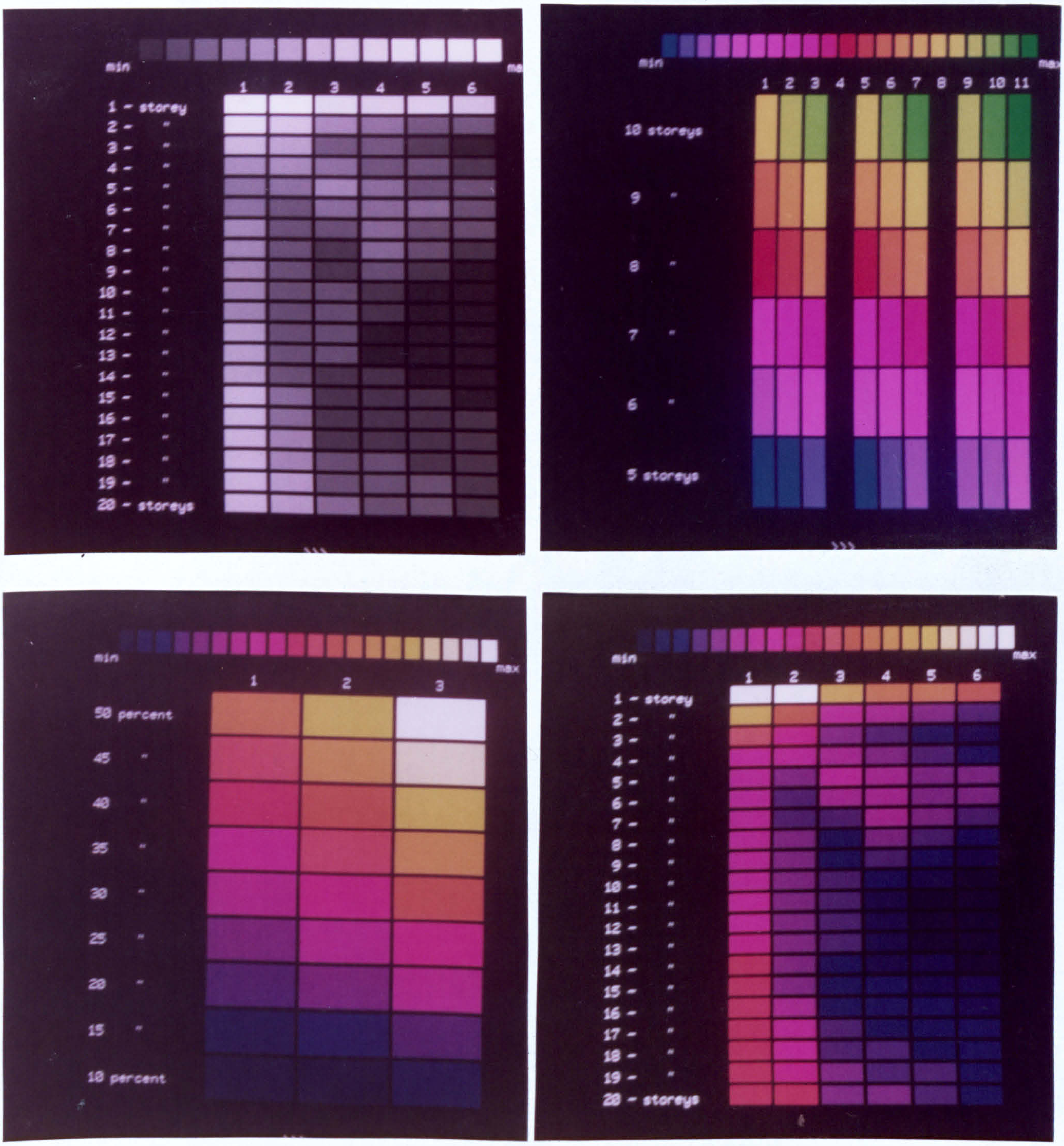


Figure 6.14: Some examples of colour matrices produced by ACE

This general scenario of model validation usefully can be partitioned into a number of more particular aspects:

(i) the relevance of the experimental frame to the intended application - is the model being tested under 'realistic' conditions: are the questions it answers appropriate, and are they posed in a way which is meaningful to the user?

(ii) the internal validity of the model - do the actual mechanics of the model/program do what they profess, and is that an acceptable procedure?

(iii) the input data - is the accuracy of the data relevant to the intended application of the model?

(iv) the results produced by the model - do these accord with 'reality'?

Before consideration is given to how the ACE system relates to each of these aspects individually, there remains the question of whether such a model can ever truly be validated.

In Appendix I mention is made of the fact that if a system is bespoke in nature so will it be more difficult, and probably less meaningful, to discern a sharp boundary between 'valid' and 'invalid'. The only techniques which provide anything like an absolute verification of a model's validity (commonly statistical hypothesis testing) relate to comparisons of the model input and output with 'real' input and output. In a unique system, having little or no previous or subsequent data with which to make such a comparison, these techniques fail. Emphasis then switches away from verification of input and output data, to verification of the actual logic within the model.

As building design tends to be bespoke in nature the emphasis of this validation study lies outwith a strict verification of input and output data. Nevertheless, a comparison of the results with other cost models and, wherever possible, 'reality' is still regarded as an important consideration.

6.3.1 The experimental frame

An experimental frame is intended to characterise a limited set of circumstances to which the model might be applied. These applications need not be exhaustive in the alternatives considered, but usefully will be selected to give an indication of the models potential.

It is intended that ACE be applied at a stage in design when project information possibly is incomplete, and serve to educate the user in how cost is affected by alternative design decisions.

Within this intended scope of application it is apparent that an appropriate scenario might be: "A designer working at the outline stage of a design process, wishing to make some tentative decision on the height and scale of the building. The decision will be influenced by many factors other than minimum cost and 'trade-offs' will therefore be paramount". Since all designs will pass through an outline stage, and the height and scale of a building are universal concerns, this would appear to be a valid experimental frame.

The simulation runs of ACE will observe the following conditions:

(i) a need to display the relationship between height and cost

(ii) a desire to interrogate the results for possible trade-offs

(iii) the following inputs:

- the project concerns an office building
- the building is to be framed
- height may vary between 1 and 20 storeys
- plan area may vary between 500 and 1000 square metres

6.3.2 The internal validity

There are two elements which govern the internal validity of a computer-based model.

(i) The model is embodied in computer-code which may or may not function correctly - the verification of computer-code ('debugging') can never be absolute when dealing with anything other than the simplest of programs. An indication that the ACE program is error-free can however be gleaned from the following:

* the program 'compiles' from program code into an executable version, and this infers that there are no syntactic errors with respect to the programming language.
* the LINT program checker (7) found no fatal errors in the code, merely a number of possibly wasteful constructions. LINT, inter alia, enforces the type rules of C more strictly than the C compiler; attempts to detect unreachable portions of the code; attempts to detect cases where a variable is used before it is set; and enforces a number of portability restrictions.
* a large number of the routines have been checked, at least once, against a manual calculation using the same data-set.
* the results so far produced have appeared relatively sound, and sensible.

(ii) The model adopts a particular procedure which, in itself, must be accepted as a valid means of obtaining the results produced. It is hoped that this thesis lends sufficient witness to the validity of the overall procedure adopted in the model.

The validity of the calculations which represent the various modes of each individual variable and unit rate however is a wholly more subjective consideration. It is assumed that each individual quantity surveyor (or indeed anyone) will have their own, slightly differing opinion as to the appropriateness of these calculations. Thus, any failing in the modes of calculation is a direct consequence of the authors own failings, not necessarily of the overall approach.

This model, of course, was never intended to provide an ultimate solution: rather, by making an explicit statement of how each variable and unit rate is derived (see user documentation (8)), this first attempt should provide the basis for a great deal of refinement and subsequent improvements.

Given this intention, the procedure actually adopted in ACE seems wholly satisfactory.

6.3.3 The input data

The accuracy of the input data bears greatly on the overall validity of a model. Rarely will the available data be absolutely accurate; the level of 'acceptable' accuracy being related to the intended model application.

In building construction, cost data is notoriously poor (see Chapter 4, Section 4.2). Any attempt to improve this data, at present, would inevitably prove expensive in monitoring more detailed activities on site, and managing the greatly increased volume of information. To circumvent the problem, estimators and quantity surveyors have tended to adopt a 'better the devil you know' approach: they show a distinct preference for data with which they are familiar (9). Published cost data exhibit a similar, almost disregard for the accuracy of the information (Ashworth (10) found a variation of up to 48% in the mean price of published data, and yet none provide any assessment of data reliability). The current paucity of quantity surveyors making use of the numerous sources of published data is due largely to the failure of these publications adequately to describe the context: few provide such 'essentials' even as the assumed labour constants, site character-isitcs, market conditions, etc. (although this failing may now be being recognised (11)).

Thus, while the accuracy of the input data is poor this appears to be acceptable, at the present time, provided that the user is familiar with the underlying assumptions: i.e. the context.

The cost data used in ACE largely is derived from Spons Architects' and Builders' Price Book for 1980 (12) and as such few of the underlying assumption are explicitly expressed. This is an obvious failing with the system as it stands, but hopefully is not sufficient a shortfall to render the total exercise invalid. For while all assumptions are not explicit, they are implicit, and it is unlikely that they would prove so outrageous as to invalidate the model within themselves - especially when the model mainly is concerned with relative, as opposed to absolute, costs.

6.3.4 The results

As discussed previously in this chapter, the nature of construction cost does not lend itself to absolute validation of a cost model. The alternative simply is to present the results, making suitable comparisons where possible and leaving it to the reader either him/herself or through some professional body, to make a subjective assessment of the sensibility/validity.

To this end the results of the simulation runs proposed in Section 6.3.1 have been compared in three styles:

(i) A comparison of the total cost output by ACE, with that of another cost model. Currently there are no other cost models which provide an equivalent degree of dynamic cost simulation as the program ACE (i.e. provide for cost relationships and unit rates to vary with each new context). The best alternatives are:

* vary the unit rates through user-prescribed cost relationships (the 'equation-based' type of model characteristic of regression analysis, etc.).
* vary cost relationships through user-prescribed unit rates, applied to changing geometries (the 'steady-state' type of approach).

As the accuracy of an equation-based model deteriorates particularly quickly over time, and no recent 'whole building' models have been published, the comparison has been made with a proven 'steady-state' type of model, as incorporated in the program GOAL (13).

GOAL (General Outline Appraisal of Layouts) allows a user interactively to evaluate several aspects of building performance, one of which is the capital cost of the project. The proposed building is described to the program through three project data files corresponding, each in turn, to the geometry, construction, and environmental, specifications. The properties of various construction and environmental choices are held in a standard data file which acts as a 'palette' from which the more project specific files may be created. A variety of cost structures may be described by the user in the standard data file, the general form being a rate multiplied by a quantity.

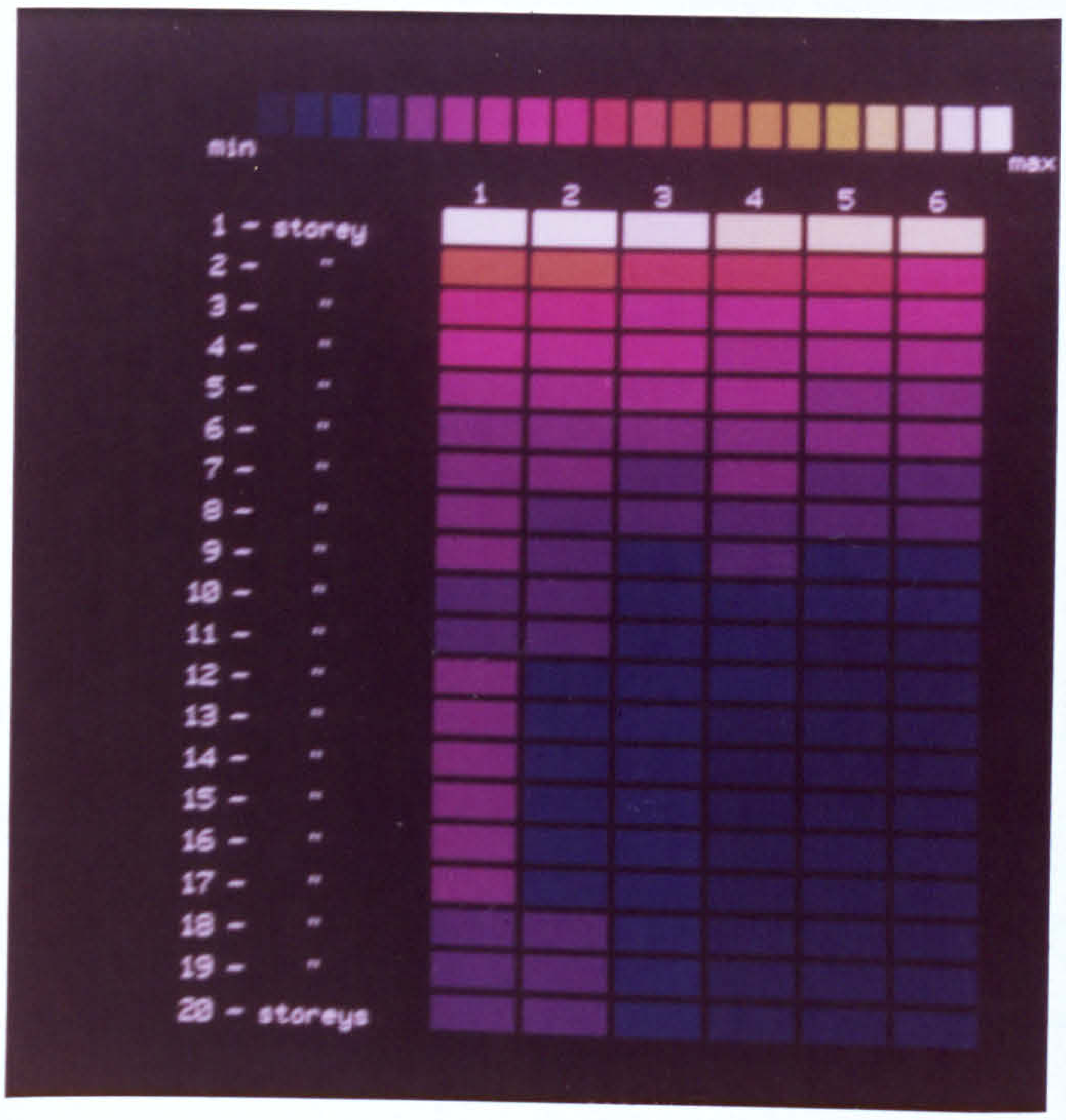
For the purposes of this comparison, the 'image' produced by ACE for a 10 storey building of 800 square metres plan area, was reproduced in a suitable format for GOAL. The cost structure was taken as the element rates from ACE, times an appropriate quantity (such as area of roof, or area of glazing, etc.) as calculated by GOAL, from the input geometry. Using this 'steady-state' the geometry of each alternative considered by ACE was described to GOAL, and the cost estimates compared.

Figure 6.15 illustrates the two comparative displays produced.

The following observations can be made:

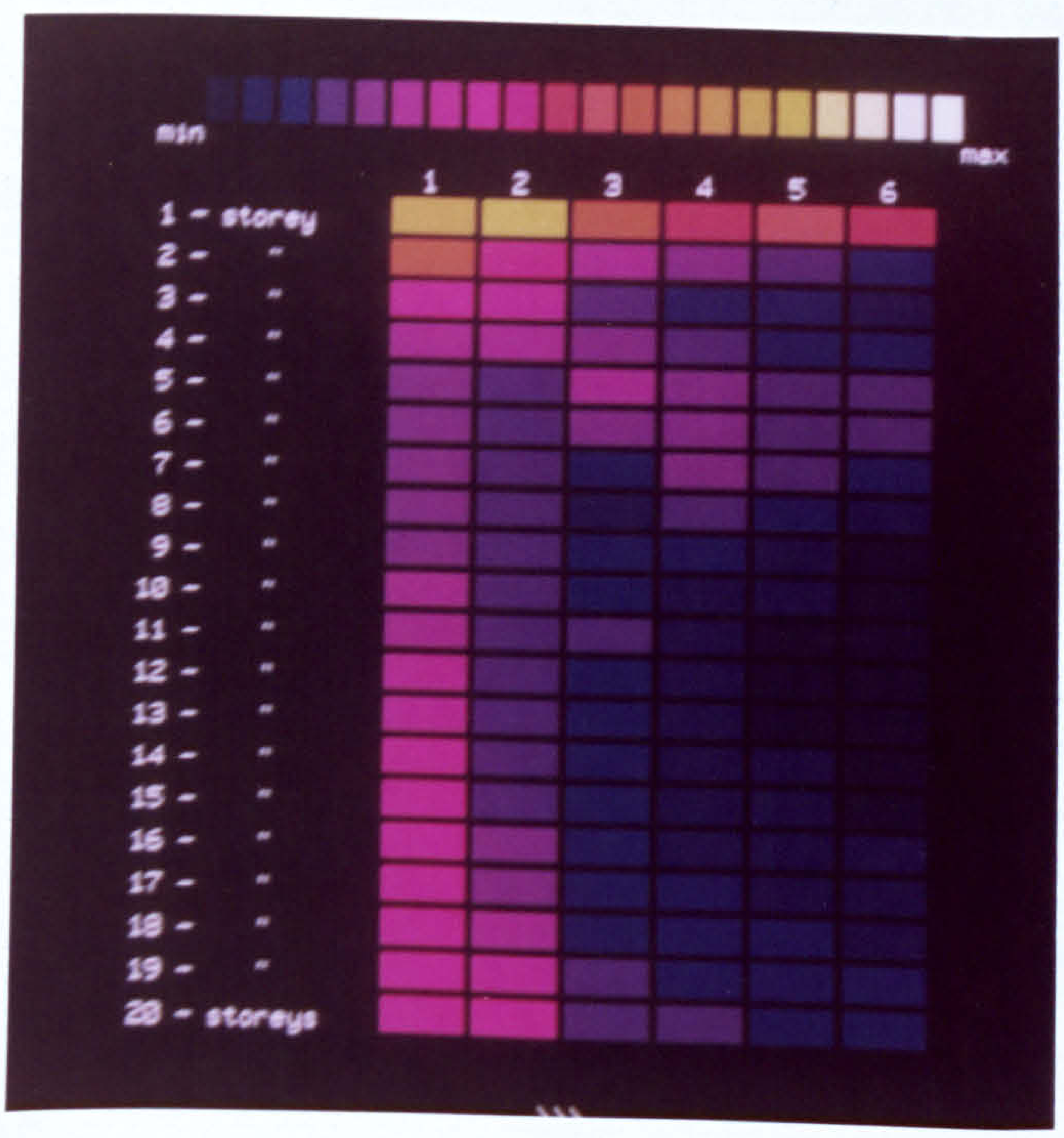
* both models follow the same basic trend of having a slightly lower cost per square metre of gross floor area as the plan area increases, and a sharp fall in cost as the height is increased from 1-3 storeys.
* the GOAL model provides a generally quite bland relationship between height and cost which is similar for all contexts. This linearity is symptomatic of the costing structure which largely is related to the gross floor area.
* the ACE model exhibits a wholly more elaborate and finely tuned set of relationships. The relationships are non-linear and discrete, with an obvious 'kink' after 3 storeys (probably caused by the introduction then of mechanical lifts) and a definite upturn in cost after about 10-14 storeys (see also Figure 6.16 which takes a 'slice' through the cost terrain).
* the linearity of GOAL points to a lower cost, the higher the building; ACE suggests that costs begin to rise again as the number of storeys is increased and would therefore appear to conform more with what might be expected in reality.

(ii) A comparison of the elemental cost relationships produced by ACE, with those of another cost model, and where possible with published cost studies. For the purpose of this comparison a 'slice' was taken through the cost terrains produced by ACE and GOAL in (i), along the line of the 800 square metres plan area. Each element then produced its own cost relationship with height, and some of these are illustrated in Figure 6.17.



(a) GOAL

1 = 500 m2 plan area
2 = 600 m2 plan area
3 = 700 m2 plan area
4 = 800 m2 plan area
5 = 900 m2 plan area
6 = 1000 m2 plan area



(b) ACE

1 = 500 m2 plan area
2 = 600 m2 plan area
3 = 700 m2 plan area
4 = 800 m2 plan area
5 = 900 m2 plan area
6 = 1000 m2 plan area

Figure 6.15: Comparative matrices of cost output by GOAL and by ACE

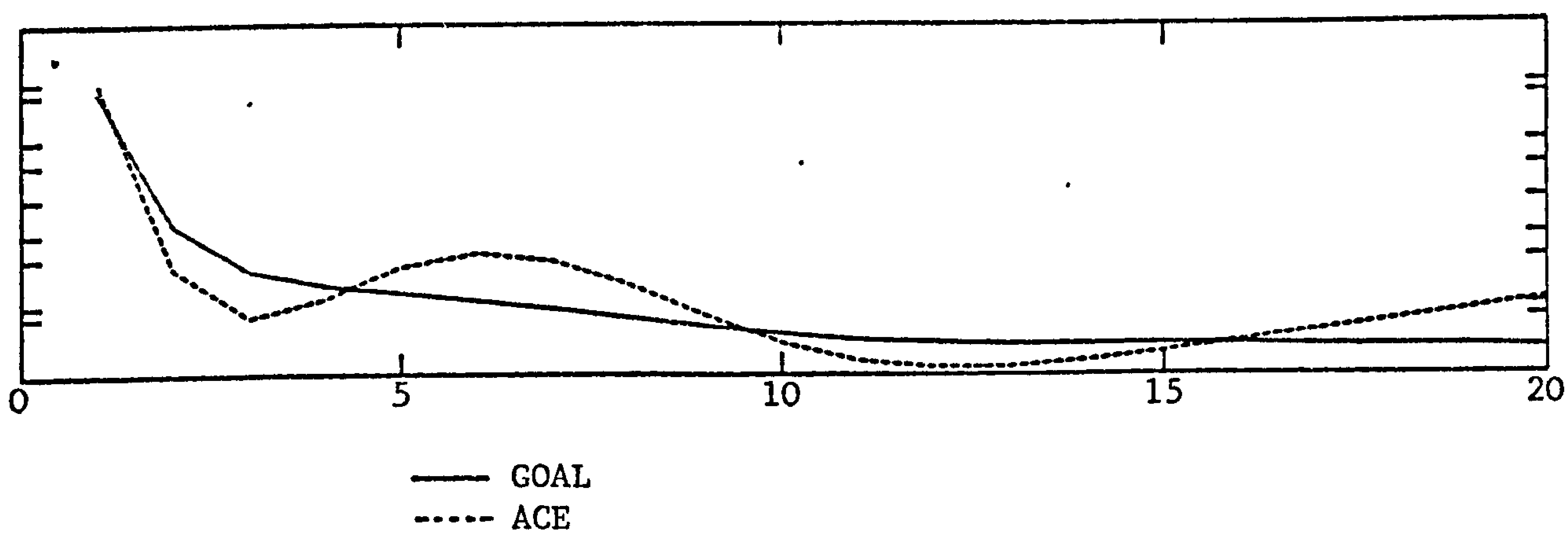
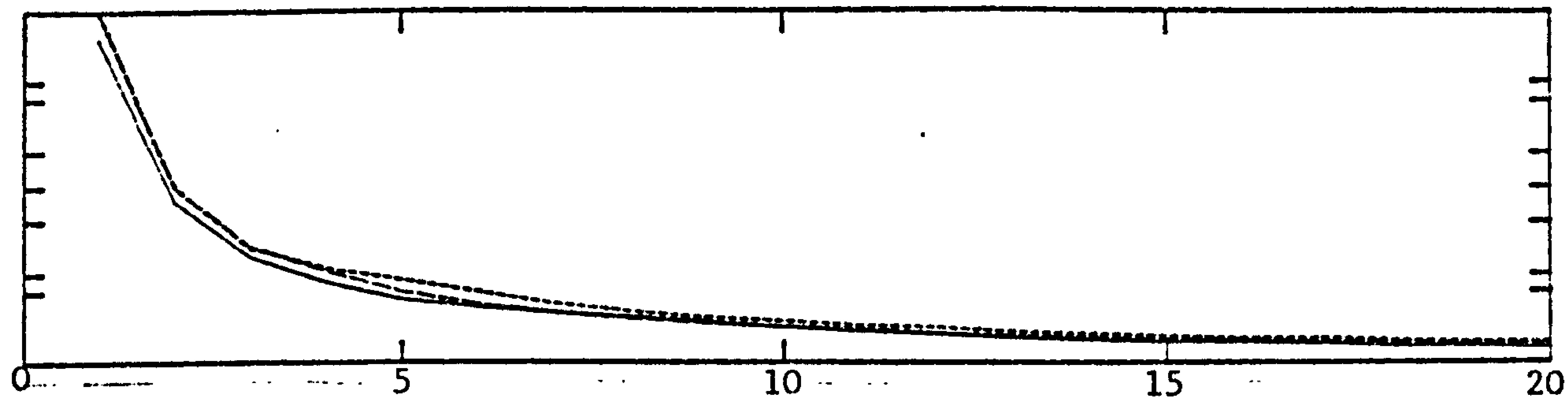
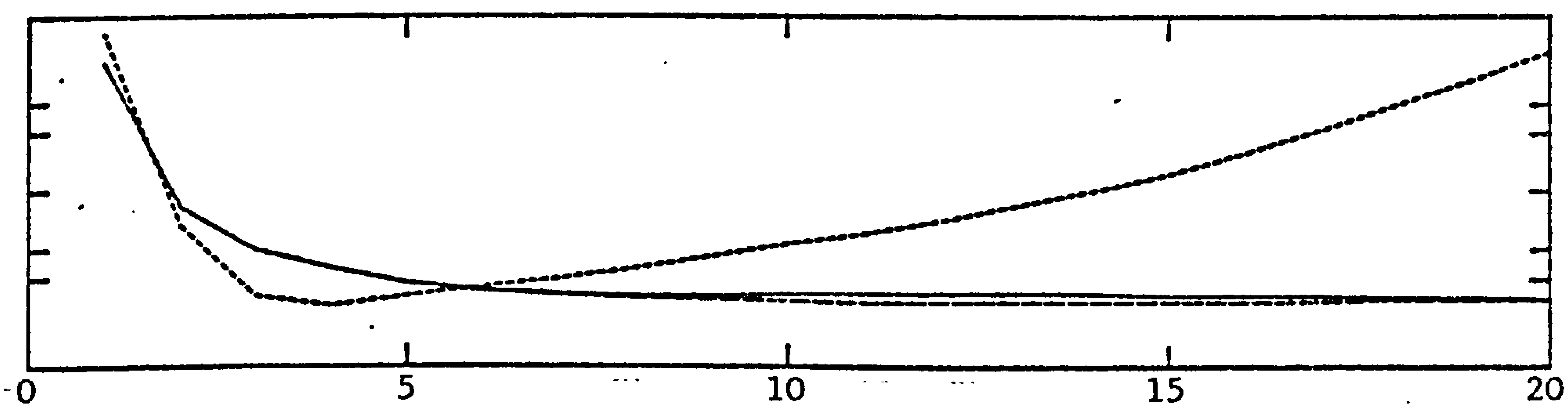


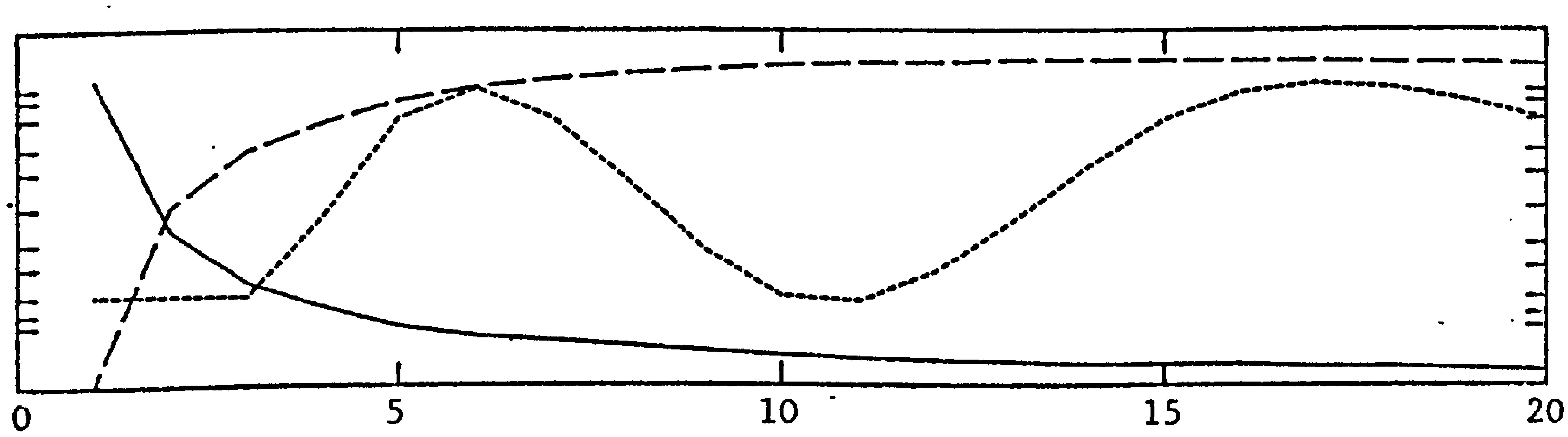
Figure 6.16: The relationship of cost to height for a plan area of 800 square metres



(a) The roof element



(b) The substructures element



(c) The frame element

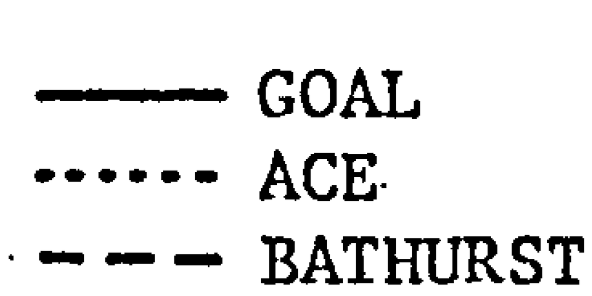
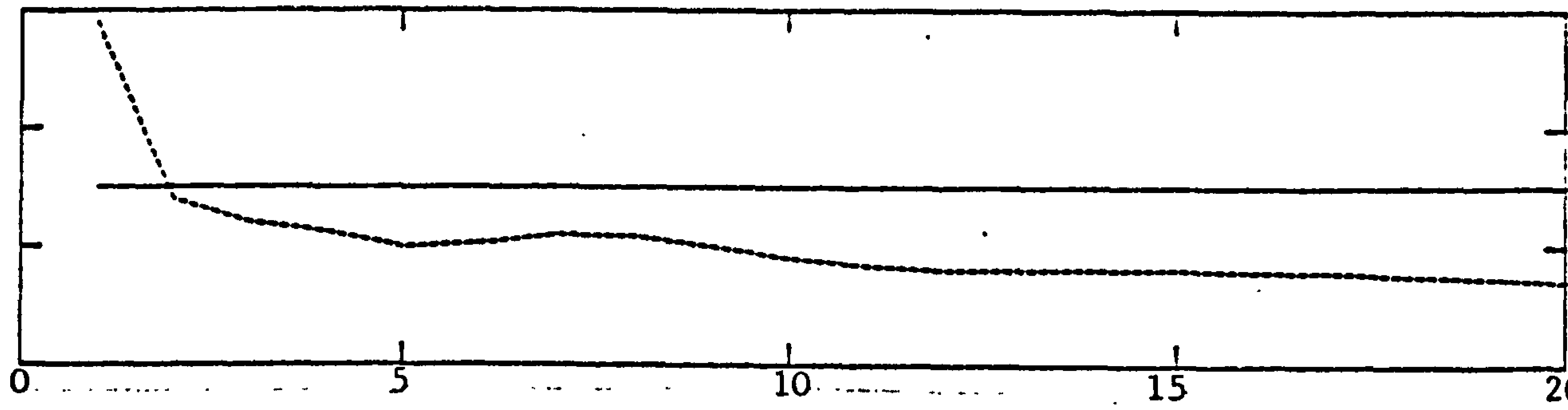
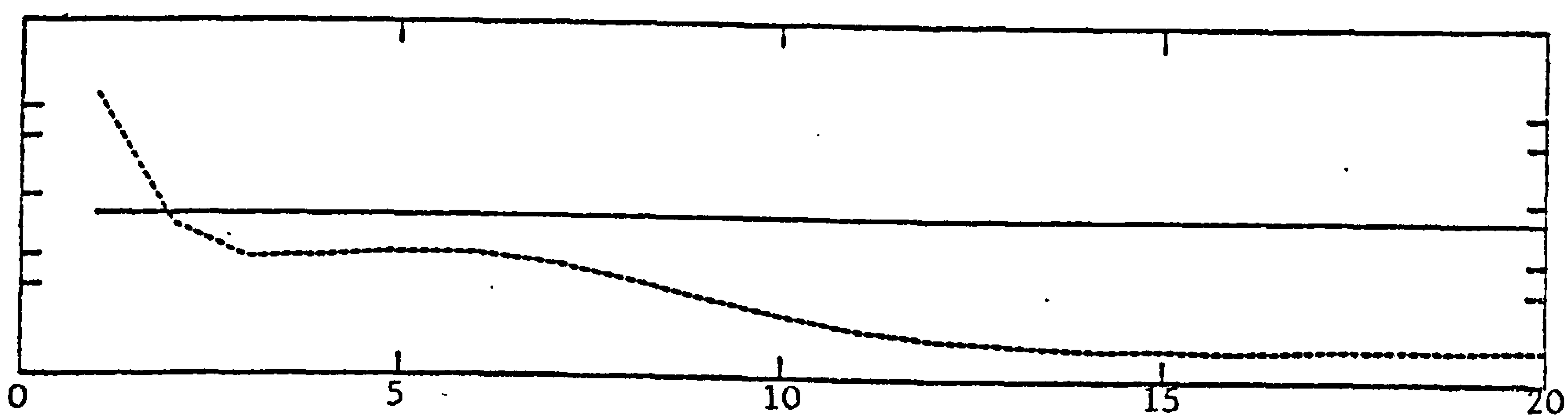


Figure 6.17: A comparison of the elemental cost relationships with height



(d) The preliminaries element



(e) The services element

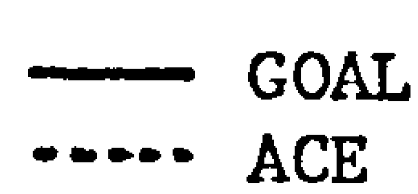


Figure 6.17: Continued

Published cost studies, certainly those which suggest figures rather than simply discuss trends, are less easily obtained: the only recourse being to use the tables given by Bathurst and Butler (14). Even here, the outcome of the study was not a series of actual costs, but rather 'quantity factors' for those elements whose cost, it is claimed, varies directly with the rate of change in quantity.

* the roof element (Figure 6.17 (a)) is certainly one in which the claim that cost largely is determined by area, has some bearing. All three relationships are quite well matched.
* the substructure element (Figure 6.17 (b)) illustrates a quite signficant discrepancy between ACE and the comparative relationships. To suggest that the foundations required to support a single storey building will be almost indentical to those provided for a twenty storey building is clearly unreasonable, and yet that is precisely the suggestion made by GOAL and Bathurst and Butler. Certainly the cost of the floor slab will be apportioned over an increasing gross floor area and therefore drop quite sharply, but the cost of column bases will continue to rise as they take more and more building load. In a situation where one cost falls sharply and then levels off, while another cost rises continuously, the cumulative effect will equate more closely with the relationship as produced by ACE.
* in the frame element (Figure 6.17 (c)) a fundamental flaw is exhibited by GOAL. The cost structure described in the GOAL standard data file equates the cost of the frame element with the area of ground floor slab which is framed - in retrospect an obvious blunder. It is to be expected that the cost of a frame will rise as it has to support more weight on the lower columns, but the actual slope of this increase in indeterminate.

* both the preliminaries element (Figure 6.17 (d)) and the services element (Figure 6.17 (e)) give a good indication of the superiority of ACE over GOAL. In GOAL these elements are wholly determined by the gross floor area while in ACE, there is an effective recognition for the economics of scale, learning curves, event-dependent costs, etc.

(iii) A comparison of how total cost is apportioned between the various elements. Table 6.2 details the mean, standard deviation and co-efficient of variation for all ACE and GOAL simulation runs; the 20 most recent cost analyses for office blocks included in the BCIS; a study of 34 commercial buildings in Australia (15); and a study of 204 general buildings from the BCIS (16).

While the proportionment made by ACE to the sub-structures element is slightly low, and that made to the services element a little high in comparison to the others, the large co-efficients of variation suggest that this is unlikely to be significant.

6.3.5 A summary of the validation exercise

The emphasis of this validation study is with the certification of the logic embodied within the simulation program: this entire thesis might be thought of as an attempt to validate the particular approach to cost modelling which ACE represents. In that respect the fact that a reasonable frame of reference was chosen, that the actual program largely has been verified, that a satisfactory choice of input data has been made, and that the results produced seem quite sensible, are all secondary considerations.

On the contrary, however, these factors often also are the most overt test of a model's validity. It is hoped therefore that any bias in this short evaluation will not have been so great as to nullify what would otherwise appear to be a very encouraging set of

	ACE		GOAL		BCIS offices		AUSTRALIAN commercial		BCIS general	
SUBSTRUCTURE	1.48	0.19 / 12.95	5.13	4.08 / 79.51	6.45	3.31 / 50.89	3.84	2.17 / 56.51	12.20	6.62 / 54.26
SUPERSTRUCTURE	39.44	4.88 / 12.37	38.29	8.63 / 22.54	36.98	8.35 / 22.58	40.19	5.44 / 13.54	45.47	12.45 / 27.38
Frame	3.49	0.36 / 10.46	8.40	6.68 / 79.54						
Floors	6.93	0.78 / 11.29	4.92	2.32 / 47.18			19.83	3.43 / 17.26		
Roof	3.81	3.12 / 81.71	3.76	2.99 / 79.52						
Extl. Walls	13.19	1.61 / 12.19	20.35	3.93 / 19.30			15.29	3.51 / 22.96		
Windows	4.63	0.57 / 12.37								
Intl. Prtns.	1.24	0.41 / 32.90	0.86	0.13 / 14.71			5.02	2.35 / 46.82		
Doors	6.69	3.21 / 47.99								
FINISHES	5.17	0.47 / 9.07	4.55	0.68 / 15.01	8.59	3.12 / 36.36	11.65	2.88 / 24.73	10.18	3.56 / 34.97
FITTINGS	inc.		inc.		1.31	1.15 / 87.89	0.86	0.62 / 72.10	4.42	5.13 / 116.06
SERVICES	48.13	6.42 / 13.34	43.86	8.44 / 19.24	29.29	7.38 / 25.20	41.41	3.46 / 8.36	27.74	15.58 / 56.16
Sanitary	1.42	0.44 / 31.08					2.66	0.87 / 32.71		
Water	4.79	0.47 / 9.72	24.49	3.70 / 15.09						
Heating	17.06	3.14 / 18.43								
Electric	19.18	1.61 / 8.40	19.37	7.59 / 39.17			38.75	3.35 / 8.65		
Lifts	5.71	5.32 / 93.09								
PRELIMINARIES	11.19	1.69 / 15.12	9.46	1.43 / 15.08	11.54	4.93 / 42.71	inc.		inc.	

mean	standard deviation
	coefficient of variation

Table 6.2: Comparison of total cost apportionment between elements

testimonies. The model certainly seems sufficiently accurate and sound for the intended application but, by its very nature, the validation study will never be fully comprehensive and can never produce an absolute verdict.

6.4 Retrospection on the ACE System

This section will consider the ACE System post hoc. To the extent that it contains some objective, hopefully informed observations of benefit to subsequent cost modelling projects of a similar type and scale, it serves its purpose. To the extent that the observations are often self-righteous, serves only to highlight the current subjectivity of computer aided architectural design in general and cost modelling in particular.

The section is split into two:

(i) a discussion of the strong and weak points of the system, focussing on mistakes that were made in progress rather than on eventual corrections.

(ii) the problem of 'where to go to from here', with recommendations and warnings to those who choose either to take this work further, or to develop their own system along similar lines.

6.4.1 The system generally

It may be held as being inconsiderate to level criticism, or for that matter praise, on a system which is still so much in its infancy. What is unquestionable however is that ACE has matured greatly over the past 15 months and is now at a very real crossroads in its development - if for no more simple a reason than that the Science and Engineering Research Council Research Studentship, which has funded its development thus far, is about to expire.

The system will be discussed under three headings:

(i) the approach

(ii) the program structure

(iii) program implementation

6.4.1.1 The approach

(i) Goals - the original objectives tended to get swamped as the problem was revealed, dictating that they be expanded considerably to match what proved to be a highly complex problem domain: namely computer aided architectural design. This expansion was absolutely necessary if research of any real consequence was to result, but meant also that a lot, in this particular case all, of the code had to be re-written - in many cases more than once. The unforeseen re-writes created large volumes of additional work and meant that a great deal more time was spent 'coding' than anticipated at the outset.

(ii) Methodology - the 'structured approach' to programming has much to commend it, at least in principle. In practice however there was often a parady caused by not knowing how best to structure the problem until it had first been successively refined. This almost 'blind' process of refinement resulted again in large amounts of abortive work. It is not known however whether this was more or less than might otherwise have occurred without a structured approach - the suggestion is that it was probably the latter!

(iii) Emphasis - under the guise of scientific rigour the primary consideration of the research was to produce a model which provided realistic results. The outcome was a model which sacrifices an efficient and more appropriate user interface for marginally, though quite substantially, improved results. Certainly the lack of an adequate provision to interrogate solution files, means that much of the model's potential is latent. Thus, while an 'all singing, all dancing' model was clearly out of the question with the resources available, it is felt that an improved interface would have contributed significantly to the utility of the model.

(iv) Documentation - the major re-writes and consequent short life-span of many routines, discouraged the documentation of coding, even to the extent of missing out comment statements in the code itself. This caused problems subsequently when up-dating routines, although the structured code and the C programming language did prove simple and easy to understand, even without comments.

6.4.1.2 The program structure

The program structure has exhibited a quite remarkable flexibility which has positively encouraged program development. The notion of separate, abstract modules for control, the database, the knowledge base, and the various processes can be well recommended.

Aspects of the structure do however give cause for concern:

(i) the user interface - except for specific diagnostics, the program is essentially 'silent-running': in that if a user-response is not required the program merrily churns away without providing any indication of what it is doing. The diagnostics proved invaluable in 'debugging' and it is conceivable that similar benefit might be derived by a user if he/she were able to follow the 'thought-processes' of the machine.

(ii) the knowledge base - embedding the knowledge base in a series of computer routines made the task of 'tuning' the rules particular difficult. Under the circumstances there was little alternative, but some form of knowledge base management system would undoubtedly prove invaluable in future work.

(iii) initialisation - getting the basic structure set up was not an insignificant problem. The UNIX documentation, though excellent in most respects, leaves it up to the individual to 'discover' the true nature of certain commands. For example, the inter-process communication channels (pipes) are not as simple as they first appear, with the outcome that a lot of time was spent looking for some particularly unpleasant 'bugs' in completely the wrong place.

6.4.1.3 Program implementation

(i) UNIX - the use of UNIX for version 2 has certainly expedited the development considerably. The adb-debugger (17) is worthy of special note as it proved so very useful, despite presenting certain problems when dealing with multi-processes. The adb allows an 'image' of the core to be married to the executable program, and then steps through the program a single line at a time until the fatal error occurs, thereby pinpointing the actual line of coding where the program fails. Overall the UNIX operating system was very pleasant to work with and provided a variety of very useful 'tools': its use can be strongly recommended.

(ii) The PDP 11/24 - the major disadvantage of having a computer such as the PDP dedicated to one or two users, is the almost seductive charm of machine management. It was very nice to get involved in the general problems of system support, but this inevitably detracted from the time spent on other, more central issues. The argument for a separate, remote computer, assumes of course that the operators there will be as sympathetic to problems as the user him/herself might be!

(iii) Coding convention - the adoption early on of a coding convention was well recommended in the literature, and in practice made program up-dates very straight forward.

6.4.2 Future versions

In the main this section deals with the most significant failings of ACE: version 2 (i.e. those aspects which only remain as part of the program either because of a lack of resources to implement them, or because the appropriate techniques are not yet available).

(i) the database system - undoubtedly, the database management system caused more consternation than any other part of the program. INGRES is capable of supporting a very much more sophisticated user than ACE. Unfortunately this great power also makes it very large and, especially on a small PDP 11/24, very, very slow. Figure 6.18 shows the amount of central processor time used by each of the various modules during a typical run. It is apparent that over 90 per cent of the total processing time is apportioned to interactions with the database.

This immense overhead effectively ruled out any large scale up-dates to the project database, as is required, for example, by a proposal to alter the design geometry. In actual fact there is no need for a sophisticated data base management system. The effectivness of having ACE split into a series of abstract modules means that ACEDATA could interact with virtually any management system without effecting the rest of the program. Thus, while something at the scale of INGRES would be needed for a fully integrated computer-aided architectural design system, it is far too sophisticated for the short-term requirements of a cost model such as ACE. It is suggested therefore that as a matter of some urgency either INGRES be replaced by a very simple, much quicker data base management system, or that the development of ACE be switched to a larger, more powerful machine such as the VAX 780s.

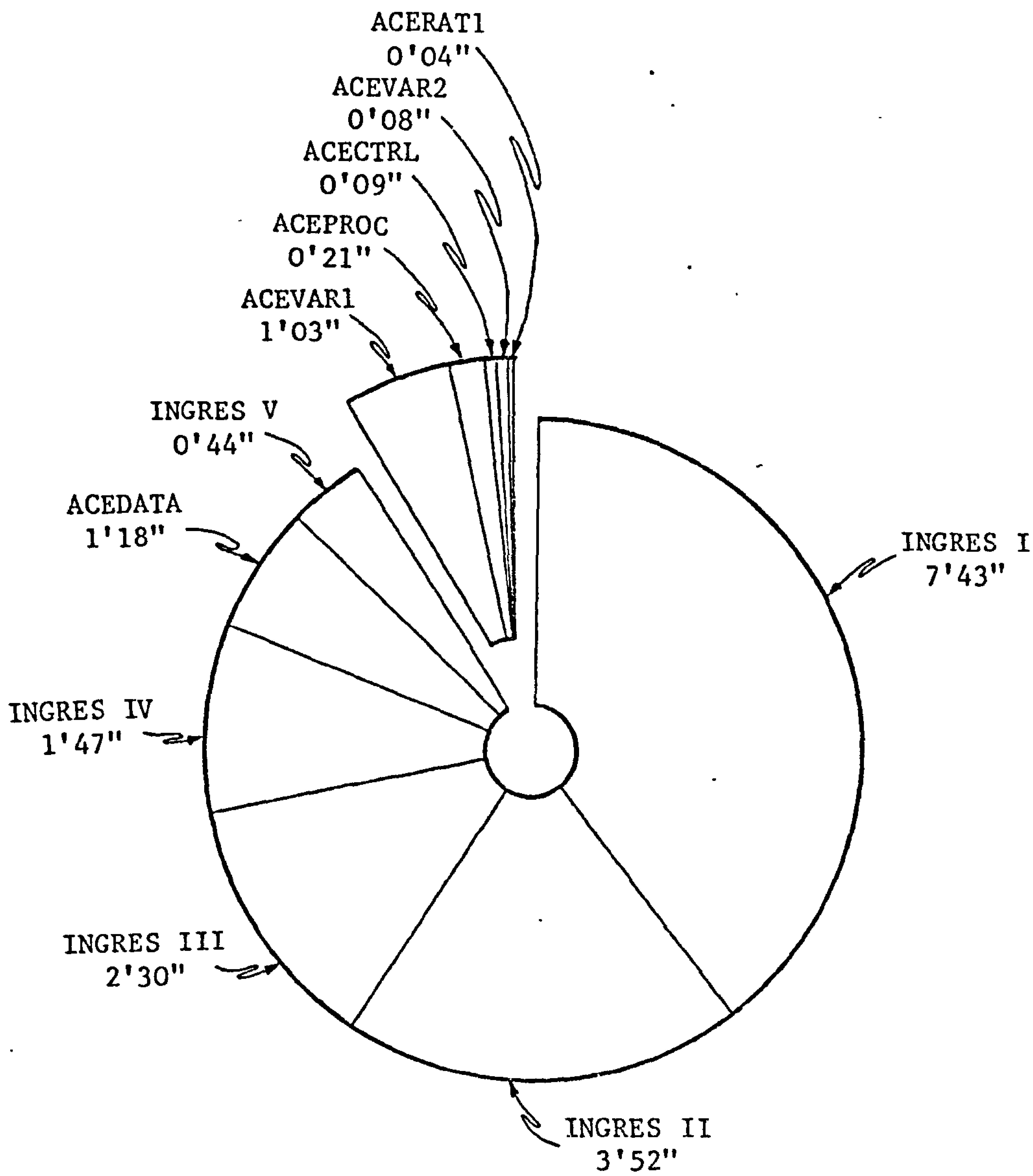


Figure 6.18: The proportionment of central processing time for a typical run of ACE

(ii) the knowledge base - the knowledge base is currently split into three modules. This should be increased immediately to six or seven so that the number of variables or unit rates in any one module is greatly reduced. Trying to squeeze as many routines as possible into each module only results in them becoming cumbersome and difficult to manage - each time a change is made to a variable the entire module has to be reloaded, and this can be very time-consuming.

An alternative solution would be to have some form of knowledge base management system but these tend to require large machines to function effectively.

(iii) data input - there is a definite lack of any error handling mechanism, data continuity checks, or data validation. These facilities - which recover from user errors, ensure that data inputs are not contradictory, and that the value of particular variables lie within a range of possible values - are essential for naive users and should be incorporated in the system if any casual users are anticipated.

(iv) cost generation - the knowledge base for unit rates should be separate from the main program. This would allow the unit rates, and the production rules which govern their selection, to be up-dated distinct from ACE generally, and at a more frequent interval.

6.5 Summary

This chapter has considered the implementation, validation and immediate prospects for the computer-based cost simulation model, ACE. The program was developed to match the specification detailed in Chapter 5 and generally confirms the practicability of most of the guidelines proposed in Chapter 4.

The model, though still very much a prototype, has been satisfactorily implemented in a computing environment well suited to the dictates of an integrated computer aided architectural design system, and in a form which makes use of many advanced computing techniques. The general structure of the program has proved to be very flexible and the modularity means that future developments of each process within ACE can proceed at their own discrete pace.

The validity of ACE: version 2 has been tested as far as is possible, but any verdict is a matter of subjective opinion. Certainly the model would appear to fail on certain aspects, but these failings are felt not to be sufficient evidence to suggest either that the approach generally, or that the particular interpretation of the approach embodied within ACE, is invalid.

A number of these failings were offered as important ammendments to future versions of ACE, along with some of the more significant lessons learned thus far. In all, this should be of considerable interest to those who choose to follow a similar course. It is hoped however that the somewhat harsh criticism of the system presented in Section 6.4, will not unduly obscure the many positive aspects and successes of ACE: version 2.

Chapter 7 will attempt to highlight the power and utility of the ACE system by exemplifying its use as an investigative tool to analyse a number of very pertinent questions relating to construction economics. Typically, such questions might be:

* What is the minimum cost configuration for natural to artificial lighting given the current geometry?
* At what point would that configuration cease to be the optimum, given a change in some other parameter such as building depth?
* Does this apply for all types of glazing?
* Which is the most cost effective column bay size?
* Does a precast frame offer cost savings over an insitu frame?

* What would be the total cost consequence of an increase in the thermal performance of the roof?
* What would be the effect of an increase in the market price of some material?
* Which are the cost significant elements?
* Is it cheaper to build upwards or outwards?
* Which costs will be affected by a change in the wall construction?
* etc.

REFERENCES

1 NEWTON S
"The ACE Documentation Set", ABACUS, 1983.

2 STONEBRAKER M et al
"The Design and Implementation of INGRES", ACM Trans. on Database Systems, Vol. 1, No. 3, September 1976, pp.189-222.

3 McGREGOR D R and MALONE J R
"The Fact Database: a system based on inferential methods", Department of Computer Science, University of Strathclyde, 1981.

4 EDINBURGH REGIONAL COMPUTING CENTRE
"Edinburgh DEC System - 10 Newsletter", Vol. 6, Issue 2, Edinburgh Regional Computing Centre, June 1983, p.9.

5 KERNIGHAN B W and RITCHIE D M
"UNIX Programming - Second Edition", Bell Labs., 12 November 1979.

6 NEWTON S
"ACE: Version 2.1 - A User Manual", ABACUS, 1983.

7 JOHNSON S C
"LINT, a C program checker", Bell Labs., 26 July 1978.

8 NEWTON S
"A Description of the Variables and Unit Rates in ACE: Version 2.1", ABACUS, 1983.

9 MORRISON N and STEVENS S
"A Construction Cost Data Base", Chartered Quantity Surveyor, June 1980, pp.313-315.

10 ASHWORTH A
"The Source, Nature and Comparison of Published Cost Information", Building Technology and Management, March 1980, pp.33-37.

11 WESSEX (ELECTRONIC) PUBLISHING LTD
"Comprehensive Building Price Book 1983/84", First Edition, Wessex (Electronic) Pubs., 1983.

12 E & F N SPON LTD
"Spons Architect's and Builder's Price Book", 105th Edition, E & F N Spon Ltd., 1980.

13 SUSSOCK H
"GOAL (General Outline Appraisal of Layouts) Version2.7: User Manual", ABACUS Occasional Paper No. 62, ABACUS, August 1982.

14 BATHURST P E and BUTLER D A
"Building Cost Control Techniques and Economics", Heineman, 1973.

15 MOONEY J
"Cost Effective Building Design", New South Wales University Press, 1983.

16 ZAHRY M
"Capital Cost Prediction by Multi-Variate Analysis", MSc Thesis (unpublished), University of Strathclyde, 1982.

17 MARANZANO J F and BOURNE S R
"A Tutorial Introduction to the ADB", Bell Labs., 5 May 1977.

CHAPTER SEVEN: AN INVESTIGATION OF COST RELATIONSHIPS AND COST THRESHOLDS USING ACE

CHAPTER SEVEN: AN INVESTIGATION OF COST RELATIONSHIPS AND COST THRESHOLDS USING ACE

7.1 The Strategy

The validation exercise undertaken in Chapter 6, Section 6.3, served only to verify that the general approach to cost modelling outlined in Part One was appropriate, and that the specification developed in Chapter 5 was practicable. It was noted however that the 'knowledge' currently embodied within ACE merely represents the very limited experience of the author. In consequence any 'results' produced by the model should not be taken as de facto, but must be assessed in the light of greater experience, and by interrogating the anterior logic and possibly less compound relationships of those variables and unit rates which compose the said 'results'.

The following investigation is intended to exemplify the range of detail at which such interrogations might be undertaken using the ACE simulation model; and thereby, hopefully, to illustrate the inordinate variability of cost relationships and cost thresholds with respect to their context. The intention is most definitely not to identify some 'optimum' building configuration nor equally to suggest that some particular cost relationship will be universally applicable. A significant observation is that cost relationships are probably as bespoke as design itself.

Figure 7.1 illustrates the sequencing of the cost relationships investigated, and how each is related. It will be seen that an attempt has been made to span a reasonable proportion of the overall solution space, while retaining some degree of cohesion through having each 'slice' of the cost terrain intersect at some point with a previous relationship - this reflects also the way a designer might iterate around a particular design proposal.

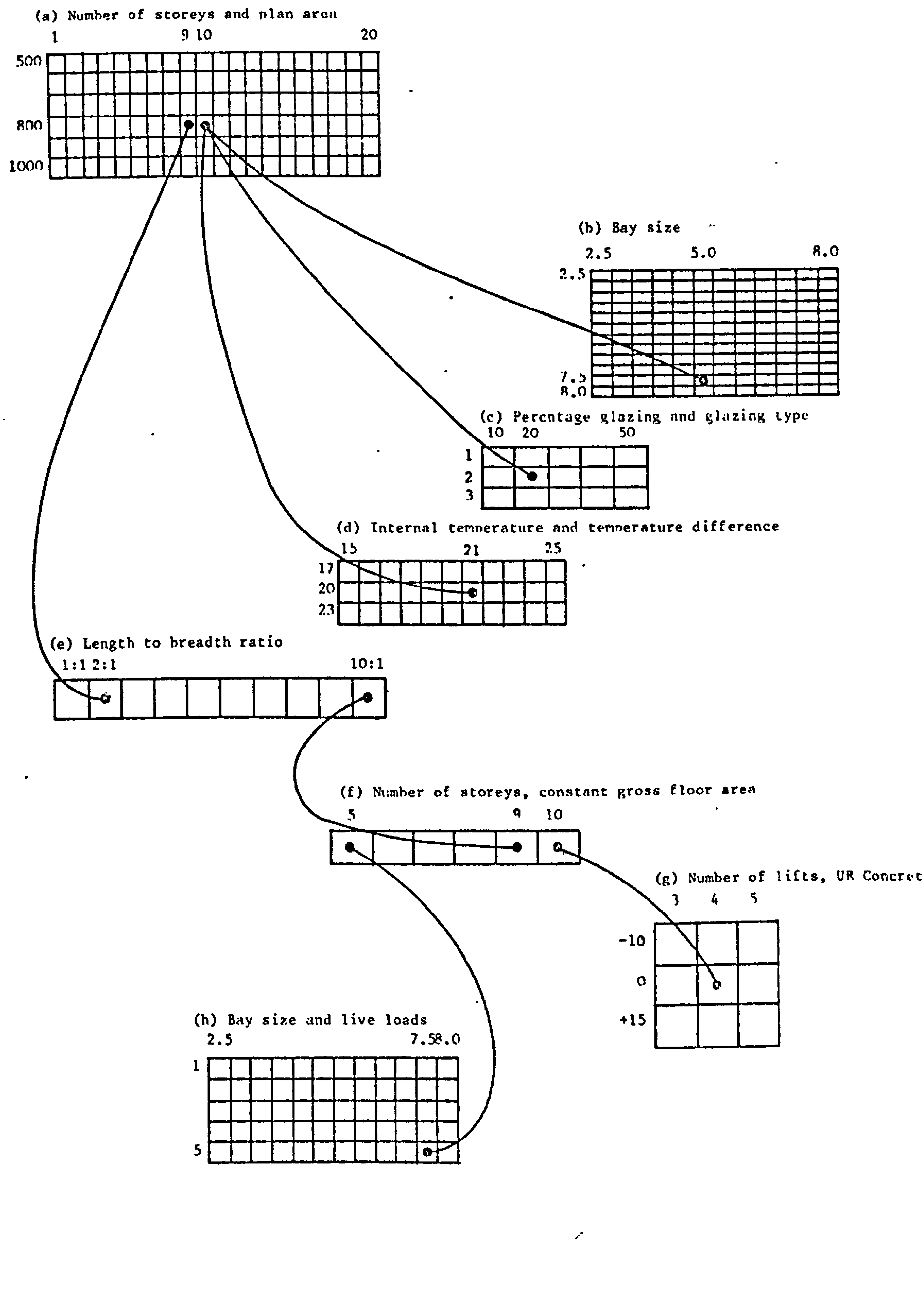


Figure 7.1: The sequence of cost relationships investigated

7.2 Common Characteristics

By its very nature, the detailed 'image' projected by ACE will change as each design alternative is proposed. This is natural when dealing with variables or unit rates which have many dependencies; or in other words, when dealing with variables or unit rates which form part of the contextual description for subsequent variables or unit rates (simply to change the number of storeys in a building without also re-determining the number of lifts, the length of ductwork, the size of foundations, etc. is unacceptable - the full extent of these dependencies is illustrated in Appendix VII). Most of the alternatives considered however largely can be equated with a 'typical' image, and rather than attempt the arduous task of detailing the specification projected for each alternative, a general set of common characteristics is described. In any case it is not intended that the details projected by ACE should impose or even should suggest a solution to the designer, but merely indicate the assumptions inherent in the results it produces.

Example details are taken from the image projected given the following inputs:

* building type - offices
* building framed - yes
* plan area - 800 m2
* number of storeys - 10
* length to breadth ratio - 2:1

The simplicity of the geometries produced by ACE in this case, is illustrated in Figure 7.2; a hidden-line perspective generated from the 'geometry' relationship in the project data base, by the program BIBLE (1).

Each surface of each space in the geometry is allocated a particular construction type dependent on whether it is a floor, ground floor, roof, internal wall or external wall. The allocations made, along with their associated properties, are shown in Table 7.1.

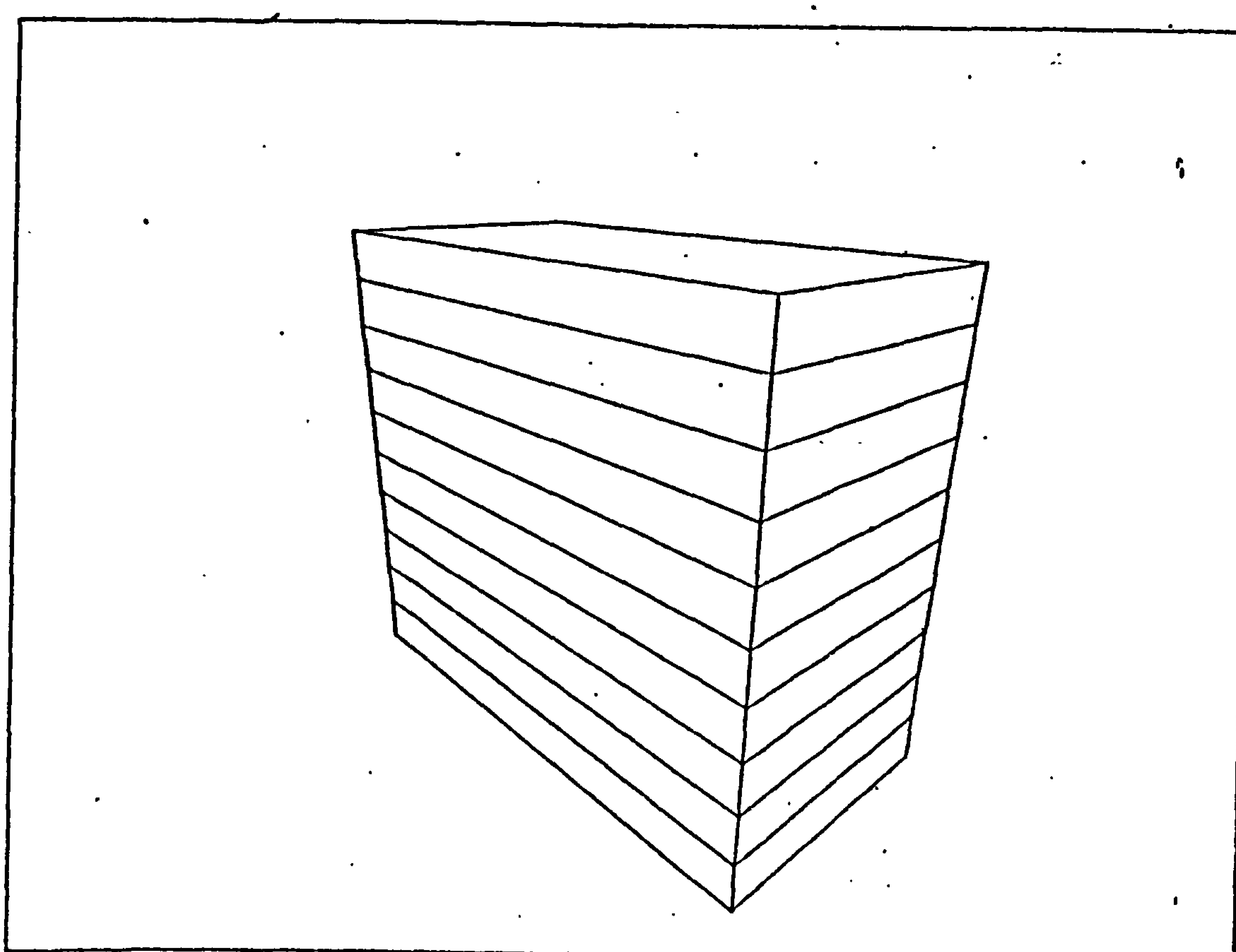


Figure 7.2: A 'typical' geometry

SUBSTRUCTURES:

Foundations:
Pad foundations (poor soil) - U-value=0.5

SUPERSTRUCTURE:

Floors:
Insitu concrete - compressive strength=21 N/mm2, U-value=0.5

Roof:
Insitu concrete, mastic covering - compressive strength=21 N/mm2
U-value=0.5

External walls:
1.5 B Cavity brickwork, faced - U-value=1.0, density factor=25

Internal walls:
0.5 B Blockwork

Glazing:
Hardwood frame, 'solar' glass - U-value=4.0, admitance=0.5,
size=1.5x0.75m

Doors:
Single flush 0.5hr. - size=1.8x1.08

FINISHES:

Floor:
Granolithic

Walls:
Painted gypsum

Ceiling:
Painted gypsum

Table 7.1: The construction specification

A similar procedure is followed for the environmental specification of each space. The result is shown in Table 7.2.

Table 7.3 shows the values determined for each variable; and Table 7.4, those for each unit rate.

These tables, taken directly from the project data base and solution files produced by ACE, may be considered as the starting point: the initial hypothesis from which subsequent alternatives propagate.

7.3 The Investigations

The relationships selected for study, aim to represent a variety of levels of detail - from the general scale and massing of the building, to specific aspects of glazing types, internal air temperature, and even the unit rate for concrete.

The graphs, etc., are intended in this thesis simply to illustrate the complexity of cost relationships and to establish certain causal effects. In all cases the relationships have been expressed in terms of cost - as ACE is foremost a cost model - but without explicitly labelling the vertical axis. This emphasis on being non-specific is made to concentrate attention on the lushness of cost information inherent within a model such as ACE (see also Appendix VII).

7.3.1 Number of storeys and plan area

This was the same investigation as undertaken in Chapter 6, Section 6.3.4, as part of the validation exercise. Figure 7.3 shows how the relationships vary for different contexts and clearly indicates the low cost solutions as dips and ravines in the overall cost terrain. The contextual dependency of this terrain makes it extremely difficult to discern a singular cost relationship either height nor plan area. However, by viewing the terrain at an angle of 90 degrees, a 'band' of relationships is formed having a greater concentration of lines towards the bottom edge (see Figure 7.4(a)).

Frame:
Insitu concrete - compressive strength=21 N/mm2, weight=0.6t/m3

Lifts:
Capacity=12 people, speed=1.50 m/sec

Sanitary:
High quality WC's, urinals and wash basins

Water services:
Basic quality fittings

Heating and AC:
Gas radiators, with high quality controls - 600 mm high

Electrical:
Sheath cable, florescent tubes, basic fire alarm - power=65W,
light output=3250 lumens

Preliminaries:
10% Insurance premium, tower crane - size=60-150 m/t

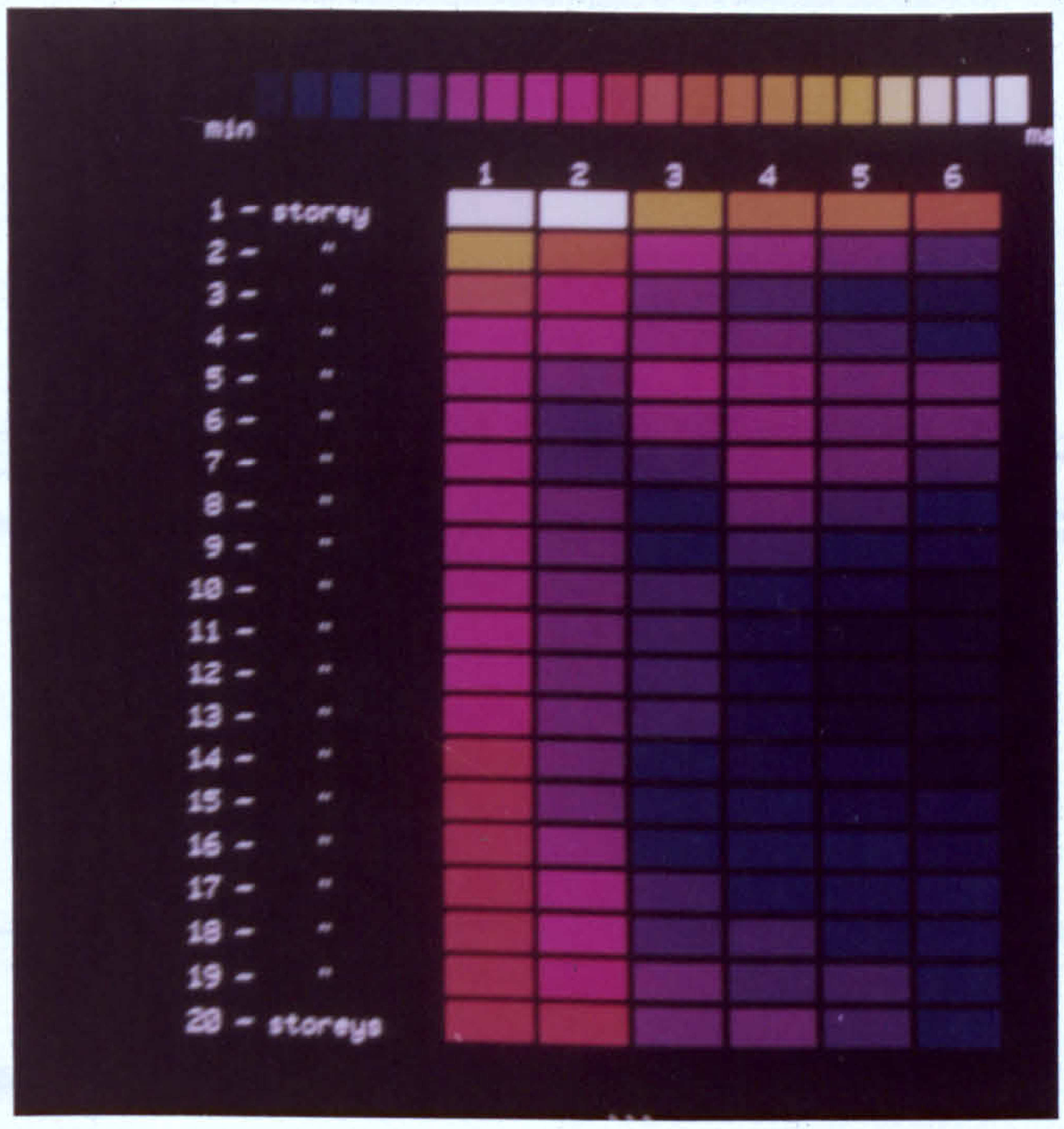
Table 7.2: The environment specification

Variable No.	Description	Value	Variable No.	Description	Value
1	No. occupants	1231	57	Excavation perimeter area (m2)	18.8
2	No. toilets	59	60	POP ratio	0.8
3	No. wash basins	59	61	No. light fittings	1231
4	Internal wall area (m2)	1665.0	63	No. outlet points	600
5	Gross floor area (m2)	8000.0	64	No. emergency lights	160
6	Ceiling area (m2)	8000.0	65	No. fire alarm points	80
7	No. storeys	10	66	Area of doors (m2)	155.5
8	No. of windows	720	67	Secondary beam width (mm)	175.0
9	Secondary beam length (m)	2000.0	68	Plan length (m)	40.0
11	No. doors	80	69	Plan width (m)	20.0
15	Column dimensions (mm)	268.2	70	Bay length (m)	7.5
16	Storey height (m)	3.5	71	Bay width (m)	5.0
17	Plan perimeter (m)	120.0	73	Main beam depth (mm)	375.0
18	Area external walls (m2)	4200.0	74	Lighting level (lumens)	500.0
19	No. corners on walls	4	75	Secondary beam depth (mm)	375.0
20	Roof thickness (mm)	350.0	76	Area of glazing (m2)	840.0
21	Roof area (m2)	800.0	77	Total floor load (N/mm2)	11.0
22	Roof live loads (N/mm2)	4.0	78	Total roof load (N/mm2)	10.0
23	Roof length (m)	40.0	79	Building height (m)	35.0
24	Roof width (m)	20.0	80	Total beam volume (m3)	214.4
25	Slab span (m)	7.5	85	Total room perimeter (m)	2400.0
27	Contract duration (weeks)	85.0	86	Floor to ceiling height (m)	2.8
28	Cranage size (m/t)	120.0	87	Main beam width (mm)	175.0
31	Plot ratio	10.0	88	Number of lifts	4
32	Perimeter of site (m)	120.0	89	Length to breadth ratio	2.0
33	Site area (m2)	800.0	90	No. urinals	20
34	Plan area (m2)	800.0	93	Floor thickness (mm)	350.0
35	Time of year (week no.)	21.0	94	Main beam length (m)	1266.7
37	Live loads (N/mm2)	5.0	95	Cold water cisterns (litres)	45547.0
39	Number of columns	32	97	Hot water tanks (litres)	5662.6
40	Total load of building (N/mm2)	116.1	99	No. Hot & cold water stacks	2
41	Hot water load (kW)	1477.2	100	Area radiators (m2)	314.9
42	Diameter soil & vent pipes (mm)	150.0	101	Heat loss (kW)	14868.8
43	Length soil & vent pipes (m)	455.0	104	External air temperature (°C)	-1.0
45	Total electric load (kW)	8121.5	107	Delivery rate for c.w. (lit/s)	12.7
46	No. distribution boards	10	108	Delivery rate for h.w. (lit/s)	1.6
47	Volume of building (m3)	28000.0	110	Length heating pipe/floor (m)	240.0
48	Length busbar (m)	320.0	111	No. Heating pipes/circuit	1.
50	Length under-floor ducting (m)	1600.0	118	Heating boiler (W)	19319.7
51	No. outlet boxes	533	119	Calorifier capacity (W)	17842.5
52	Column base area (m2)	5.8	120	No. auto-controls, radiators	157
53	Soil bearing pressure (N/mm2)	50.0	121	Environmental design temp. (°C)	20.0
54	Column base volume (m3)	7.0	124	Heat output by lights (W)	80015.0
55	Excavation volume (m3)	18.4	125	No. heating circuits/floor	4
56	Column base perimeter area (m2)	11.6	126	Length each heating circuit (m)	60.0

Table 7.3: The variables determined

Unit rate	Description	Value
1	Base concrete (m3)	47.71
2	Base excavation (m3)	25.93
3	Base formwork (m2)	9.19
4	Base earthwork support (m2)	6.81
5	Fabric reinforcement (m2)	2.63
6	Roof concrete (m3)	46.95
7	Slab formwork (m2)	20.81
10	Flat roof coverings (m2)	7.97
17	Sanitary pipework (m)	45.24
18	WC appliances	64.10
19	Ceiling finishes (m2)	4.60
20	Wall finishes (m2)	5.55
21	Glazing (m2)	30.54
22	Window frames	97.31
23	Doors	39.32
25	Labour to brickwork (m)	2.91
26	0.5 B Brickwork walls (m2)	10.64
27	1.0 B Brickwork walls (m2)	35.23
28	Formwork to walls (m2)	13.12
29	Bar reinforcement (m2)	1.83
30	Concrete walls (m2)	11.18
32	Security (m)	50.38
33	Accommodation and welfare (week)	161.37
35	Site staff (week)	1172.50
36	Plant (week)	1098.00
40	Water and power (week)	3.15
41	Floor finishes (m2)	5.05
45	Forming cavity (m2)	0.62
46	Lifts	41876.44
49	Slab concrete (m3)	58.95
53	Concrete beams (m3)	50.12
55	Concrete columns (m)	63.25
56	Formwork to columns (m)	13.25
59	Urinals	293.75
60	Basins	83.75
61	Cold water cisterns	187.50
62	Water pipes (m)	41.25
63	Hot water tanks (litre)	1.09
64	Insulation to pipework (m)	8.53
66	Pressed steel radiators (m2)	20.06
69	Pumps	574.93
77	Main boiler (W)	8.29
78	Heating calorifier (W)	1.65
79	Zone control valves	248.30
80	Radiator controls	22.79
81	Lighting circuits	23.44
82	Electrical outlets	27.19
83	Emergency lighting (point)	146.25
84	Fire alarms (circuit)	475.00
85	Telephone ducts (m)	17.06
86	Electrical controls to plant (total)	4649.31
87	Distribution boards	487.29
88	Busbar (m)	125.00
89	Electrical substation (W)	36.88
90	Telephone outlets	41.88
95	Internal brick walls (m2)	14.31

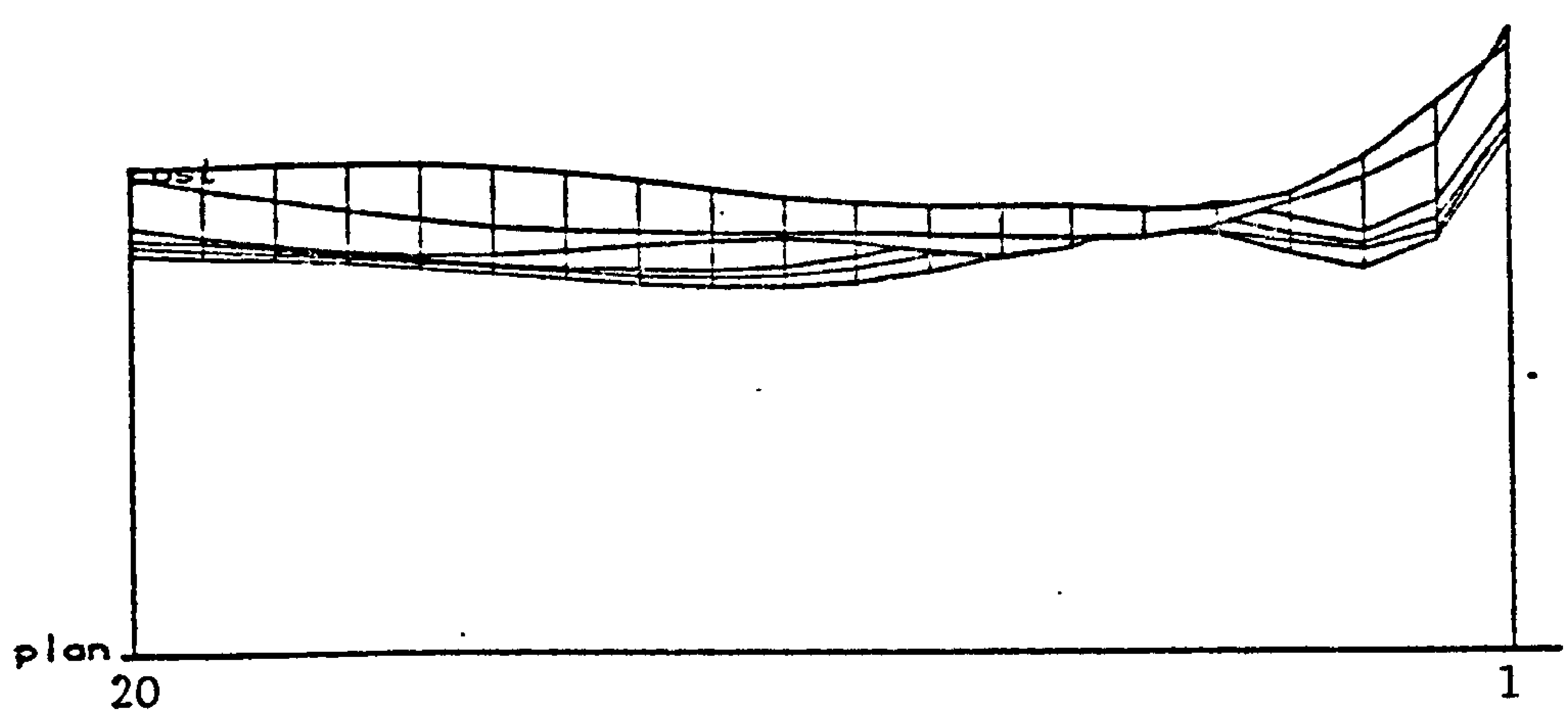
Table 7.4: The unit rates determined



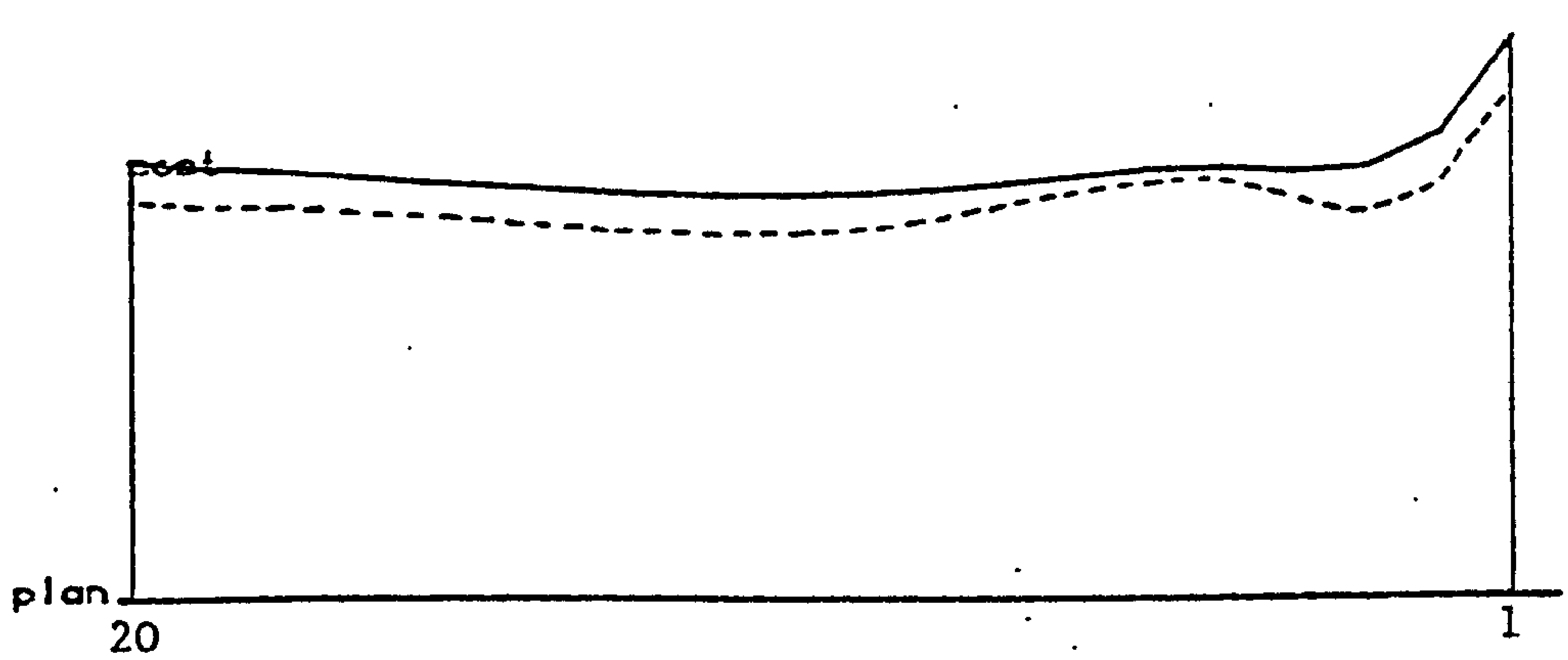
where: 1 = 500 m2 plan area
2 = 600 m2 plan area
3 = 700 m2 plan area
4 = 800 m2 plan area
5 = 900 m2 plan area
6 = 1000 m2 plan area

Figure 7.3: Matrix of number of storeys and plan area

PLAN_v_STOREY
plan ROTN = .0 cost ROTN = 90.0
YSCALE = 1.000 ZSCALE = 50.000



(a) 'Band' of relationships



(b) Average an Pareto relationships

—— AVERAGE
--- PARETO

Figure 7.4: Cost relationship with number of storeys

This 'band' encompasses all of the deviations in the cost relationship with height caused by a variation in the plan area. The width of the band gives an indication of the sensitivity of the relationship to a change in plan area and overall gives a useful impression of the general trends.

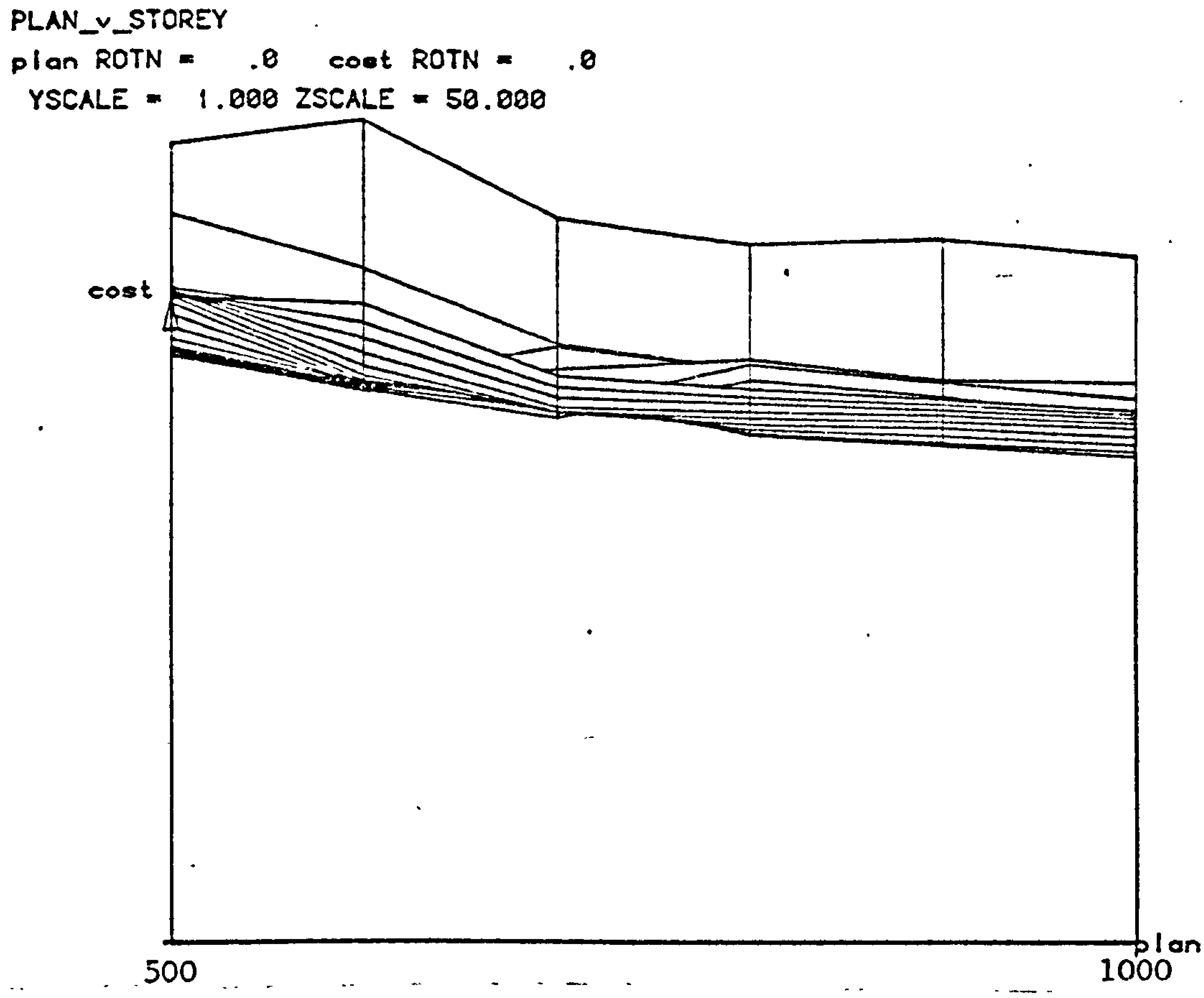
A singular relationship might then be described by the 'average' of these (see Figure 7.4 (b)). An alternatqive to this simplistic (and only of limited use to the designer) approach is a procedure based on the concept of Pareto optimisation (2). Given that the cost relationship with height will vary for changes in the plan area, there is no obvious indication as to which solution should be preferred. A set of all solutions that are not dominated (or bettered) by any other solution no matter what the plan area, will lie along the boundary of the feasible region. They are known formally as the set of non-dominated, non-inferior or Pareto optimal solutions.

In optimisation this concept applies to the set of non-dominated solutions which form a surface in n-dimensional space. In the context of a cost relationship the 'Pareto-line' will provide a useful description of the 'best' solution possible, given any plan area (again see Figure 7.4 (b)). Certainly the Pareto-set is a deal more useful than the somewhat non-descript 'average'.

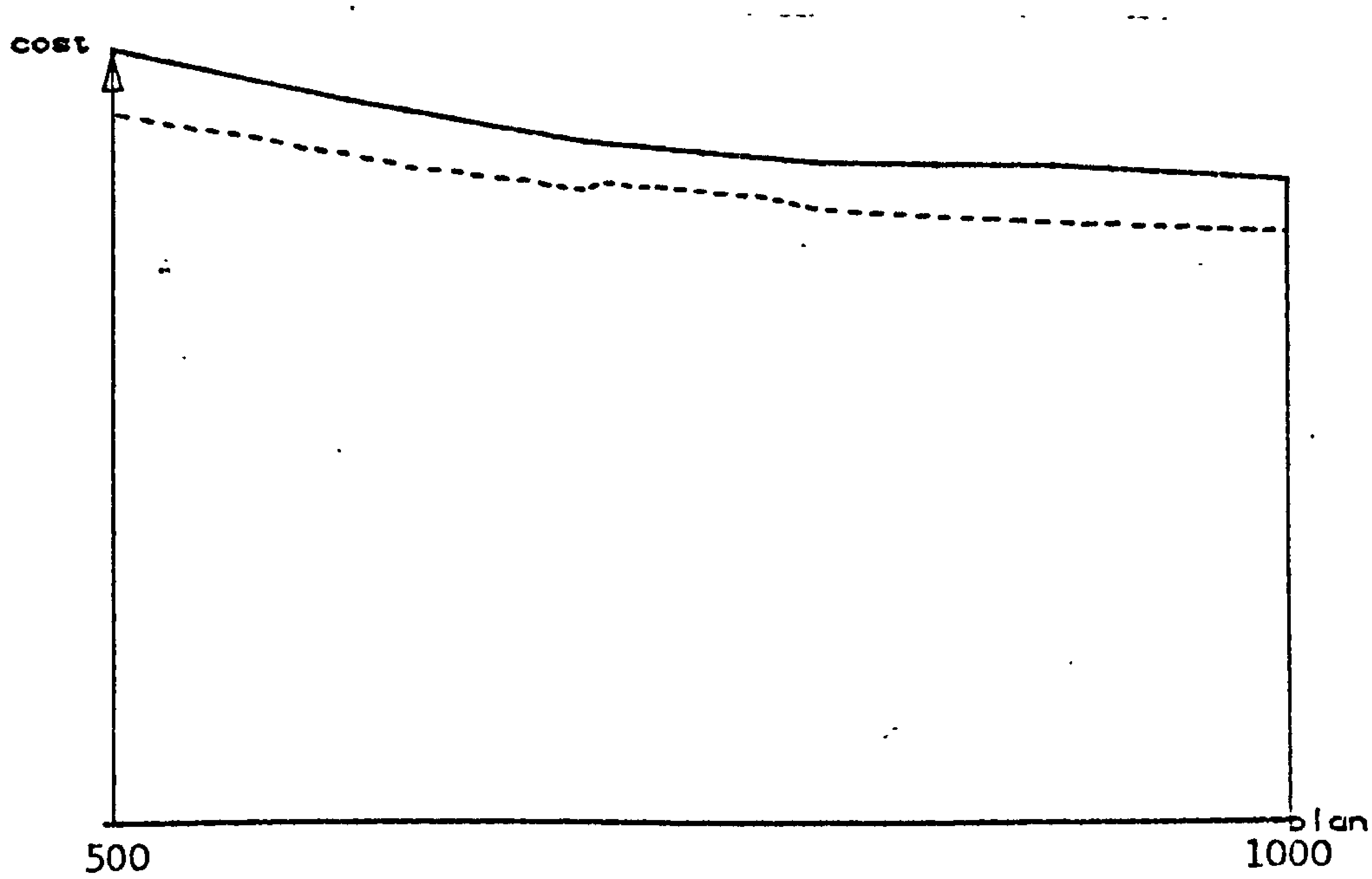
Figure 7.5 illustrates an equivalent exercise for the cost relationship with plan area.

7.3.2 Bay size

The point of departure from the cost terrain formed by varying storey height and plan area, is where the number of storeys is 10 and the plan area is 800 square metres. At this point the bay size as determined by ACE is 7.5 x 5.0 metres.



(a) 'Band' of relationships



(b) Average and Pareto relationships

Figure 7.5: Cost relationship with plan area

The bay size was varied from 2.5 x 2.5 metres in 0.5 metre stages to a 8.0 x 8.0 metre span, for every combination of bay length and bay width - in actual fact, only unique combinations were generated so that a bay size of 3.0 x 6.5 metres was taken as equivalent to a bay size of 6.5 x 3.0 metres (this is not wholly correct, but will suffice in the current situation).

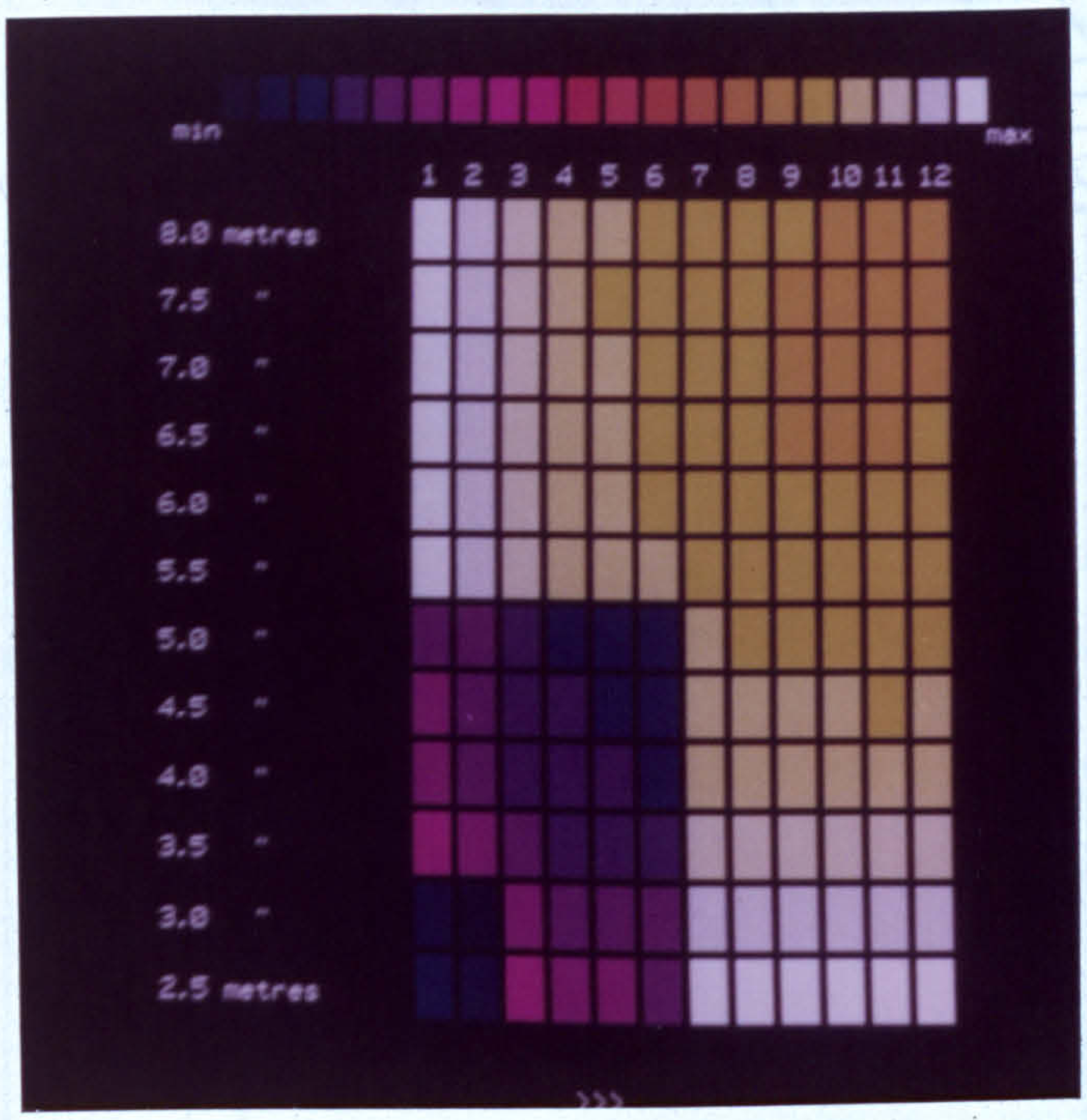
Figure 7.6 illustrates how significant cost thresholds appear at 3.5 and 5.5 metre spans, while in between these the cost tends to fall gradually with increasing span. The scale of the threshold is better illustrated in Figure 7.7.

Taking a slice through the cost terrain so formed, along the line of square bays, the cost relationship for the frame span is given as in Figure 7.8 (a). Again the thresholds are quite marked, and in an attempt to identify the cause of these jumps, the cost per square metre of gross floor area for each of the elements was plotted also (see Figures 7.8 (b) and 7.8 (c)).

Quite significantly the actual cost of the frame falls as the span increases (suggesting that columns are more expensive than beams) except for a kink at the 5.5 metre span.

The variation in floor and roof costs is explained by Figure 7.9 (a) which shows how the thickness of the floor increases from 250 to 350 mm to compensate for additional spans. This has a concomitant effect on the dead weight of the floor.

The average depth (over all floors) of the main beam is determined almost entirely by the span rather than the load it carries and this tends to reduce the area of internal walls commensurably (see Figure 7.9 (b)). The area of internal walls, and therefore the area of finishes, are decreased further at each increase in the depth of the floor slab - i.e. for equal storey heights the floor to ceiling height is progressively reduced.



where: 1 = 2.5 metres
2 = 3.0 metres
3 = 3.5 metres
4 = 4.0 metres
5 = 4.5 metres
6 = 5.0 metres
7 = 5.5 metres
8 = 6.0 metres
9 = 6.5 metres
10 = 7.0 metres
11 = 7.5 metres
12 = 8.0 metres

Figure 7.6: Matrix of bay sizes

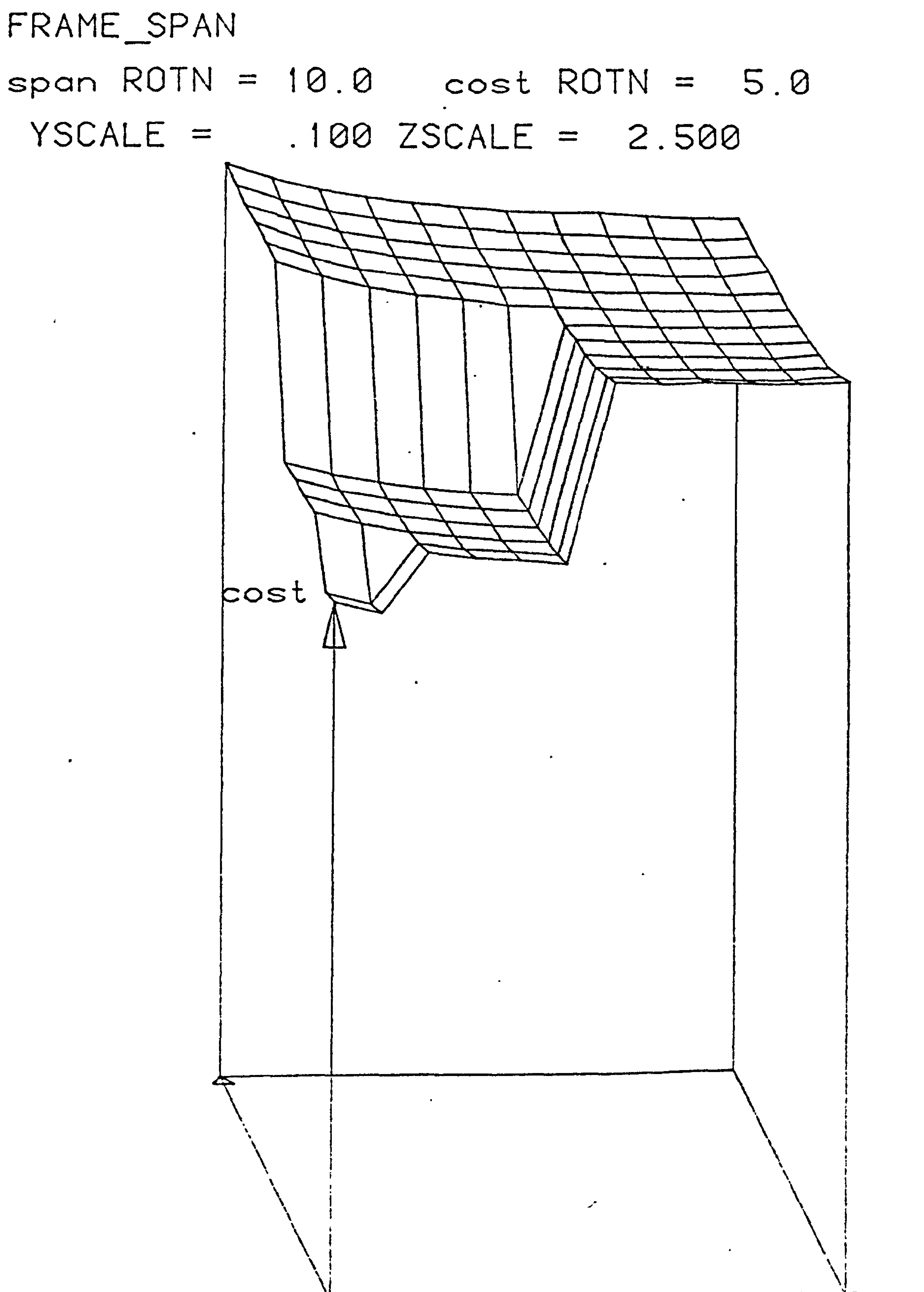
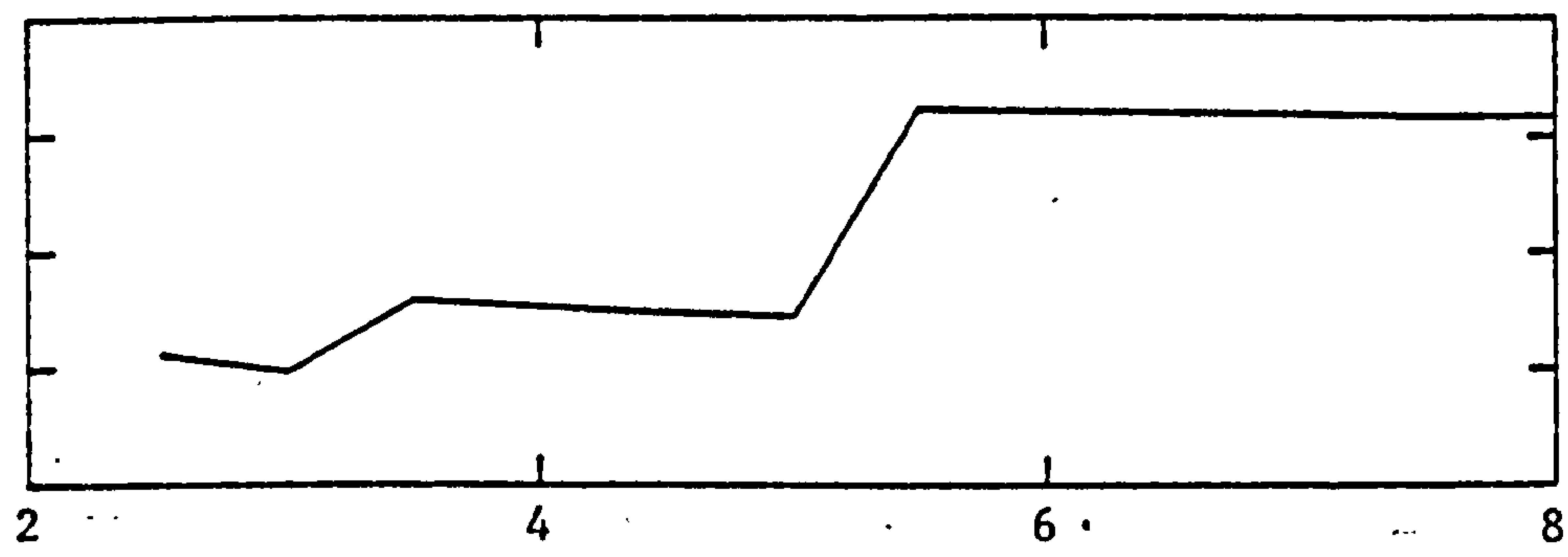
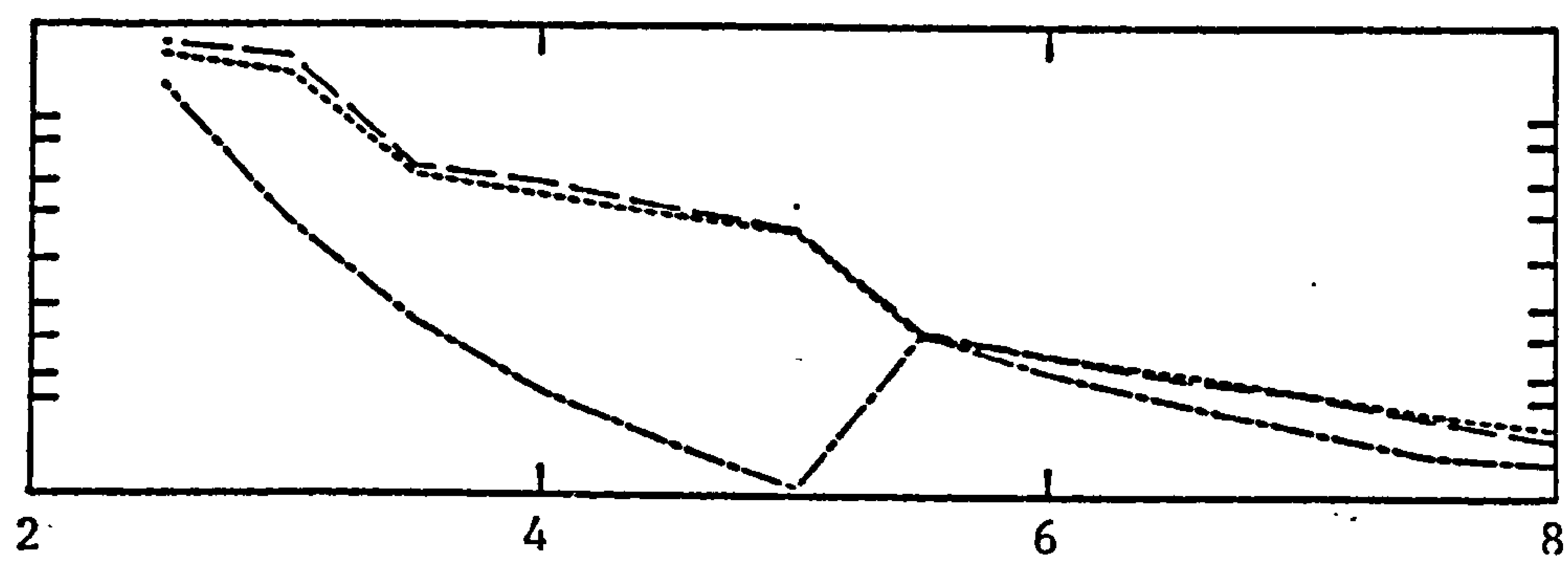


Figure 7.7: Plot of bay sizes

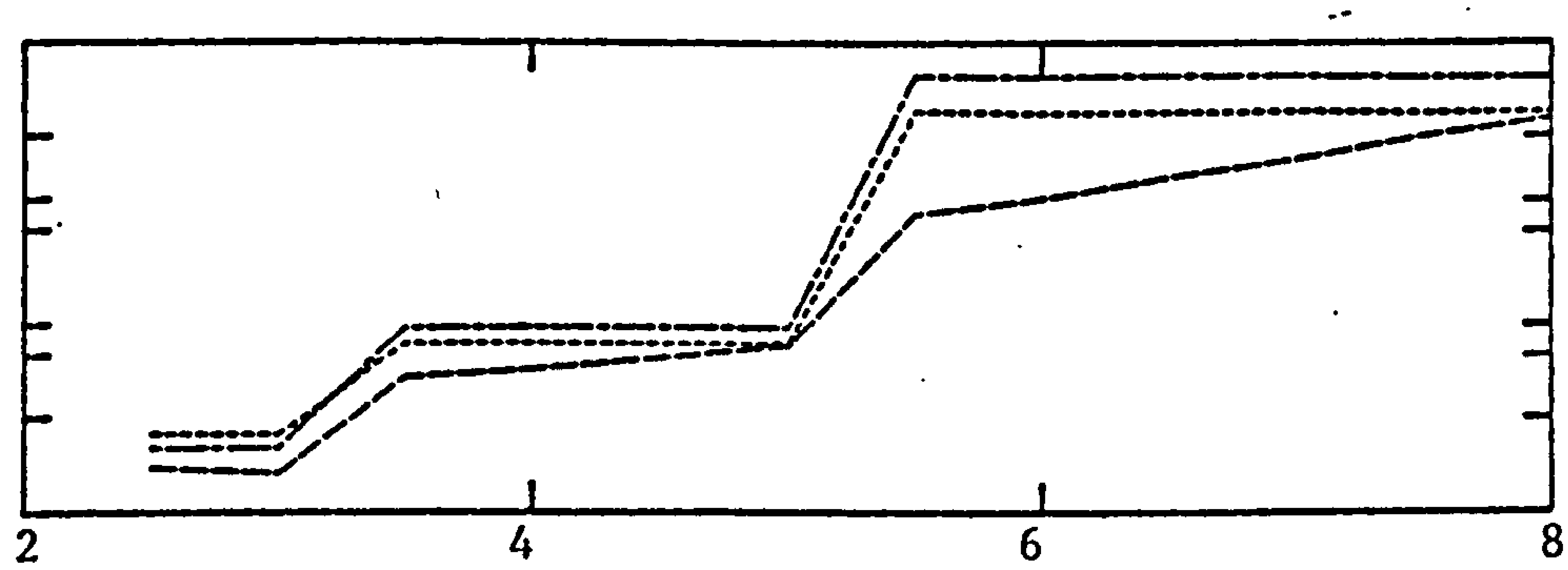


(a) Total cost



(b) Frame, finishes and internal walls elements

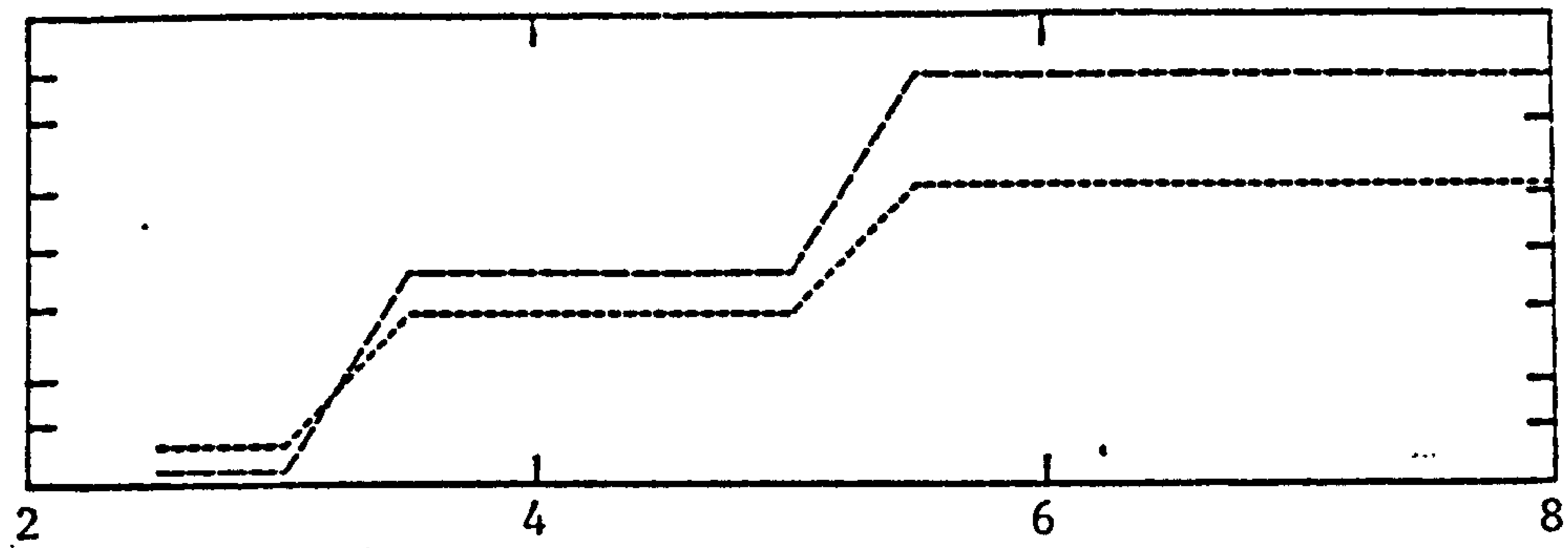
—·— FRAME
······ FINISHES
– – – INTERNAL WALLS



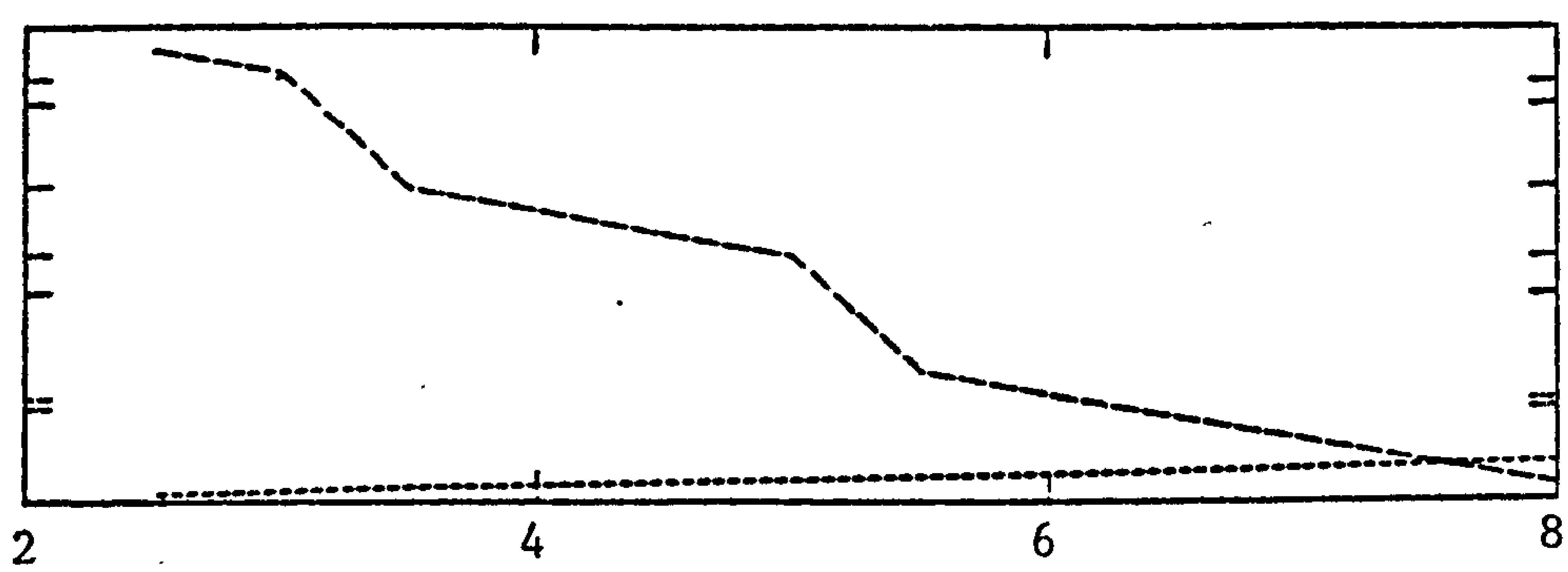
(c) Substructure, roof and floors elements

– – – SUBSTRUCTURE
······ ROOF
—·— FLOORS

Figure 7.8: Cost relationship with bay size (Total and Element cost)



(a) Slab thickness and dead weight



(b) Area of internal walls and main beam depth

Figure 7.9: Cost relationship with bay size (slab thickness and dead weight, area of internal walls and finishes)

Given the increase in total weight of the building and the reduction in the number of columns to carry that weight (see Figure 7.10 (a)), it is natural that the area of each pad foundation will increase, as also will the average size (over all floors) of the columns (see Figure 7.10 (b)). The average column size stays relatively static up to a 5.0 metre span, indeed even begins to decrease slightly, but makes a sharp upturn as the 5.5 metre threshold is reached: thus accounting for the 'kink' in the elemental cost for the frame as a whole.

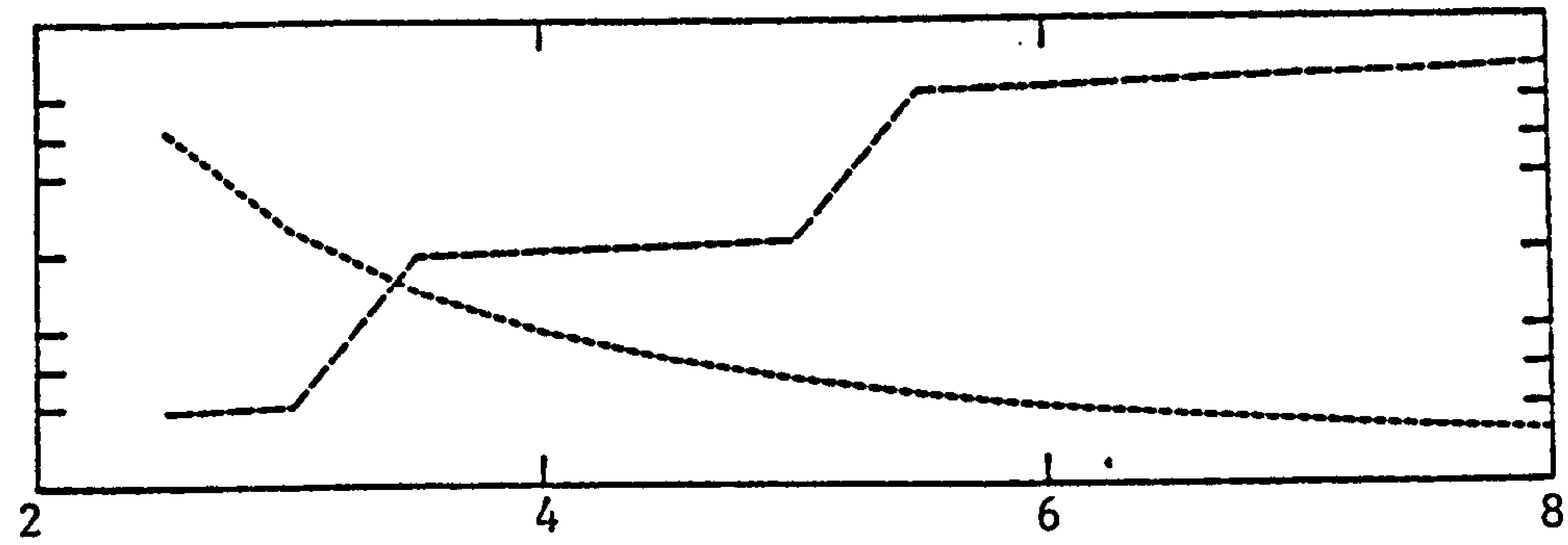
7.3.3 Percentage glazing and glazing type

Taking the same 10 storey, 800 square metre plan area, 7.5 x 5.0 metre bay size and 20 per cent glazing, the percentage of external wall glazed was varied between 10 and 50 per cent. The procedure was then repeated for different window and glazing types, the respective properties being shown in Table 7.5.

The trends illustrated in Figure 7.11 (a) show no great difference between the various glazing types, simply a change in degree. Figure 7.11 (b) shows how the additional cost of glazing over external wall is increased by creating also a greater heat loss, and therefore more expensive boilers, radiators, etc. The full list of dependencies is illustrated in Figure 7.12.

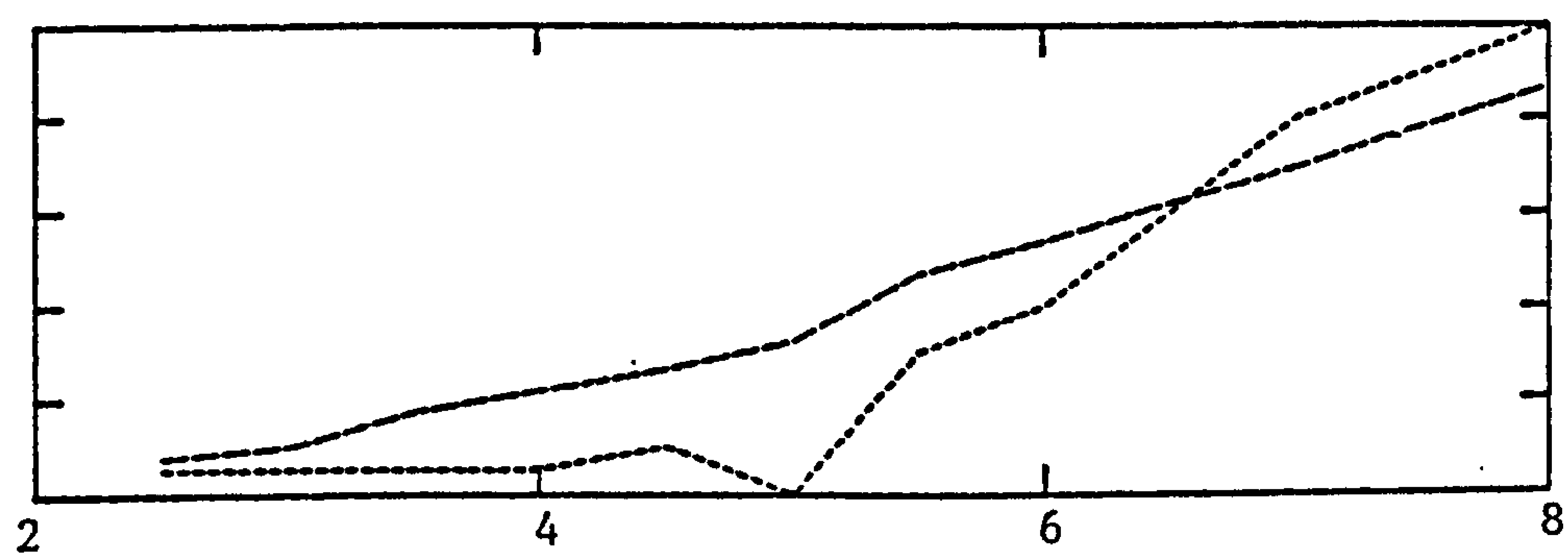
7.3.4 Internal design temperature and temperature difference

The impact of heat loss on cost can be quite significant and is influenced by a variety of factors . An interesting exercise involves changing the internal design and assumed external temperatures. Figure 7.13 (a) shows how the cost relationship of temperature difference is not affected by a change in the internal design temperature until the difference exceeds about 21 degrees, at which point the lower internal design temperatures tend to become less expensive. This is surprising, as ACE uses only a simple 'steady-state' heat loss calculation, and the total heating load will remain



(a) Total building weight and number of columns

— — — TOTAL BUILDING WEIGHT
------- NUMBER OF COLUMNS



(b) Area of column base and column dimensions

— — — AREA OF COLUMN BASE
------- COLUMN DIMENSIONS

Figure 7.10: Cost relationship with bay size (total building weight and number of columns and column dimensions)

1. Softwood window frame, float glass:

U-value = 5.0

admitance = 0.5

width = 1.50 metres

height = 0.75 metres

2. Hardwood window frame, 'solar' glass:

U-value = 4.0

admitance = 0.5

width = 1.50 metres

height = 0.75 metres

3. Metal window frame, toughened glass

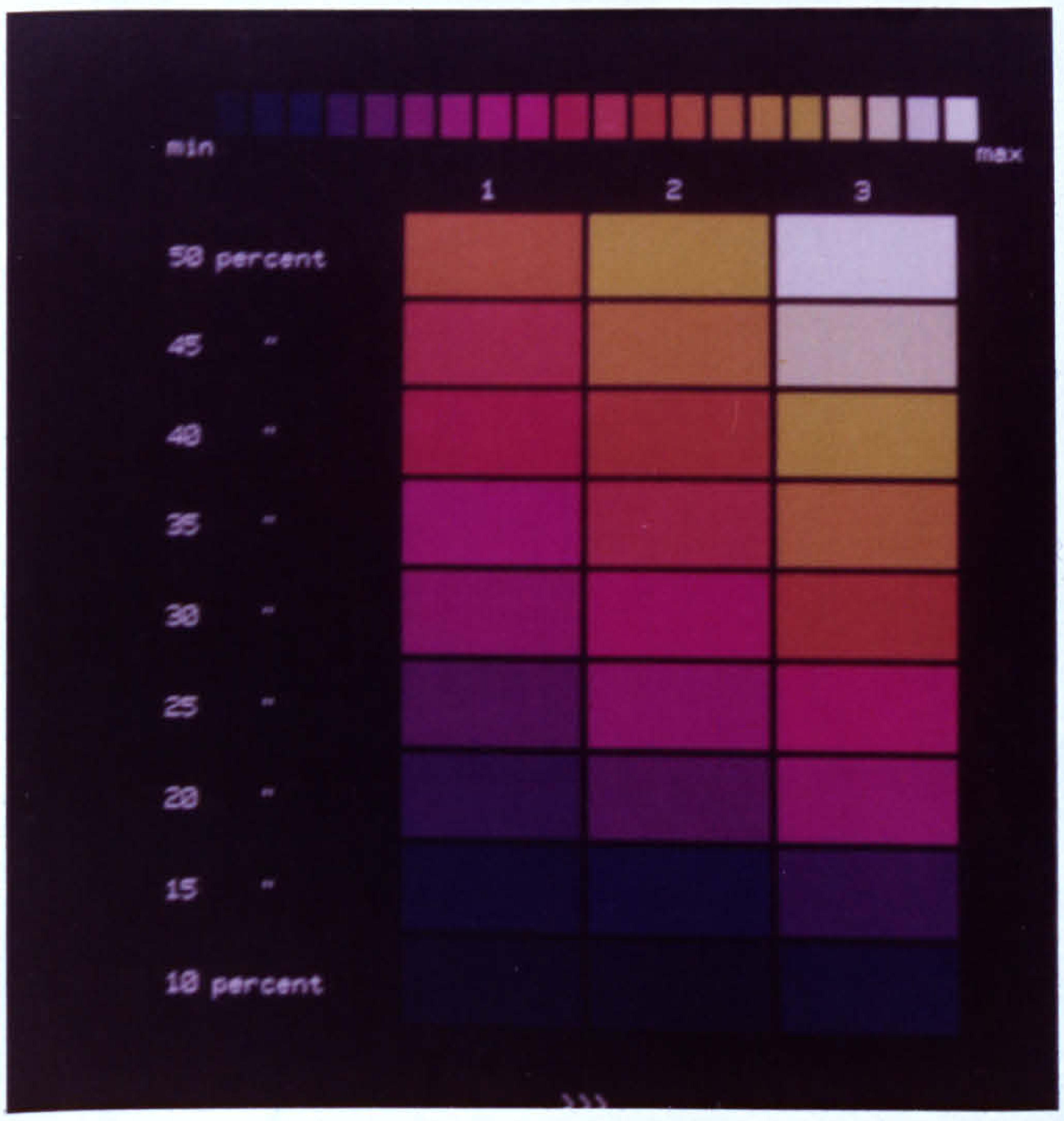
U-value = 5.0

admitance = 0.5

width = 1.50 metres

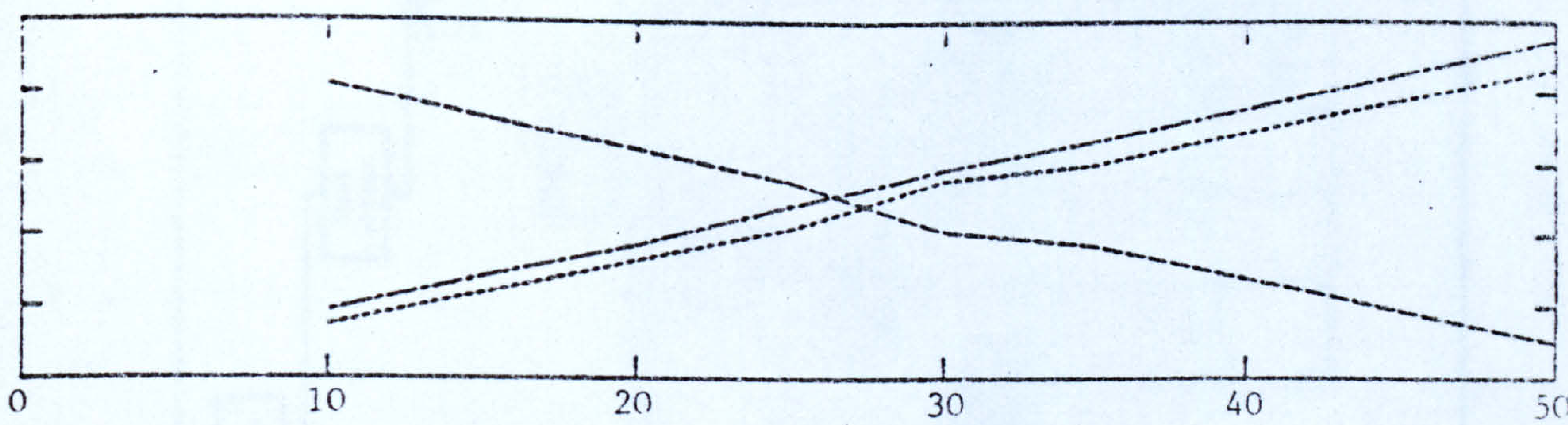
height = 0.75 metres

Table 7.5: Glazing properties



1 = Softwood window, float glass
2 = Hardwood window, solar glass
3 = Metal window, toughened glass

(a) Percentage glazing and glazing type



(b) Glazing, external walls and heating elements

—·—·— GLAZING
- - - - EXTERNAL WALLS
-------- HEATING

Figure 7.11: Matrix of glazing, cost relationship with glazing, roof and heating elements

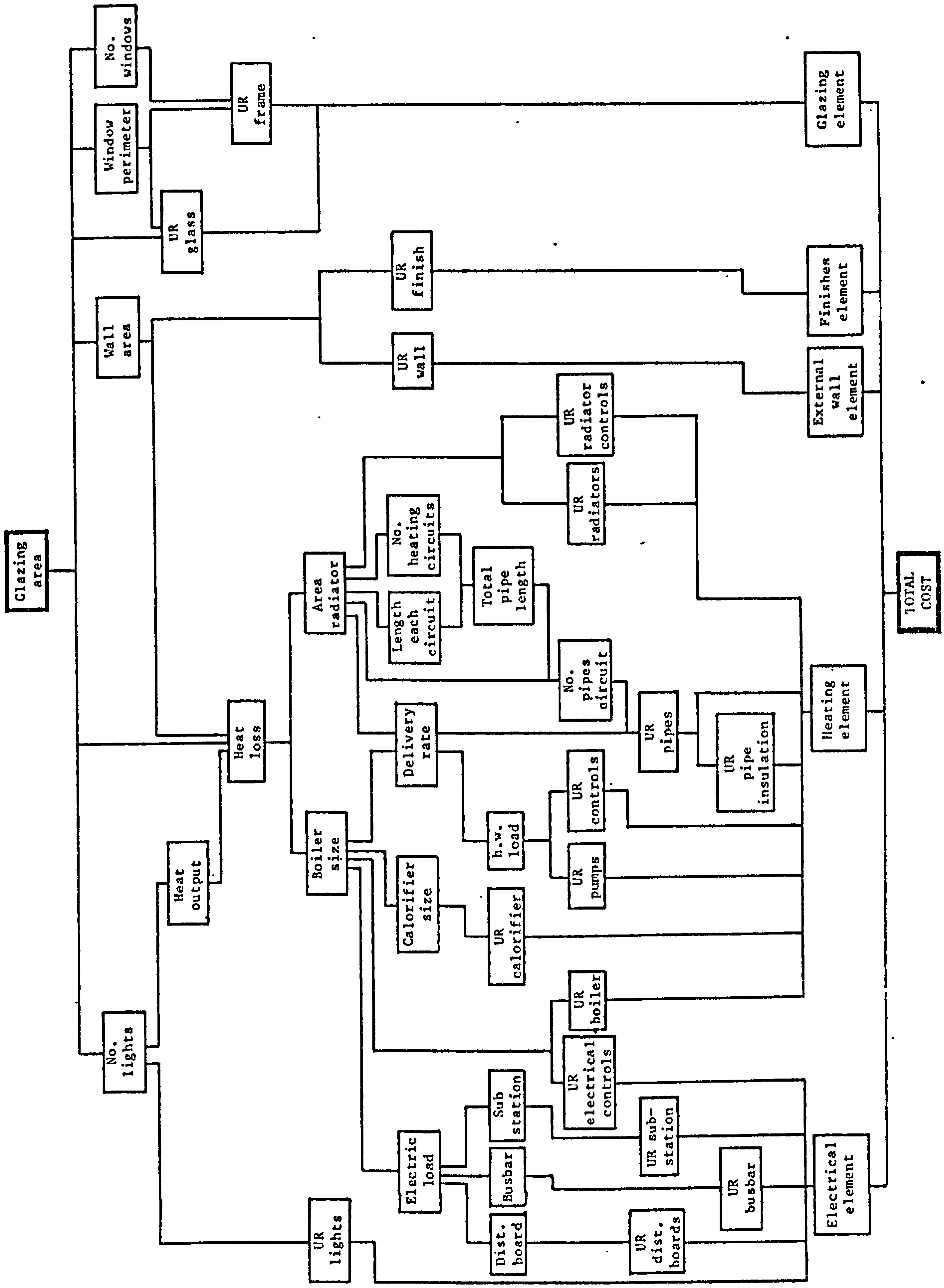
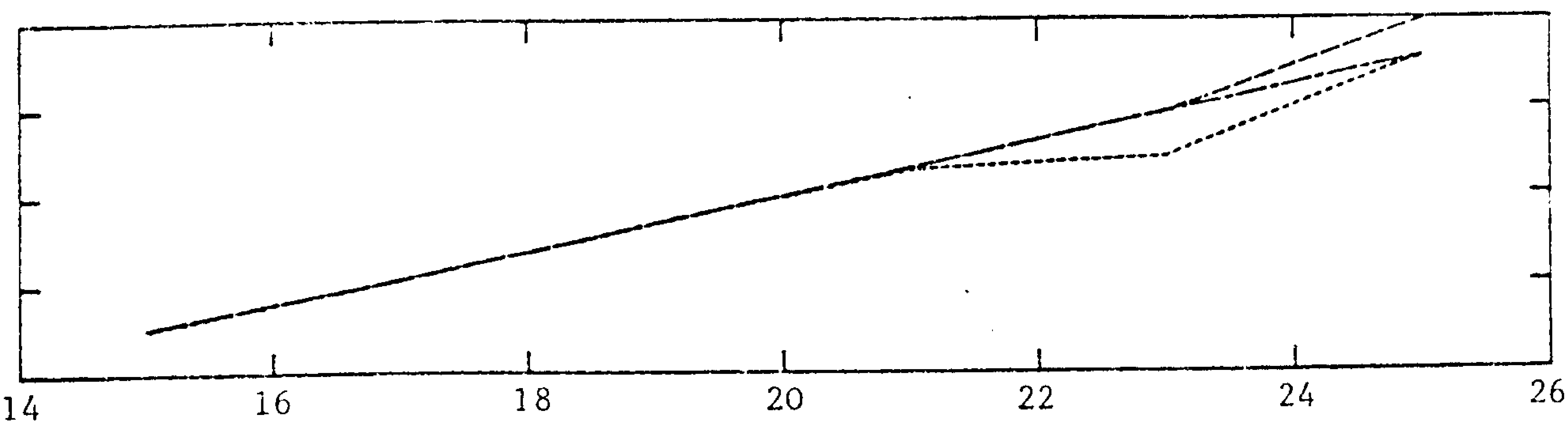
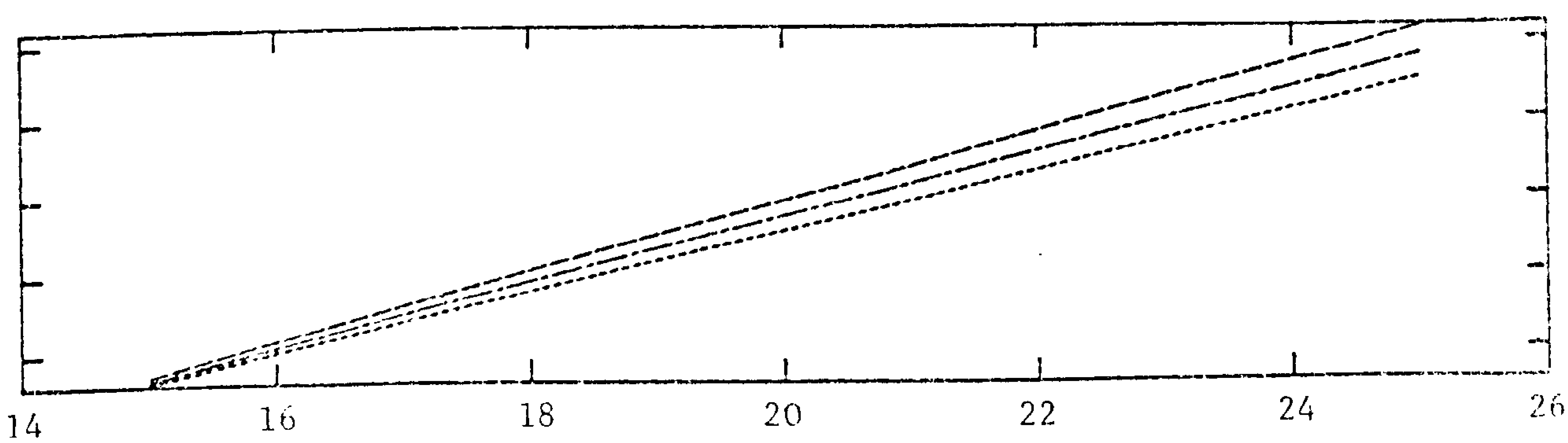


Figure 7.12: Hierarchy of glazing dependencies



(a) Total cost

------ 17 DEGREES
— - — 20 DEGREES
– – – 23 DEGREES



(b) Area of radiators

------ 17 DEGREES
— - — 20 DEGREES
– – – – 23 DEGREES

Figure 7.13: Cost relationship with temperature difference, design temperature and radiators

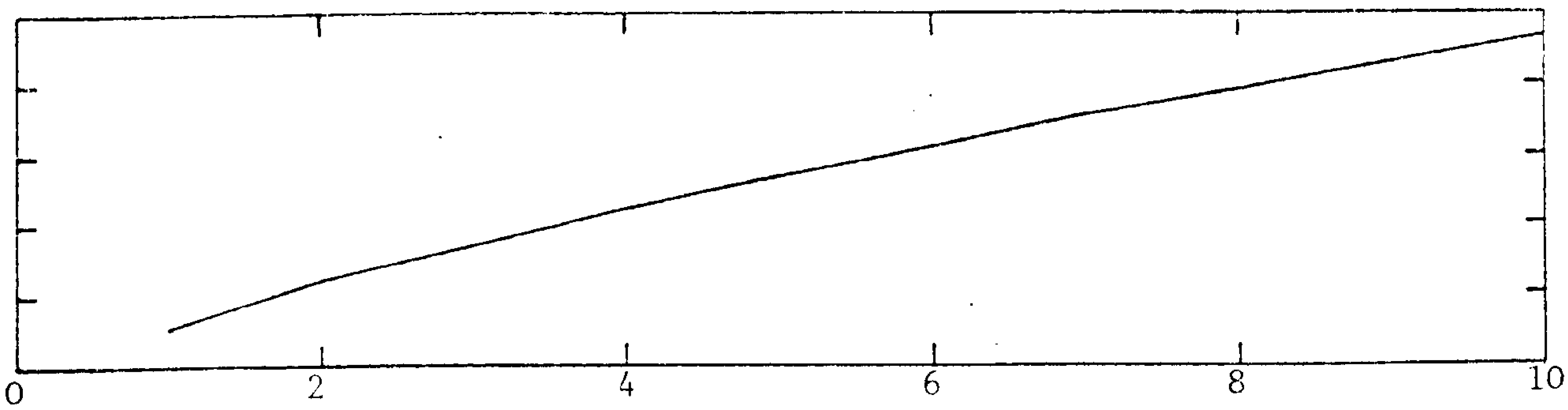
constant for any given temperature difference. The difference in cost is caused by the increasing surface area of radiator required to produce the necessary heat - the higher the internal design temperature the smaller the difference between the input temperature for the radiator and the air temperature; the less efficient is each square metre of radiator surface (see Figure 7.13 (b)).

7.3.5 Length to breadth ratio

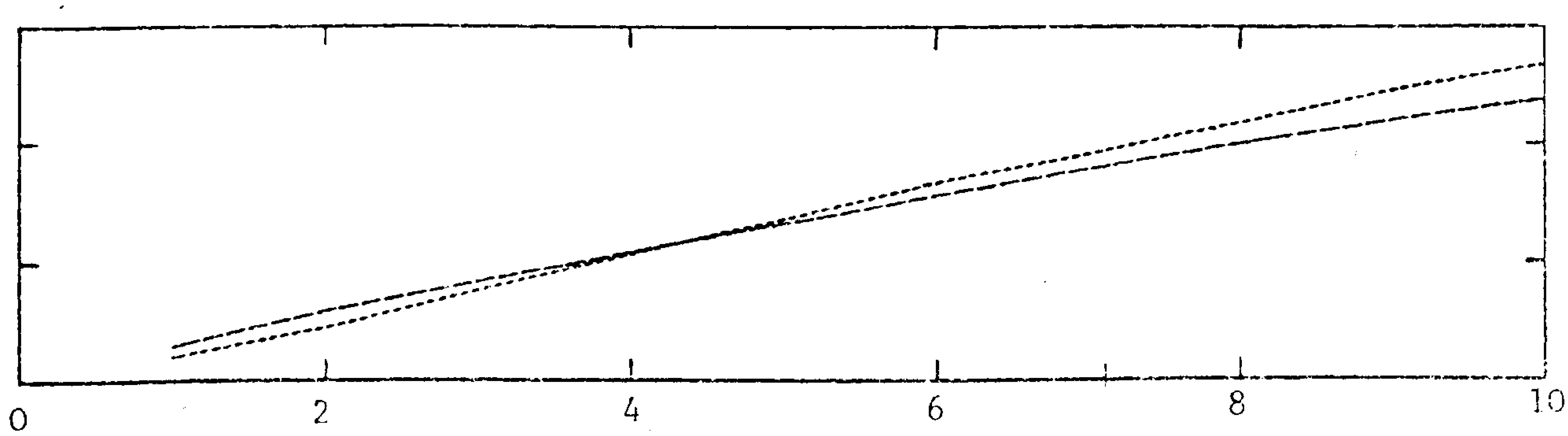
Taking a gross floor area of 8000 square metres, the shape of a 9 storey building was varied between a cube (length to breadth ratio of 1:1) and a length to breadth ratio of 10:1

Figure 7.14 (a) shows how cost increases linearly with the change in shape - the longer the building the greater the external wall area per square metre of gross floor area; the greater the building cost. More interestingly, Figure 7.14 (b) illustrates the cost relationship for the frame and internal partitions' elements. As the building is elongated so both the frame (with more perimeter columns) and the internal partitions (with greater 'travel' distances) become less efficient.

The water services and heating elements (see Figure 7.15 (a)) are similarly affected, although to a lessening degree. Figure 7.15 (b) illustrates the rather sharp increase in preliminary costs between a 1:1 and 2:1 length to breadth ratio. The cost of security (a function of site perimeter length) increases steadily, as might be expected. The unit rate for cranage increases sharply however and is clearly equated with the total cost of preliminaries. The rise does not accord with the more gradual increase in the size of crane required: rather, it reflects a discrete jump from one crane type (size) to the next - the cost then levels out until the next threshold is reached.



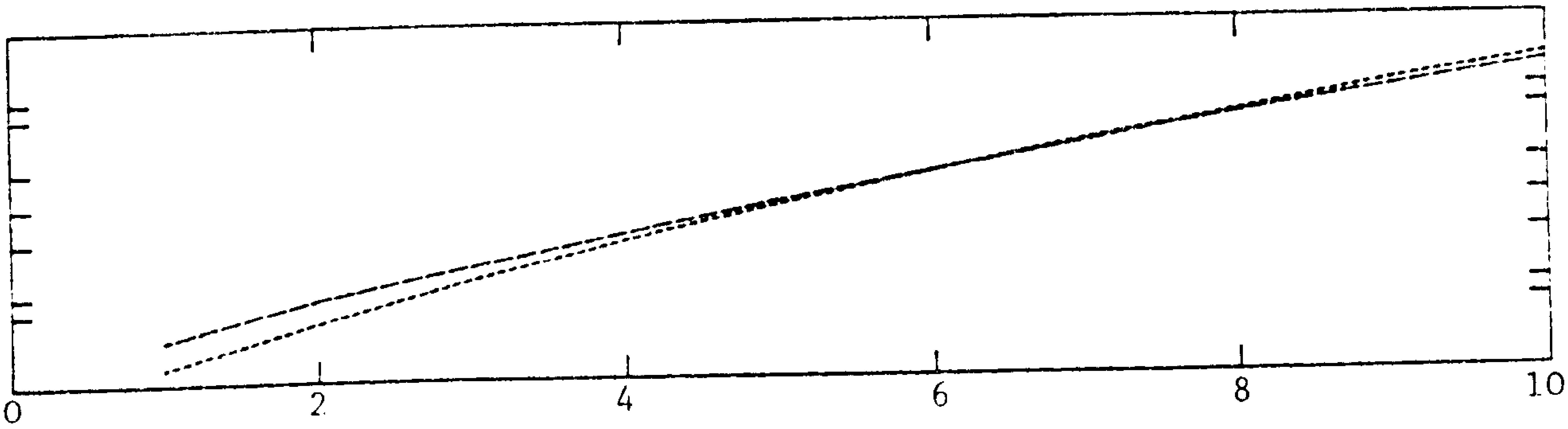
(a) Total cost



(b) Frame and internal partitions elements

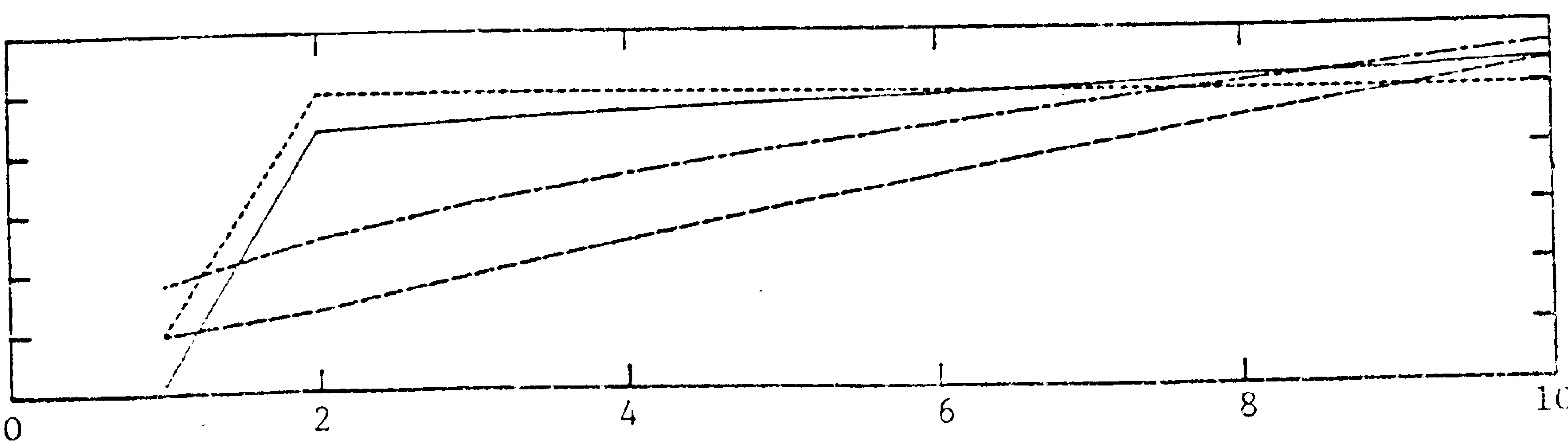
------ FRAME
— — — INTERNAL PARTITIONS

Figure 7.14: Cost relationship with length to breadth ratio (total and frame and internal partitions elements)



(a) Water and heating elements

------ WATER
— — — HEATING



(b) Preliminaries element

——— TOTAL
— — — U.R. SECURITY
------ U.R. CRANAGE
—-— SIZE CRANAGE

Figure 7.15: Cost relationship with length to breadth ratio (water and heating elements, preliminaries element)

7.3.6 Number of storeys for a constant gross floor area

Taking a length to breadth ratio of 10:1 from the previous example, the number of storeys was varied between 5 and 10 for a constant floor area of 8000 square metres. The elemental cost relationships produced were then compared with the equivalent parts of those produced in Section 7.3.1 for a constant plan area of 800 square metres.

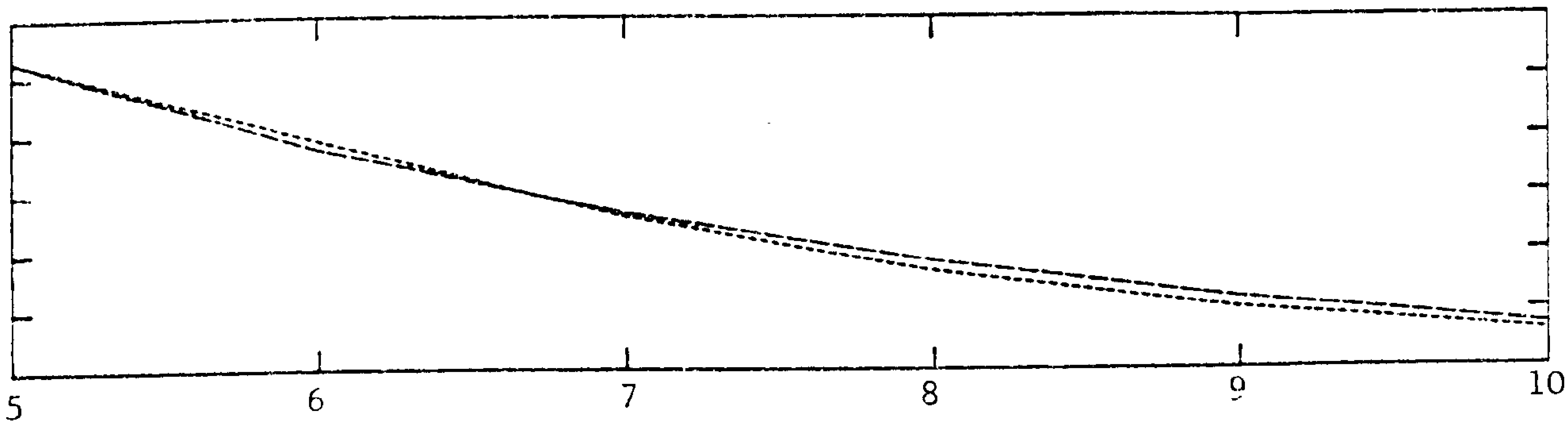
The impact of an additional storey on the cost of the roof element is equivalent for both a constant gross floor area, and a constant plan area (see Figure 7.16 (a)) although the greater proportion of perimeter length in certain situations (i.e. the length to breadth ratio of 10:1 for the constant gross floor area example in this instance) dampens the relationship slightly. Conversely, the cost relationship of substructures is accentuated by the increasing impact of perimeter column bases, etc. (see Figure 7.16 (b)).

Other relationships (see Figure 7.17) show how the smaller plan area associated with an increase in height for constant gross floor area, can increase the costs of services, frame, preliminaries, etc., when they would otherwise remain at a more or less stable level of cost, or even decrease with economics of scale.

7.3.7 Number of lifts and the unit rate for concrete

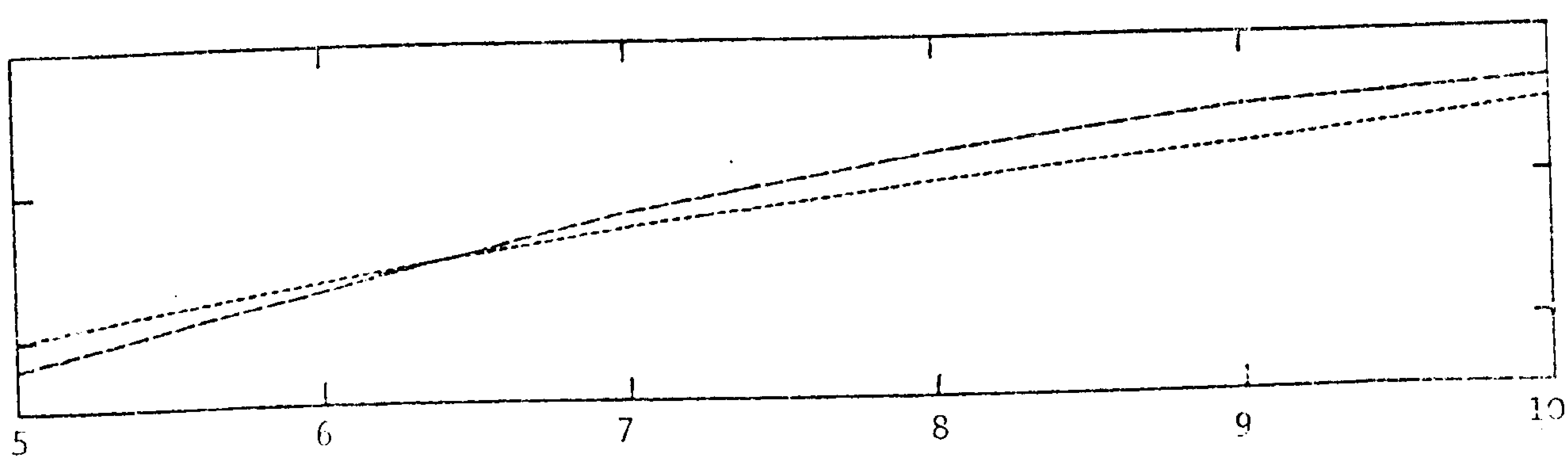
As a sequel to the previous example (Section 7.3.6) it was decided to investigate the effect on the cost relationship with height, of variations in the number of lifts, and of variations in the unit rates for concrete.

Figure 7.18 illustrates the change in cost relationship with height for each combination of having 3, 4 and 5 lifts against a -10%, zero and +15% change in the unit rates for concrete (in beams, columns, lift shafts, foundations, etc.). The relationship is not



(a) Roof element

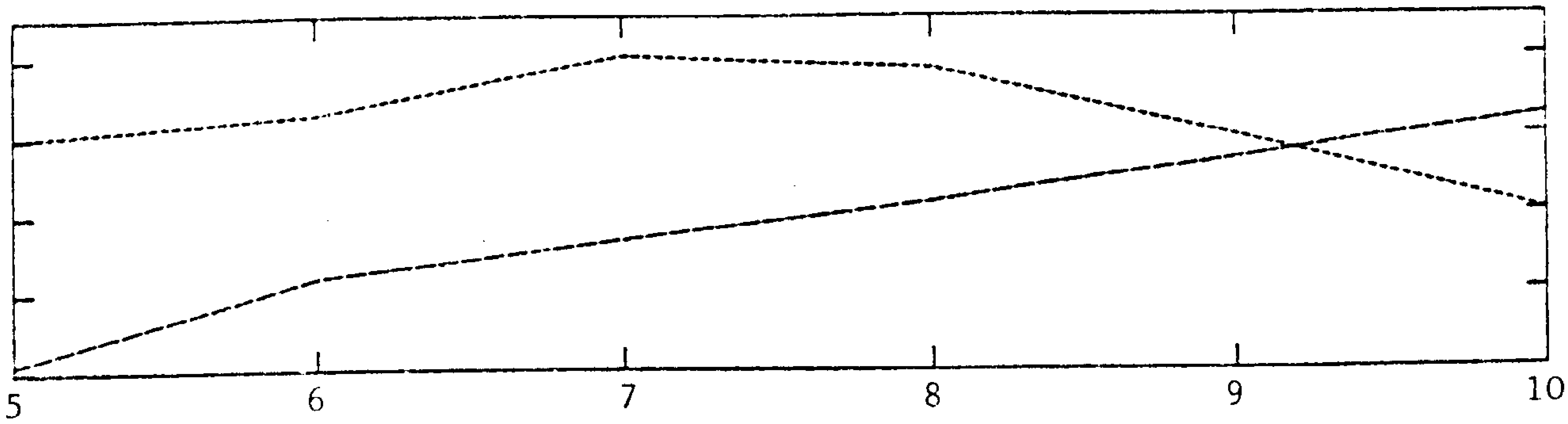
— — — CONSTANT GROSS FLOOR AREA
- - - - - - CONSTANT PLAN AREA



(b) Substructures element

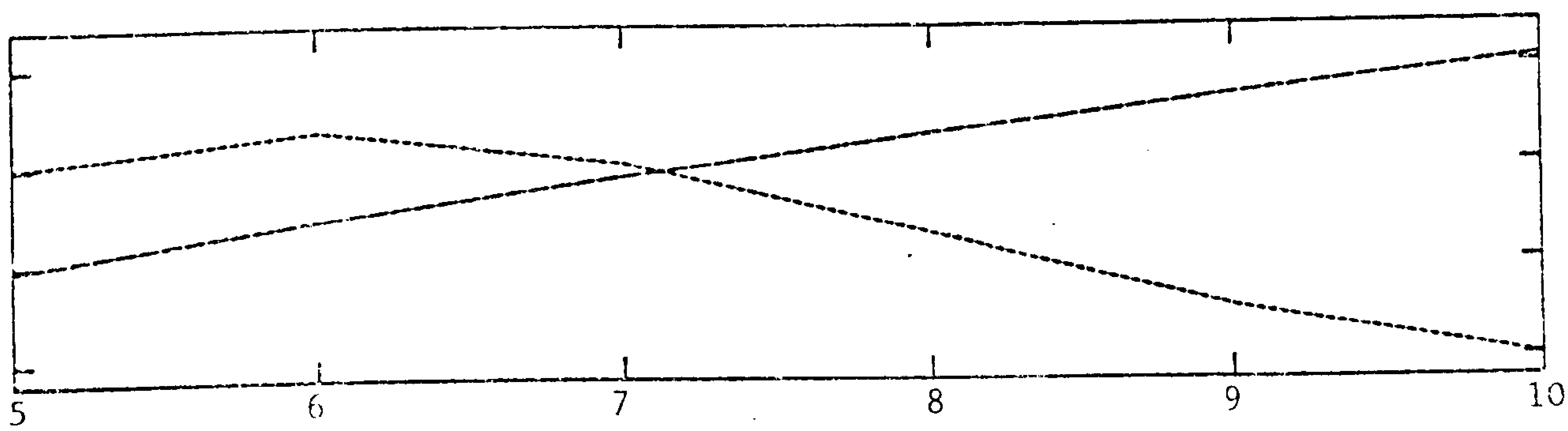
— — — CONSTANT GROSS FLOOR AREA
- - - - - - CONSTANT PLAN AREA

Figure 7.16: Cost relationship with height (roof and subs element)



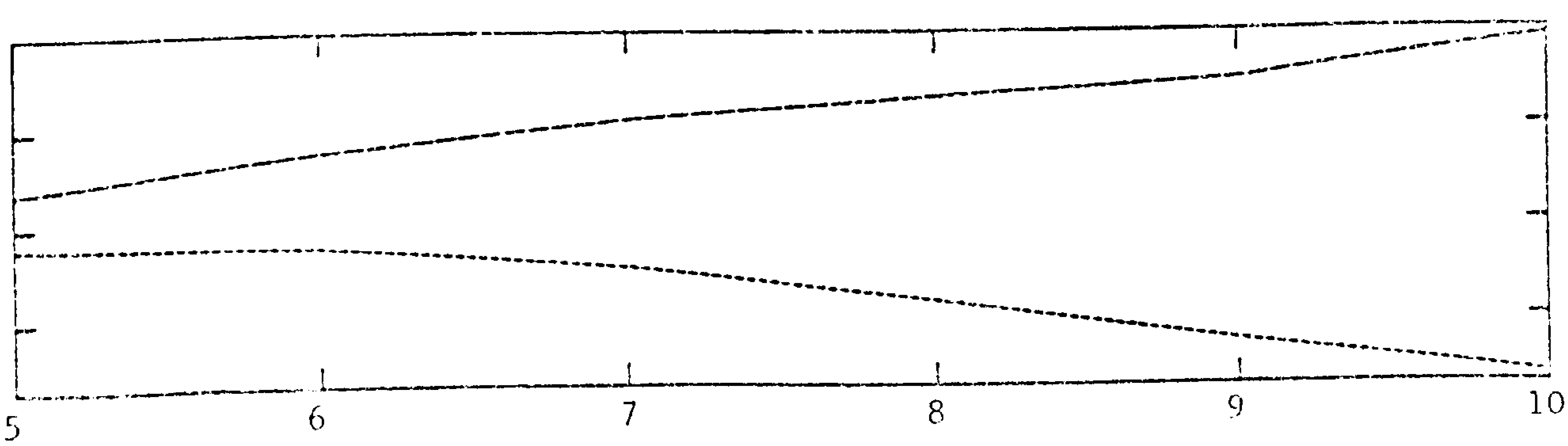
(a) Services element

— — — CONSTANT GROSS FLOOR AREA
------ CONSTANT PLAN AREA



(b) Frame element

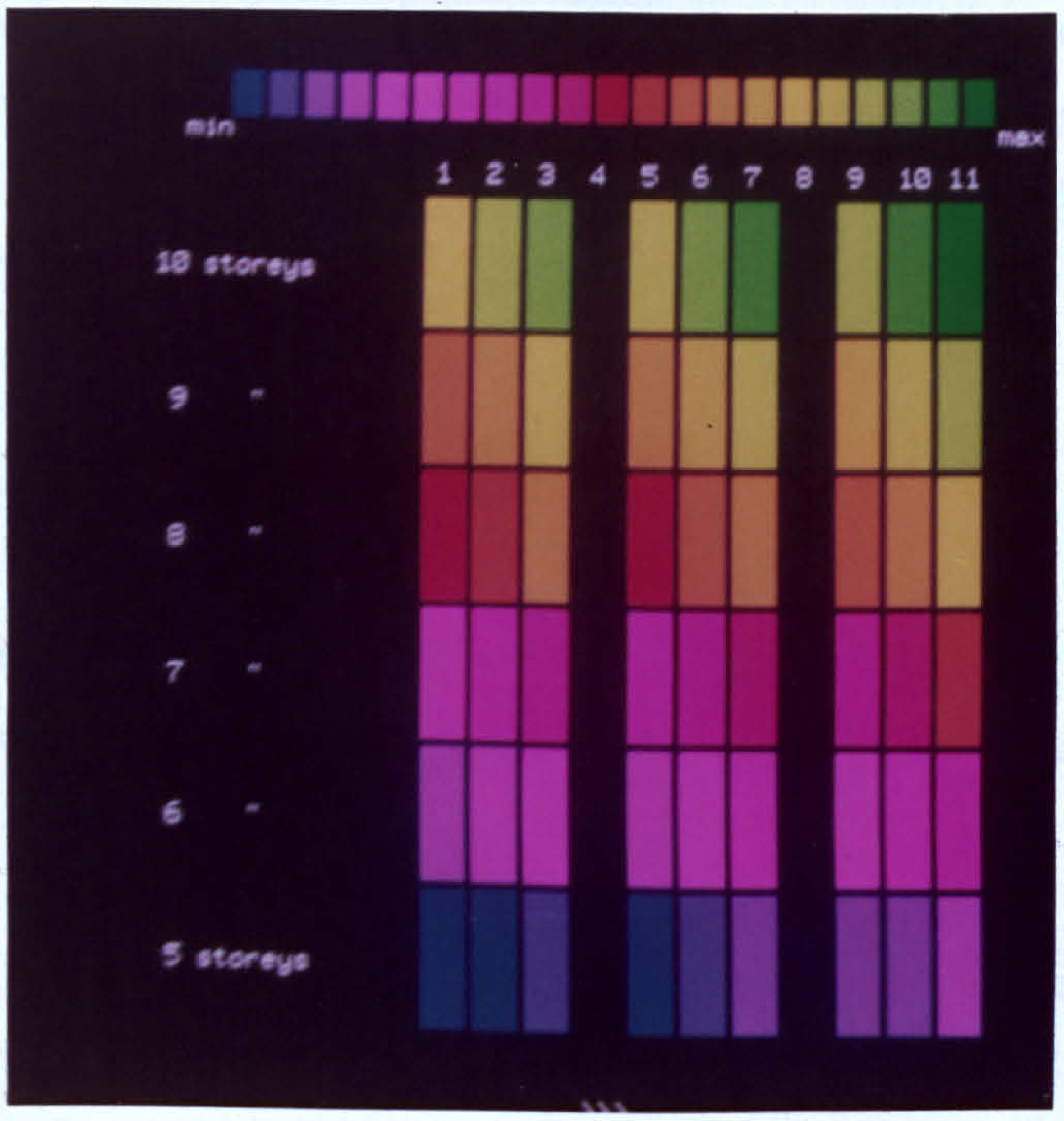
— — — CONSTANT GROSS FLOOR AREA
------ CONSTANT PLAN AREA



(c) Preliminaries element

— — — CONSTANT GROSS FLOOR AREA
------ CONSTANT PLAN AREA

Figure 7.17: Cost relationship with height (services, frame and preliminaries)



where:
1 = 3 No. lifts, -10% UR concrete
2 = 3 No. lifts, 0% UR concrete
3 = 3 No. lifts, +15% UR concrete
5 = 4 No. lifts, -10% UR concrete
6 = 4 No. lifts, 0% UR concrete
7 = 4 No. lifts, +15% UR concrete
9 = 5 No. lifts, -10% UR concrete
10 = 5 No. lifts, 0% UR concrete
11 = 5 No. lifts, +15% UR concrete

Figure 7.18: Matrix of lifts and unit rates for concrete

affected significantly, except in degree, by either set of variations. It is interesting to note however that the effect of an additional lift is almost exactly equivalent to the reduction in total cost produced by lowering the unit rate for concrete. That is, if the price of concrete fell by, say, 10%, then the designer could afford to provide an additional lift at no extra total cost.

Thus, not only can the model determine various trends in cost relationships, it can also be used as a direct comparison of possible trade-offs. The distinction is subtle, but potentially very useful in the often highly constrained environment of commercial design.

7.3.8 Bay size and live loads

Finally, the quite marked cost thresholds observed in respect to variations in bay sizes (see Section 7.3.2) were tested under rather different conditions.

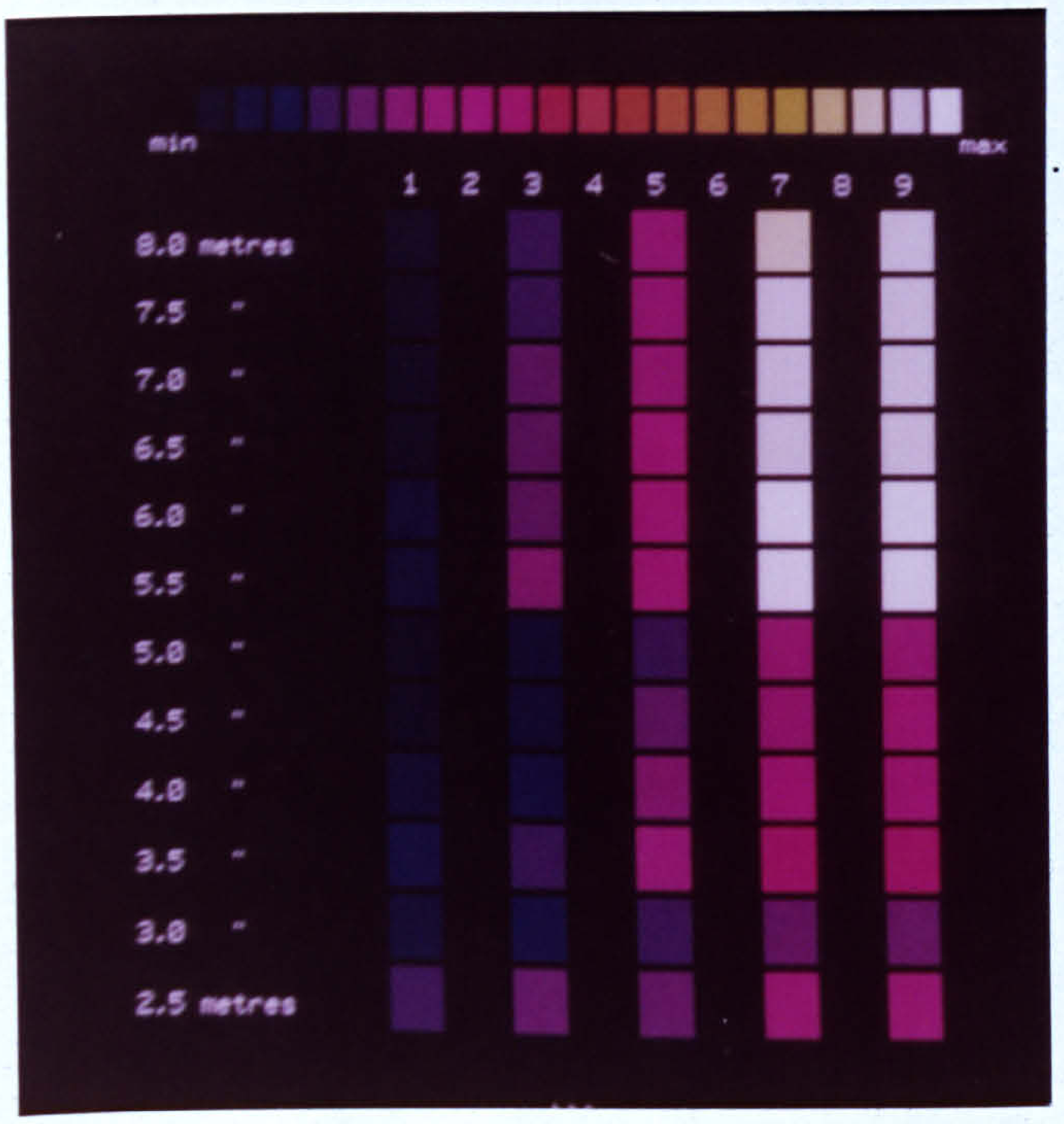
A 5 storey building was selected from the previous example (Section 7.3.6 and section 7.3.7) and the bay size varied from 2.5 x 2.5 metres, through squares of 0.5 metre increments to 8.0 x 8.0 metres. Figure 7.19 illustrates how the 5.5 metre threshold is still very pronounced, but pales considerably as the live loads are reduced from 5 N/mm^2 to 1 N/mm^2. Figure 7.20 further illustrates this complete transformation of the cost relationship with bay size, as the live loads decrease.

A most striking example of how the context influences each cost relationship.

7.4 Summary

This chapter has attempted to convey the potential of ACE as an investigative tool.

The actual investigation undertaken, largely has followed a relatively plain course through an arbitrary series of cost relationships. Nevertheless several important observations can be made:



where: 1.= 1 N/mm2
3 = 2 N/mm2
5 = 3 N/mm2
7 = 4 N/mm2
9 = 5 N/mm2

Figure 7.19: Matrix of bay size and live loads

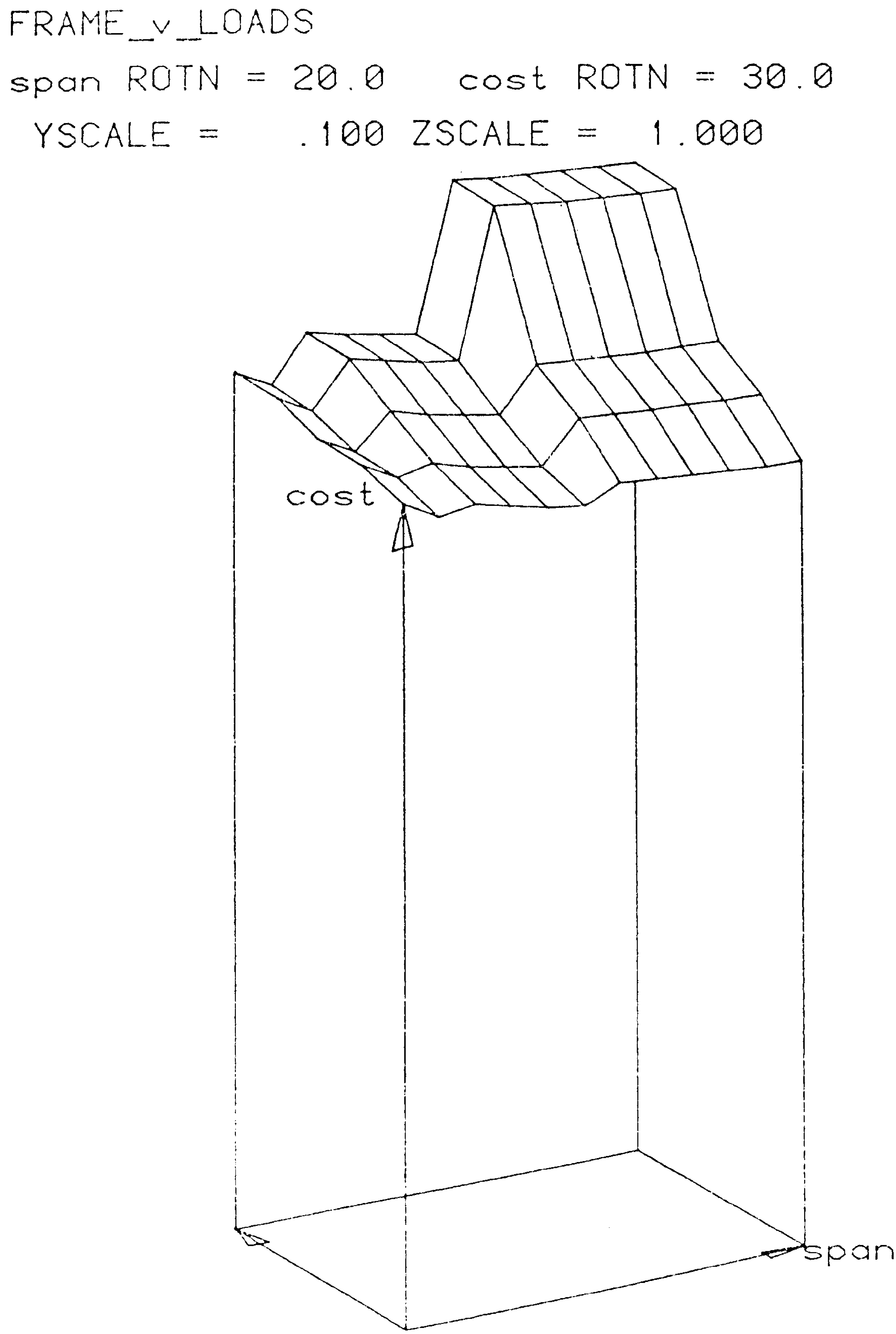


Figure 7.20: Plot of bay size and live loads

(i) The large number of dependencies make each cost relationship and cost threshold often very dependent upon context. In various situations then these relationships and thresholds will become opaque - obviously some more than others. The mere fact however that this change occurs in some relationships, determines that all other relationships and thresholds should be taken as variable also, until otherwise shown (i.e. shown to remain constant in a large number of contexts). A limited investigation such as described in this chapter is grossly insufficient evidence to suggest any particular cost relationship or cost threshold as being universally applicable.

(ii) Each representation - be it colour matrix, 3-D plot, a 'band' of relationships, the average, the Pareto line, or whatever - can only communicate a certain aspect of each relationship. To experience the full character of a relationship the representations available through ACE must be considerably improved and extended. The psychology of representation is a highly specialised field, but the need for research was made very apparent during the course of this investigation.

(iii) The results produced, though inevitably limited, would appear to indicate that the model is well able to cope with the labyrinth of interdependencies which constitute the solution space. This ability has two very significant applications:

* the model can abstract single dimension relationships, the value even of particular trade-offs, from the n-dimensional solution space - meaning that a naive user can begin slowly to appreciate cost trends and the cost consequences relating to general building characteristics.

* the model can interrogate specific cost relationships in some detail - providing the experienced cost adviser with a novel and effective vehicle with which to undertake cost research.

These two applications define each extreme on the range of potential cost model users, and greatly encourages further development of the approach in future.

REFERENCES

1 PARKINS R P
"BIBLE - A computer program for the generaton of perspective views of buildings", ABACUS Occasional Paper No. 75, University of Strathclyde, 1979.

2 RADFORD A D and GERO J S
"On Optimisation in Computer Aided Architectural Design", Computer Report CR34, Department of Architectural Science, University of Sydney, 1980.

CHAPTER EIGHT: CONCLUSIONS AND FURTHER WORK

REFERENCES

CHAPTER EIGHT: CONCLUSIONS AND FURTHER WORK

In the frailty of the current world economy as competition for scarce resources continues to rise, as profit margins are further eroded and as the proportion of venture capital locked up in physical assets such as building and plant increases prodigiously, so a growing pressure is placed on those who contribute to the built environment to produce effective and economical design solutions. However the measure of effectiveness is severely complicated by the inherent role of social and artistic considerations in building evaluation. Increasingly, it is realised that, as in a court of law, subjective value judgements should be made on the basis of the most complete, most explicit and most neutral evidence available (1).

By virtue of its numerical form, cost is often seen as the bastion of such objective absoluteness. By default almost, it is inevitably put forward as being the prime constituent of an explicit appraisal process. The original impetus of this present research was to provide such a metric.

It was soon realised however that a substantial characteristic of cost is the inherent uncertainty in current cost generation procedures. A theoretical analysis of the costing function revealed that contrary to popular belief, the uncertainty in cost data arises largely through inexactitudes in human decision-making rather than as a result of some random determination within the range of equally possible costs. The misconception is propagated by an inadequate scientific base to quantity surveying generally: the emphasis of the thesis was switched therefore towards a more global consideration of the problem.

The merit of Part Two of the thesis is that it manages to implement and actually to apply the theory of Part One through the development of a computer-based cost simulation model: ACE (Analysis of Construction Economics). Preliminary investigations with the model suggest that opposite to being objective and absolute, cost may well be as bespoke and subjective in nature as design itself: this does not negate the argument for explicit design information, but would probably disqualify cost from being the universal metric.

A way to test this contention would be to run the program in a large number of controlled contexts, and then to examine the variability of the cost relationships produced. To be useful, however, before such runs were undertaken, the appropriateness of the knowledge base would first have to be evaluated. Since the validity of ACE is dictated by the validity of the knowledge base this is an important priority for future work.

Much remains to be done to many aspects of ACE, certainly before any significant proportion of its true potential willbe realised. The more pressing work is discussed in Chapter 6, Section 6.4.

Most of the advances which ACE has made over previous cost models are indicative of the developments in computer aided architectural design (CAAD) generally. Building design is moving away from the model based on architectural drawings to one which is computer-based: from the descriptive to the prescriptive; the static to the dynamic; the implicit to the explicit (2) - similarly with ACE. In practice, access to computer based appraisal techniques is known to increase the search coverage by ten fold (3): not only is the search coverage extended, it is also much more purposefully directed.

A research proposal which aims to consider the impact of a knowledge based, dynamic cost simulation model such as ACE, on the utility of a range of CAAD software (from the general appraisal model to the detailed finite difference model) has already been submitted for approval to the Science and Engineering Research Council.

CAAD programs already offer the potential, rapidly to extract building quantities - even qualities - within an integrated and comprehensive design environment. Developments so far have tended largely to be triumphs in software engineering not theoretical ones. In emerging from the not inconsiderable technical problems, a new and exciting era begins in which the question of 'what?' CAAD should be doing, is given an equivalent prominence to the question of 'how?' it might be achieved.

This is only the first step. The dictates of quantity surveying (and all other humanistic systems) proffer an entirely new set of technical problems, at least an order of magnitude more complex than those of computer graphics and quantitative analysis - certainly the 'whats?' of cost modelling have resulted in an enormous number of additional 'hows?'.

It is the contention of this thesis that the list of preferred characteristics given in Chapter 4, Section 4.4, adequately describe the 'whats?' which are of most significance to the costing function, currently. Subsequent application of these criteria to the development and successful implementation of a new generation of costing function strongly encourages and reinforces the mandate they present.

It remains to apply the mandate also to parallel research endeavours such as cost in use models, development and investment appraisal models, energy costing, etc.

Some of the technical issues relating to 'how?' the preferred characteristics might best be implemented in a capital cost model are examined in Chapter 5, Section 5.2. They were subsequently expressed in a specification which formed the basis of ACE. Many issues remain unresolved.

The treatment of uncertainty is particularly crucial in distinguishing ACE from other cost models. This thesis promotes the view that cost variation, and therefore cost uncertainty, is a function of the human decision-making process rather than a random event. To this extent probability calculus is discounted as an appropriate predictive mechanism (though the effectiveness of a statistical analysis to measure and to express uncertainty is not disputed). The contention is, that because uncertainty stems from imprecision it will more readily equate with a system in which all the states are known, but in which the particular state adopted at any one time, is not. Thus ACE has developed along the lines of a decision-structure (the knowledge base) in which all possible states of the system are governed by fixed decision rules which only vary the output of the model for changes in context.

It is suggested that even this very simplistic implementation of the approach achieves a wholly more realistic approximation to the uncertainty encountered in reality than ever produced by a probabalistic interpretation.

Finally, at the more general level of selecting an appropriate research method applicable to the current state of the quantity surveying 'science', this thesis has lain emphasis on the testing of hypotheses by attempting to falsify the deductions inferred from them (a 'top-down' approach). The approach successfully has opened up the scientific knowledge base of quantity surveying bringing, it is suggested, a far greater proportion of the total problem into perspective. It is most crucial in the genesis of a new scientific base that this sort of reconnaissance be encouraged. In a practical subject such as quantity surveying there is a very real danger that discrete research endeavour will become localised, and loose sight of, or worse still never see, the overall objectives.

This process of 'fleshing-out' may be the major part of generating a scientific knowledge base, but the effort is largely wasted without some framework within which to work. The onus is placed squarely on the Royal Institute of Chartered Surveyors (the representatives of the profession) to ensure that research policy is reviewed more frequently and on a less prescribed basis, and that funds are made available for dedicated research in selected issues. Alternatively, they might relax the penalty on recent graduates wishing to undertake further research through the auspices of the SERC, either by waiving the Test of Profession Competence (the mechanism already exists (4)), or by providing a more appropriate Test paper (as has been done already for those in civil and heavy engineering).

In summary, what first appears as a simple numerical exercise of multiplying a unit rate by a unit quantity, can in reality be a highly complex process dealing with inherently uncertain cost data in an ill-defined, dynamic design environment.

The solution to the problem lies in a sophisticated computer-based model which exhibits similar qualities to the professional quantity surveyor in practice, but with the advantage of being much faster, and more controllable. Given this formal representation of the costing function, a user may:

(i) use the model as an investigative tool with which to compare the cost consequences of alternative design, examine cost relationships, establish sets of causal relationships, locate optimal design solutions, etc.

(ii) use the model itself as an expression of the costing function and interrogate the logical form to determine cost dependencies, etc.

The model provides an opportunity to naive user and expert alike to extend their comprehension building economics in a way that manual methods never could. Rather than mechanise the user however the knowledge that explicit cost data is available on request tends to focus increased attention on subjective value judgements, not less.

By recognising the true nature of the costing function in a computer-based model, or at least a close approximation to 'true' nature, it is hoped that cost will play a greater role in influencing the early design decisions relating to scale, shape, etc. of a building. Only then will the QS be able correctly to claim that all costs are being controlled.

REFERENCES

1 MAVER T W
"The Impact of Computer-Based Models on Design Decision-Making", in 'Rebuild', R Derricott and S S Chissick (Eds.), Wiley, 1982, pp.95-141.

2 MAVER T W
"Computer Aided Design: Applications in Architecture", in 'Human Interactions with Computers', H T Smith and T R Green (Eds.), Academic Press, 1980, pp.203-230.

3 KERNOHAN D et al
"West Fife District General Hospital: Use of PHASE", ABACUS Report No. R36, University of Strathclyde, 1977.

4 POLICY REVIEW COMMITTEE OF THE RICS
"The SITE Report", RICS, 1980, p.25.

BIBLIOGRAPHY

1. *Essential Reading*

1 ARBIB M A
'The metaphorical brain', Wiley-Interscience, 1972

2 BARR A and FEIGENBAUM EA
'The handbook of artificial intelligence: Volume I', Pitman Books, 1981

3 BEIGHTLER CS et al
'Foundations of optimisation', Prentice Hall In., 1967

4 Bell System Technical Journal
'Special issue on databases', Bell System Tech. Journal, Vol.61, No.9, November 1982

5 Bell System Technical Journal
'Special issue on UNIX', Bell System Tech. Journal, Vol. 57, No. 6, July/August 1978

6 BIJL A et al
'Integrated CAAD systems', EdCAAD Report No.79/11, March 1979

7 BRANDON PS (Editor)
'Building cost techniques: New directions', E and F N Spon, 1982

8 BRUNER JS et al
'A study of thinking', Willey, 1956

9 CODD E F
'Relational database: A practical foundation for productivity', The 1981 American Computer Manufacturers Turing Award Lecture, in Comms. of American Computer Manufacturers, Vol.25, No.2, Febuary 1982, pp109-117

10 DOWIE J and LEFRERE J (editors)
'Risk and chance', 1980

11 FLANAGAN R
'Tender price and times prediction in construction work', PhD Thesis (unpublished), University of Aston, 1980

12 GHEZZI C
'Programming language concepts', Willey and Sons, 1982

13 KAUFMANN A
'Introduction to the theory of fuzzy subsets Volume I - Fundamental theoretical elements', Academic Press, 1975

14 KERNIGHAN B W and RITCHIE D M
'The C programming language', Prentice-Hall, 1978

15 LATOMBE J-C (Editor)
'Artificial intelligence and pattern recognition in computer aided design', Proceedings of IFIP Working Conference, North-Holland, 1978

16 LAWSON B
'How designers think', The Architectural Press, 1980

17 MICHIE D (editor)
'Expert systems in the micro electronic age', Edinburgh University Press, 1979

18 NEWMAN WM and SPROULL RF
'Principles of interactive computer graphics', McGraw Hill, 1973

19 PUGH B
'Cost considerations' in Architects Journal, Vol.154, No.22, 18 August 1971, pp375-383

20 POPPER K
'The logic of scientific discovery', Basic Books, 1959

21 RADFORD AD and GERO JS
'On optimisation in computer-aided architectural design', Dept. Arch. Sci., University of Sydney, Computer Report CR34, 1980

22 RITTEL H
'The universe of design', Berkley Institute of Urban and Regional Development, University of California, 1966

23 RUBINSTEIN M F
'Patterns of problem solving', Prentice-Hall, 1975

24 SOMMERVILLE I
'Software engineering', Addison-Wesley Pubs., 1982

25 STONEBREAKER M et al
'The design and implementation of INGRES', American Computer Manufacturers Transactions on Database Systems, Vol.1, No.3, September 1976, pp189-222

26 TAVISTOCK INSTITUTE
'Interdependence and uncertainty', Tavistock, 1966

27 University of Reading
'Construction cost data base: A report prepared on behalf of PSA', Property Services Agency, 1980

28 ZADEH LA
'Outline of a new approach to the analysis of complex systems and decision processes', IEEE Trans. on Systems, Management and Cybernetics, Vol. SMC-3, No.1, January 1973

2. *Problem Solving*

References in this field all tend to become 'classic' texts. They are invariably 'heavy' reading (possible exceptions being ACKOFF and RUBINSTEIN) but well worth the effort:

29 ACKOFF R L
'Scientific method: Optimising applied research decisions', Wiley, 1962

30 KAUFMANN A
'The science of decision-making', World University Library, 1968

31 KHUN T
'The structure of scientific revolutions', University of Chicago Press, 2nd Edition, 1970

32 KLEINMUNTZ S J (Editor)
'Problem solving: Research, method and theory', Wiley, 1966

33 POPPER K
'Conjectures and refutations', Routledge, 1963

34 POPPER K
'The logic of scientific discovery', Basic Books, 1959

35 RUBINSTEIN M F
'Patterns of problem solving', Prentice-Hall, 1975

36 SIMON H A
'Models of discovery' in 'Boston studies in the philosophy of science Volume LIV', edited by COHEN RS and WARTOFSKY MW, Reidel Pubs., 1977

37 SIMON H A
'The sciences of the artificial', MIT Press, 1969

The best bibliographies are in RUBINSTEIN and KAUFMANN.

3. Systems and Models

An easy introduction to these simle, but highly effective concepts, is contained in:

38 THE OPEN UNIVERSITY
'Technology foundation course Unit 1 on systems', The Open Uni. Press, 1971

39 THE OPEN UNIVERSITY
'Technology foundation course Unit 4 on modelling', The Open Uni. Press, 1972

40 THE OPEN UNIVERSITY
'Technology foundation course Unit 18 on modelling', The Open Uni. Press, 1972

41 THE OPEN UNIVERSITY
'Technology: A third level course on systems, models and decisions', Open Uni. Press, 1975

4. *Simulation Techniques*

The literature in this field is being supplemented continuously. A basic and easy to follow introduction to simulation models and systems can be found in:

42 BARTON R F
'A primer on simulation and gaming', Prentice-Hall, 1970

43 RUBINSTEIN R Y
'Simulation and the monte carlo method', Wiley, 1981

For consideration of the factors which influence model validation, see:

44 CELLIER FE (Editor)
'Progress in modelling and simulation', Academic Press, 1981

Finally, a number of excellent papers with substantial bibliographies were published in:

45 American Computer Manufacturers
'Special edition on simulation', Communications of American Computer Manufacturers, Vol.24, No.4, April 1981

5. *Cost Control*

The traditional standard text is:

46 Property Services Agency
'Cost control in building', Research and Development No.4, HMSO, 1965

Perhaps the best two recent 'standard' texts are:

47 CARTLIDGE D P
'Cost planning and building economics', Hutchinson, 1973

48 FERRY D J and BRANDON P S
'Cost planning of buildings', 4th Edition, Granada, 1980

An historical record of the development in cost control is given in:

49 FLANAGAN R
'An historical study of construction industry measurement practice', MSc Thesis (unpublished), University of Aston, 1971

Other general interest references are:

50 CIB
'Assessing the economic of buildings', CIB Report No.30b, Rotterdam, 1974

51 GEORGE WH
'Cost planning', in Building Economics, Vol.12, No.3, December 1973, pp148-158

52 HUNT WD (Editor)
'Creative control of building costs', for The American Institute of Architects, McGraw-Hill, 1967

53 LIDDLE C
'A philosophy of cost control', Chartered Quantity Surveyor, Vol.2, No.3, October 1979, pp58-60

54 RICS Engineering Services Committee
'Cost control of M & E services', in Chartered Surveyor Building and QS Quarterly, September 1975

55 SMITH G
'Cost planning the design process' in Chartered Quantity Surveyor, August 1980, pp13-16

Bibliographies include:

56 CJB Information and Library Service
'Cost engineering - Select bibliography and supplements', CJB Information and library services, 1970

57 RICS
'Cost planning and control - a select bibliography', RICS Abstracts and Reviews, Vol.10, No.4, April 1974

6. Building Economics

The best two references dealing with a variety of issues relating to building economics generally, undoubtedly are:

58 BRANDON PS (Editor)
'Building cost techniques: New directions', E and F N Spon, 1982

59 FLANAGAN R
'Tender price and times prediction in construction work', PhD Thesis (unpublished), University of Aston, 1980

Others which discuss the theoretical aspects of the subject are:

60 BATHURST E P and BUTLER D A
'Building cost control techniques and economics', Heinemann Ltd., 1977

61 BRANDON P S
'A framework for cost exploration and strategic cost planning in design', MSc Thesis (unpublished), Bristol University, 1977

62 Ministry of Technology
'Report of the steering group on development cost estimating: Volumes 1 and 2', HMSO, 1966

63 SOUTHWELL J
'Building cost forecasting', Research Report, RICS, 1971

64 SWINBURNE H
'Design cost analysis for architects and engineers', McGraw-Hill, 1980

Particularly useful cost studies can be found in:

65 BANKS G D
'The uses of a length to breadth index and a plan to shape index', in Building and Quantity Surveying Quarterly, Autumn 1974

66 BRABY RH
'Costs of high rise buildings', in Building Economist, Vol.14, No.2, 1975, pp84-86

67 CREASY LR
'Economics of framed structures', Proceedings of Institute Civil Engineering, Vol.12, March 1959

68 DUNICAN P
'Structural steelwork and reinforced concrete for framed buildings', in Chartered Surveyor, August 1960, pp74-77

69 GRAY C
'Analysis of the preliminaries element of building production costs', MPhil Thesis (unpublished), University of Reading, 1981

70 PUGH B
'Cost considerations' in Architects Journal, Vol.154, No.22, 18 August 1971, pp375-383

71 STEYERT R S
'The economics of high rise apartment buildings of alternate design construction', Construction Research Council, American Society of Civil Engineers

72 TREGENZA P
'Association between building height and cost', in Architect Journal, Vol.156, No.44, 1 November 1972, pp1031-1032

73 Wilderness Cost of Building Study Group
'An investigation into building cost relationships of the following design variables: storey heights, floor loadings, column spacings, number of storeys', RICS, 1964

Work looking at the cost generation process, ir reported in:

74 PAULSON B C
'Designing to reduce construction costs', American Society of Civil Engineers Journal of Construction Division, Vol.102, No.CO4, December 1976, pp587-592

75 SHAW W T
'Do builders estimate? Or do they price?', Surveying Technician, Vol.2, No.8, August 1973, pp16-18

76 SKITMORE R M
'Bidding dispersion - an investigation into a method of measuring the accuracy of building cost estimates', MSc Thesis (unpublished), University of Salford, 1981

77 SKITMORE M
'Why do tenders vary?', in Chartered Quantity Surveyor, December 1981, pp128-129

78 SKOYLES E R
'Prices or costs', in Quantity Surveyor, Vol.33, No.9, April 1977, pp165-168

Bibliographies:

79 American Institute of Civil Engineers
'A ready reference index of cost engineering information', in The Cost Engineer, Vol.13, No.3, 1974

80 Institute of Building
'A decade of quantity surveying: review of the literature 1970-1979', IOB, 1980

81 Institute of Quantity Surveyors
'International survey of research into building economics and quantity surveying 1976', IQS, 1976

82 Property Services Agency Library Service
'Quantity surveying development: An annotated bibliography', DOE, 1978

7. Cost Data

83 ASHWORTH A et al
'An analysis of the accuracy of some builders estimating' in Quantity Surveyor, Vol.36, No.4, April 1980, pp65-70

84 ASHWORTH A
'The source, nature and comparison of published cost information', in Building Technology and Management, March 1980, pp33-37

85 BENNET JB and BARNES M
'Outline of a theory of measurement', in Chartered Quantity Surveyor, Vol.2, No.3, October 1979, pp53-56

86 Cost System Engineering Inc.
'The ORR system of construction cost management: an overview', Cost System Engineering Inc.

87 RAFTERY JJ
'Cost data, sources and suitability', Liverpool Polytechnic Internal Memo, August 1981

88 TYSOE B A
'Construction cost and price indices: description and use', E and F N Spon, 1981

89 University of Reading
'Construction cost data base: A report prepared on behalf of PSA', Property Services Agency, 1980

8. Uncertainty

Publications generally range from the philosophical:

90 DOWIE J and LEFRERE J (editors)
'Risk and chance', 1980

through the theoretical:

91 TAVISTOCK INSTITUTE
'Interdependence and uncertainty', Tavistock, 1966

to sophisticated applications in building:

92 DUDNIK EE
'Uncertainty and the design of building subsystems - a linear programming approach', in Build. and Env., Vol. 12, No. 2, pp111-116

93 SPOONER JE
'Probabalistic estimating', Jrnl of Construction Div., ASCE, March 1974, p65

and finally, those concerned with promoting the recognition of uncertainty in cost generation:

94 DUFF AR
'Control of costs allowances for uncertainty', BT and M Vol.14, No.7, July/August pp19 and 45

95 STACEY CN
'Assessing the uncertainty of an estimate', QS Vol.36, No6, June 1980, pp105-107

9. *Design Method*

There is a large volume of research reported in this field. Perhaps the best general source is:

96 LAWSON B
'How designers think', The Architectural Press, 1980

The other highly recommended reference is a particularly rigorous treatment of design:

97 RITTEL H
'The universe of design', Berkley Institute of Urban and Regional Development, University of California, 1966

The best of the 'standard' texts span the entire range of alternative view-points on design method:

98 ALEXANDER C
'Notes on the synthesis of form', Harvard University Press, 1964

99 ASIMOW M
'Introduction to design', Prentice Hall, 1962

100 BROADBENT S and WARD A (Editors)
'Design methods in architecture', Architectural Association, 1969

101 JONES JC
'Design methods (Seeds of human futures)', Wiley-Interscience, 1973

Rather than cite a large number of publications, reference will only be made to several of the reported design conferences - as these tend to reference a large proportion of other research in the field:

102 HAWKES D (Editor)
'Models and systems in architecture and building', Construction Press, 1975

103 MITCHELL W J (Editor)
'Environmental design: Research and practice', Proceedings of EDRA3, 1972

104 MOORE G T (Editor)
'Emerging methods in environmental design and planning', Proceedings of The Design Methods Group 1st Int. Conf., MIT Press, 1970

105 RODGERS W E and ITTELSON W H (Editors)
'New directions in environmental design research', Proceedings of EDRA9, 1978

106 SPILLERS W R (Editor)
'Basic questions of design theory', North Holland, 1974

Of particular note are the following:

107 ABEL C
'In defense of rationality in design', in Design Methods and Theories, Vol.13, No.3, July 1979, pp107-112

108 GILL R
'Approaches to design', Design Studies, Vol.1, No.3, January 1980, pp141-145

109 MAVER T W
'Appraisal in design', in Design Studies, Vol.1, No.3, January 1980, pp160-165

10. *Computer Aided Architectural Design*

A tremendous reference to anyone interested in CAAD (but most especially Architects) is:

110 BIJL A et al
'Integrated CAAD systems', EdCAAD Report No.79/11, March 1979

Again a lot of published work is in conference proceedings, but these tend to be dated somewhat. The only reports containing papers of particular note are:

111 VLIETSTRA J and WIELINCA R F (Editors)
'Principles of computer-aided design', Proceedings of IFIP Working Conference, Eindhoven, 1972

Others in which the papers are poor, but which contain a useful bibliography, are:

112 EASTMAN C M (Editor)
'Spacial synthesis in computer-aided building design', Applied Science, 1975

113 GERO J
'Computer applications in architecture', Applied Science, 1977

114 NEGROPONTE N (Editor)
'Reflections on computer aids to design and architecture', Petrocelli, 1975

Straight books range from the practical:

115 BENSASSON S
'Micros in construction', Cambridge Press Ltd., 1980

116 PATERSON J
'Architecture and the micro processor', Wiley, 1980

to the theoretical:

117 MITCHELL W J
'Computer-aided design', Petrocelli, 1977

and on to the futuristic:

118 NEGROPONTE N
'The architecture machine', MIT Press, 1970

11. Databases

The growing importance of databases to all fields of endeavour is reflected in the volume and quality of research within databases themselves. For an introduction 'off the deep end':

119 Bell System Technical Journal
'Special issue on databases', Bell System Tech. Journal, Vol.61, No.9, November 1982

120 IBM System Journal
'Special issue on databases', IBM System Journal, Vol.12, No.1, 1973

An alternative strategy, possibly, is to understand one system, and to then relate others to it. The development of INGRES, because it represents the promissing 'relational' approach, is perhaps a good starter (see also Appendix IV):

121 CODASYL
'Data base task group report', American Computer Manufacturers, 1971

122 CODD E F
'Relational database: A practical foundation for productivity', The 1981 American Computer Manufacturers Turing Award Lecture, in Comms. of American Computer Manufacturers, Vol.25, No.2, Febuary 1982, pp109-117"

123 STONEBREAKER M et al
'The design and implementation of INGRES', American Computer Manufacturers Transactions on Database Systems, Vol.1, No.3, September 1976, pp189-222

124 STONEBREAKER M
'Retrospection on a database system', American Computer Manufacturers Transactions on Database Systems, Vol.5, No.2, June 1980, pp225-240

Work which is related specifically to design, is well presented by:

125 BARTLEY J
'An architectural interface: Graphical and non-graphical interfaces with a CAAD system relational database', PhD Thesis (unpublished), University of Bristol, 1980

Further discussion is to be found in the references relating to CAAD, and in:

126 EASTMAN C M
'Information and databases in design: A survey of uses and issues in building design', in Design Studies, Vol.1, No.3, January 1980

<u>12. Artificial Intelligence</u>

Artificial intelligence is another rapidly expanding field of investigation. The basic concepts are now quite well founded, and tend to be taken as distinct from the more specific, current issues. A useful spread of references can be found in the following:

127 ARBIB M A
'The metaphorical brain', Wiley-Interscience, 1972

128 BARR A and FEIGENBAUM EA
'The handbook of artificial intelligence: Volume I', Pitman Books, 1981

129 FEIGENBAUM E A and FELDMAN J (Editors)
'Computers and thought', McGraw-Hill, 1963

130 SCHANK R C and COLBY K M (Editors)
'Computer models of thought and language', WH Freeman, 1973

Few links have been forged specifically with design. The most obvious exception being an excellent conference proceedings:

131 LATOMBE J-C (Editor)
'Artificial intelligence and pattern recognition in computer aided design', Proceedings of IFIP Working Conference, North-Holland, 1978

In addition there is the more recent:

132 BERGER S R
'Artificial intelligence and its impact on computer-aided design', Design Studies, Vol.1, No.3, January 1980, pp166-171

133 WILLEY D S
'Approaches to computer-aided architectural sketch design', CAD Vol.8, No.3, July 1976, pp181-186

A particular aspect of artificial intelligence follows an approach known as cybernetics. Several relevant publications are:

134 AMKREUTZ J H A E
'Cybernetic model of the design process', CAD Vol.8, No.3, July 1976, pp187-192

135 ASHBY W R
'An introduction to cybernetics', Methuen and Co. Ltd., 1976

136 EVANS C R and ROBERTSON A D J (Editors)
'Cybernetics: Key papers', Butterworths, 1968

13. Expert Systems

The best text on expert systems is:

137 MICHIE D (editor)
'Expert systems in the micro electronic age', Edinburgh University Press, 1979

Some work has been done with respect to the construciton industry:

138 LANSDOWN J
'Expert systems: A memorandum on their scope and nature', BOCAAD No.38, November 1980, pp25-36

A particular application is described by:

139 WILLEY DS and TOLLER DR
'SPA: Automating bathroom design', CAD Vol.13, No.3, May 1981, pp137-144

14. Optimisation

The major optimisation techniques are described in:

140 BEIGHTLER CS et al
'Foundations of optimisation', Prentice Hall In., 1967

141 DUFFIN RJ et al
'Geometric programming, theory and applications' Wiley, 1967

142 NORMAN JM
'Heuristic procedures in dynamic programming', Manchester University Press, 1972

143 WHITE DJ
'Dynamic programming', Oliver and Boyd, 1969

144 WILDE DJ
'A review of optimisation theory', Ind. and Eng. Chem., Vol.57, No.8, August 1965

Applications abound, the best report in building design is:

145 RADFORD AD and GERO JS
'On optimisation in computer-aided architectural design', Dept. Arch. Sci., University of Sydney, Computer Report CR34, 1980

See also:

146 GERO JS
'Computer-aided design by optimisation in architecture', Design Studies, Vol.1, No.4, April 1980, pp227-230

Others more pertinent to building economics, are:

147 RUSSELL AD and CHOUDHARY KT
'Cost optimisation of buildings', ASCE, Jrnl. Stuct. Division, Vol.106, January 1980, pp238-300

148 RUSSELL AD and GHOLAM-ALI A
'Objective functions for optimal building design', in CAD Vol.13, No.6, November 1981, pp327-338

149 WILSON AJ and TEMPLEMAN AB
'An approach to the optimum thermal design of office buildings', in Build. and Env., Vol.11, No.1, 1976, pp39-50

15. Software Engineering

Computing is fast becoming blessed with a number of very simple and easy to follow texts. A prime example is:

150 SOMMERVILLE I
'Software engineering', Addison-Wesley Pubs., 1982

Possibly more technical aspects are dealt with admirably by:

151 ALAGIC S and ARBIB M A
'The design of well-structured and correct programs', Springer-Verlag, 1978

152 Infotech State of the Art Report
'Structured software development: Volumes 1 and 2', Infotech int., 1979

153 KERNIGHAN B W and PLAUGER P J
'Software tools', Addison-Wesley Pubs., 1976

For the more experienced reader, the following are recommended:

154 DAHL O-J et al
'Structured programming', Academic Press, 1972

155 GHEZZI C
'Programming language concepts', Willey and Sons, 1982

Finally, some 'classical' references relating to the fundamental precepts of modern software engineering:

156 ANON
'A note on the psychology of abstraction', ACM SIGSOFT, Software Engineering Notes, Vol.4, No.1, January 1979, p21

157 DIJKSTRA E W
'GOTO statement considered harmful', Comms. ACM, Vol.11, March 1968, pp147-148

158 PARNAS D L
'On the criteria to be used in decomposing systems into modules', Comms. ACM, Vol.15, No.12, December 1972, pp1053-1058

16. UNIX

The popularity of UNIX has prompted a sudden flood of introductory texts. Most simply reproduce the user manual. A possible exception is:

159 BANAHAN M and RUTTER A
'UNIX the book', Wiley, 1983

For those better versed in UNIX:

160 Bell System Technical Journal
'Special issue on UNIX', Bell System Tech. Journal, Vol. 57, No. 6, July/August 1978

See also:

161 American Computer Manufacturers
'25th Anniversary special issue', Comms. American Computer Mans., Vol. 26, No. 1, January 1983

The standard, though quite technical reference for the C programming language is:

162 KERNIGHAN B W and RITCHIE D M
'The C programming language', Prentice-Hall, 1978

The main arguments for its further adoption in CAAD, are well expressed in:

163 ROSENTHAL DSH
'UNIX as a basis for CAD software', in CAD Vol.14, No.3, May 1982, pp131-135

17. Man/machine Interaction

The following, all raise significant points relating to man/machine interaction and the need for further research:

164 JONES PF
'Four principles of man-computer dialogue', Computer Aided Design Vol.10, No.3, May 1978, pp197-202

165 JONES JC
'The designing of man-machine systems', Ergonomics Vol.10, 1967

166 MILLER CL
'Man-machine communications in civil engineering', Jrnl. of Structural Div., American Association of Civil Engineers, Vol.89, 1963, pp5-39

167 MARTIN J
'Design of man-computer dialogues', Prentice-Hall, 1973

168 WISEMAN NE
'An approach to computer graphics', Computer Aided Design Vol.7, No.2, April 1975, pp119-121

The best is undoubtedly:

169 NEWMAN WM and SPROULL RF
'Principles of interactive computer graphics', McGraw Hill, 1973

18. Human Cognition

This is a technical and specialised field. Really, one can only 'wet the appetite':

170 BARTLETT FC Sir
'Remembering', Cambridge University Press, 1961

171 BOBROW D and COLLINS A (editors)
'Representation and understanding: Studies in cognitive science', Academic Press, 1975

172 BRUNER JS et al
'A study of thinking', Wiley, 1956

173 MILLER GA
'The magic number seven, plus or minus two: Some limits on our capacity for processing information' in Psychological Review, Vol.63, 1965, pp81-97

174 SHELLY MW and BRYAN GL (editrs)
'Human judgement and optimality', Wiley, 1964

19. Fuzzy Sets

The two definitive works are:

175 ZADEH LA
'Outline of a new approach to the analysis of complex systems and decision processes', IEEE Trans. on Systems, Management and Cybernetics, Vol. SMC-3, No.1, January 1973

176 ZADEH LA
'Possibility theory and soft data analysis', Memorandum No. UCB/ERL M79/66, Elect. Research Lab., University of California, August 1979

An alternative description is given by:

177 KAUFMANN A
'Introduction to the theory of fuzzy subsets Volume I - Fundamental theoretical elements', Academic Press, 1975

Undoubtedly some knowledge of set theory is needed. See:

178 HALMOS PR
'Naive set theory', Science Editions, 1960

Fuzzy sets in design are the subject of:

179 GERO JS and OGUNTADE OO
'Fuzzy set evaluators in architecture: preliminary studies', Dept. Arch. Sci., Univ. of Sydney, Computer Report CR29, 1978

APPENDICES

APPENDIX I: SYSTEMS AND MODELS

1. Introduction

Consider a garden: it has trees, shrubs, flowers, grass. Then consider a tree: it has fruit, leaves, branches, trunk, roots. Then consider the fruit: it has a skin, flesh, pips. Then consider skin: it is made up of various cells, in turn comprising various molecules, of various atoms, and so on.

It is apparent that the relationships considered are in the form of a hierarchy, as illustrated in Figure 1. The hierarchy has a series of levels, each level being a more detailed refinement of the previous. These hierarchical levels are also refered to as levels of abstraction and most persons will operate at a level or set of levels of abstraction, best suited to their own purpose. For instance, study of the plant cell may be irrelevant detail to a gardener, while the fact that a tree has roots is meaningless to a microbiologist.

Minsky (1) proposes that:

"When one encounters a new situation (or makes a substantial change in one's view of the present problem) one selects from memory a substantial structure called a frame. This is a remembered framework to be adapted to fit reality by

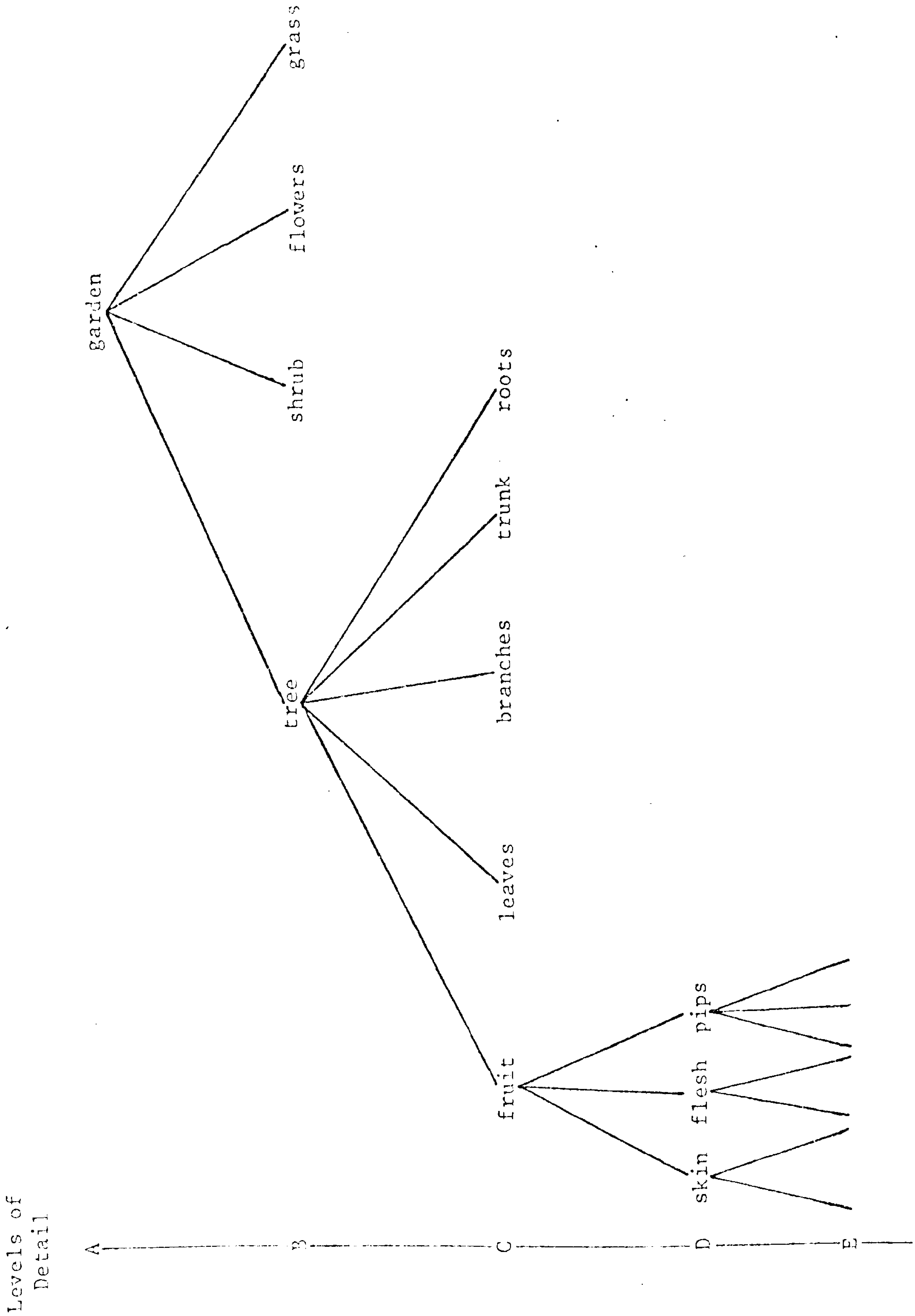


Figure 1: The hierarchical structure of progressive abstraction

changing details as necessary".

This is only one of several emerging theories relating to intelligence (contrast for example with Newell and Simon (2), or Abelson (3)), but it does illustrate the central theme of them all; that a person holds a view of the world (his Weltanschauung) arrived at through experience and which is applied to, and therefore effects, the appreciation of any new situation (4).

It would appear then, that human cognition proceeds at various levels of abstraction; that a given person will operate at a given level, and that the person constructs a frame of reference which is applied to any new situation (the natural form for this framework being hierarchical). Indeed these factors have proved so fundamental to the human learning process that they now have been incorporated in to what are certainly two of the most successful problem solving concepts:

(i) Systems – which provides a means of selectively isolating the level at which a problem is considered, and

(ii) Models – which represent to a particular level of detail, the salient features of subsequent levels, and facilitates their interrogation.

The two approaches form a basic thread from which much of this thesis is woven. This appendix attempts to describe the concepts in more detail.

2. Systems Theory and the Systems Approach

Systems appear everywhere. They are found at both extremes of size: an astrologer concerns himself with the solar system, a vast assembly containing our sun and its planets; while the physisist studies atomic systems of electrons and protons. There are mechanical systems, for example engines and generators; there are biological systems, man and other animals, plants; there are social systems, factories, political parties, families; there are natural systems, forests, weather. That such diverse kinds can all be termed a 'system' says much for the ubiquity of the concept.

In its raw sense, a system is merely an interconnected set of components. To have meaning to an individual, the system must also have its boundaries defined: someone must identify the particular assembly which constitutes the system (5). For instance, a hospital can be considered as a system, with doctors, operating theatres, wards, and patients as the components of the system. The components have certain attributes, or characteristics, that have some logical or numerical value (for example the number of patients, the skill of the doctors, the quality of operating facilities - in any component there will be an almost infinite number of different properties which could be defined, examined and measured (6)). A number of activities, or relationships, exist among the components, and consequently the components interact. These activities cause changes in the system. Thus, a doctor needs a theatre in which to operate on a patient and if the theatre is unavailable, the patient does not have the operation.

But what of the system boundary? No system can include everything in the universe unless it is dealing with the one special system, the universe as a whole. It follows that any system must have some limit to it, that there is always an outside to a system and an inside. The boundary to a system is an interface between the 'inner' environment, the substance and organisation of the system itself, and an 'outer' environment, the surroundings in which it operates. It is useful therefore to consider both internal and external relationships.

The internal relationships connect the components within the system while the external relationships connect these components with the environment, that is, with the world outside the system. For instance, the internal relationship between doctor, operating theatre, and patient has already been exemplified; an external relationship might be the order in which patients arrive at casualty.

A system can be represented diagramatically as illustrated in Figure 2. Clearly, the system is influenced by its environment through the input it receives from that environment. It impacts upon its environment by changes in its own state, the output. When a system has the capacity to react to changes in its own state, the system is said to contain feedback. A non-feedback, or open-loop, system lacks this characteristic. For an example of feedback, consider a line of waiting patients; when there are more than a certain number of patients, the hospital may add more doctors to handle the increased workload.

The state of a system is defined by the attribute values of the system components at a particular moment in time. To continue the previous example, the systems state would be described by the number of patients waiting in the line. When a patient arrives at or leaves the hospital, the system moves to a new state.

To summarise, the description of a system will contain:

* a set of inputs,
* a set of outputs,
* a set of states,
* a mode of change when the system is provided with a given input, and
* a way to determine what output the system will yield with a given input when in a given state.

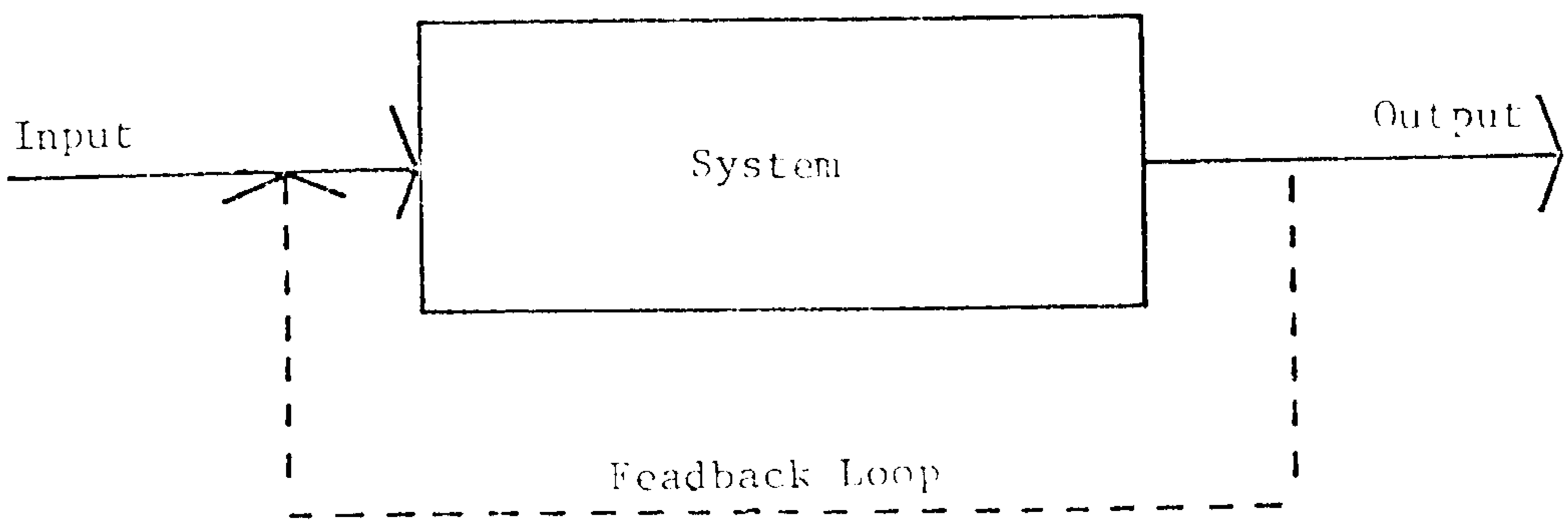


Figure 2: Graphical representation of a system

Simon (7) has shown how complex systems will evolve from simple systems if there are stable intermediate forms (a hierarchy) much more rapidly than if there are not, and uses this to explain the observed predominance of hierarchies among the complex systems of nature. That is, that a complex system is composed of interrelated components, each of the latter being in turn a sub-system, hierarchic in structure (see Figure 3).

This hierarchic nature of systems allows a distinction to be made between the interactions among subsystems, on the one hand, and the interactions within subsystems - that is, among the components of those subsystems - on the other. The interactions of trees, shrubs, flowers and grass in a garden can be distinguished from the interactions of fruit, leaves, branches, trunk, and roots of a tree; flower, leaves, stem, and roots of a flower; etc. The interactions at different levels may be, and often will be, of different orders of magnitude. For example, in the formal organisation of - say - a hospital, there will generally be more interaction between two porters than between a porter and a consultant surgeon. In organic substances, intermolecular forces will generally be weaker than molecular forces, and molecular forces weaker than nuclear forces. In a rare gas, the intermolecular forces will be negligible compared to those binding the molecules and, for many purposes, can therefore be treated as if they were independent of each other.

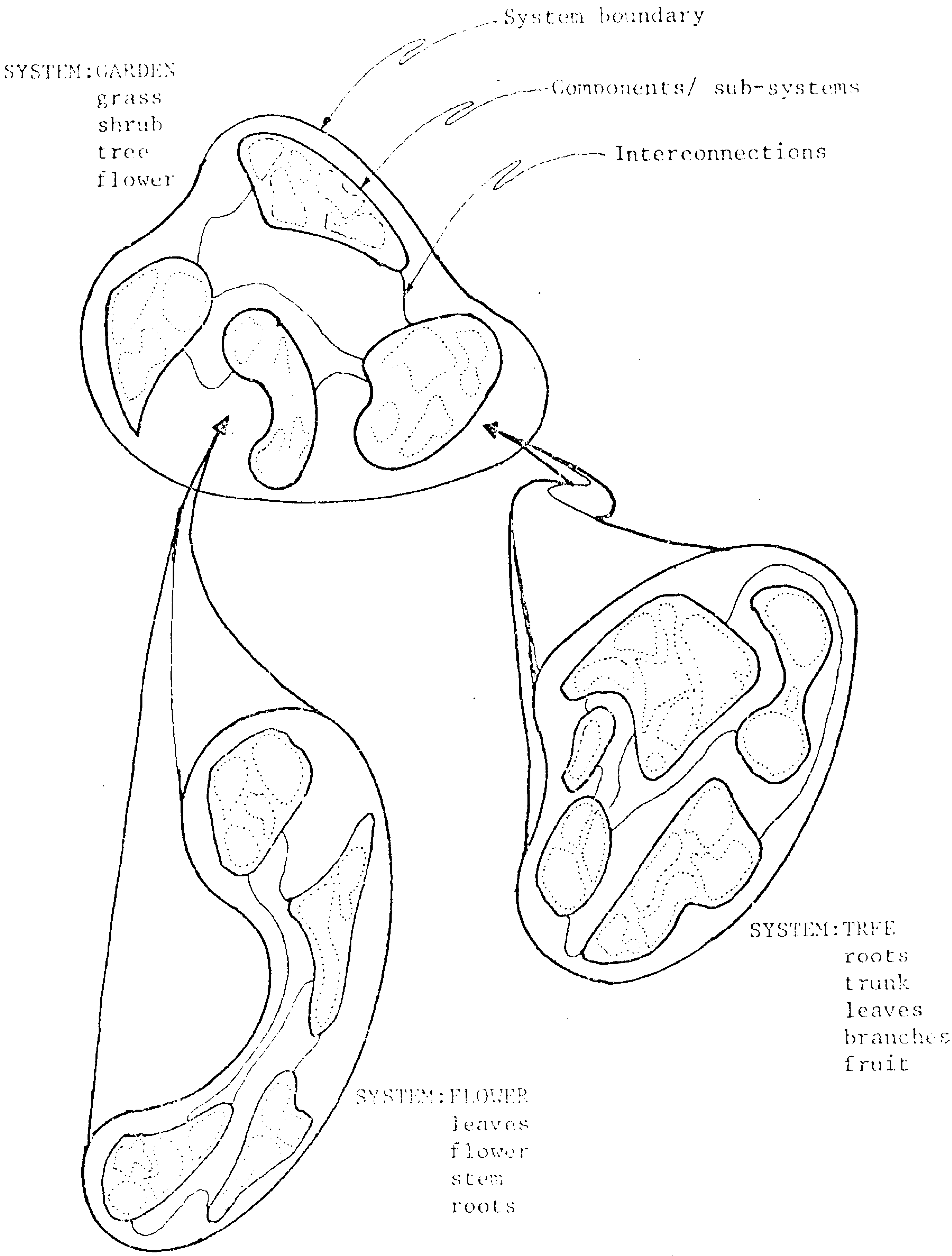


Figure 3: The hierarchical nature of systems and sub-systems

Such a system is described as being decomposable, or nearly decomposable.

Thus, when certain components of a system only interact in an aggregate fashion the detail of their interaction can be ignored. It transpires that most of the complex systems considered in this way have a high degree of such redundancy (though perhaps the social sciences to a lesser degree (8)). Decomposition removes the redundant detail and provides for a more economic description. If a complex system is completely non-redundant - if no aspect of its structure can be inferred from any other - then it is its own simplest description and analysis of its behaviour may well involve such a detailed knowledge and calculation of the interactions of elementary components as to be beyond the capacity of memory or computation.

An ability to decompose a complex structure, as engendered by the systems approach, can simplify greatly the description of that structure.

The degree of simplication however, is influenced significantly by the 'depth' of the structure. A deep hierarchy is one with many intermediate levels and therefore one in which each subsystem is likely to have a relatively narrow span: each level is partitioned into only a few components. For example, the 'family tree' is a deep structure because at each level its span increases by a factor of only 3 or 4 (the number of children and their spouses). The shallow hierarchy is partitioned into a large number of components which generate a large number of complex interactions, difficult to aggregate. For example, indefinite chains of single-banded carbon atoms can be built up, because the atoms form crystals with the exact same valence as the number associated with the individual atoms (the valence number 2).

To summarise, the systems approach provides a means of describing an otherwise complex structure, economically. This is achieved by decomposing the system at any level of detail, and thereby allows the investigator to consider a problem at his own best level of abstraction. Neither his perspective on the overall objectives, nor his awareness of the connections between components is penalised by considering individual components in this way.

3. Modelling

3.1 Model types

The systems approach makes it easier to understand how the information needed for the reproduction of a system can be stored in reasonable compass. Once reproduced, a system can be interrogated by manipulating the parameters which describe that system. The reproduction is termed a model of the system.

To an observer B, an object A* is a model of an object A to the extent that B can use A* to answer particular questions that interest him about A (9).

Of the various types of model, the three most common classifications are (10):

(i) Iconic models - which represent the relevant attributes and properties of reality (the object system) by the same attributes and the same properties, but usually to a different scale. For example, maps, photographs, globes of the earth.

(ii) Analogue models - which use one set of properties to represent another set of quite different properties. For example; an abscissa, where length represents a variety of properties; contour lines, which represent height or temperature. The objective is to select a set of analogues properties which are more familiar and better understood than those of the system under investigation. It is assumed that a translation rule or an appropriate legend can be formulated from one property to the other.

(iii) Symbolic models - which use letters, numbers, and other types of symbols to represent the system variables and the relationships between them. For this to be possible the symbols must have rules of manipulation (for example, algebra or language) and a means of controlling such manipulation.

Clearly, all models have certain relationships to what they represent - called homomorphism, every component of the object system has its counterpart in the model and any relevant relationships in fact are represented by corresponding relationships in the model. This does not mean that the mapping in a model is one to one, but one part of the model may correspond to several in the object (an aggregate).

Further, the iconic model appears to be the most specific, simple to produce, but concrete rather than abstract and therefore difficult to manipulate for experimental purposes. Symbolic models, on the contrary, will normally take the form of mathematical relationships through equations, or 'inequations'. They are the easier to manipulate expermentally and therefore yield more consistent results than either iconic or analogue models. the more abstract a model, the more general its range of application, and the more useful it will be for prediction. But amodel can help in the understanding of a system in many ways (11):

* highlighting the salient features,
* predicting how the systems will behave under different conditions,
* allowing an investigation of what causes particular responses,
* generating wholly new ideas for designing or operating the system,
* communicating insight to others, and so on.

3.2 Symbolic forms

It is apparent that the most useful and general model types are symbolic, and yet they are also the most difficult to formulate, interpret and understand. With recent developments in computer technology, the experimenter is now provided with a unique and powerful medium within which to control and manipulate even the most sophisticated model. In problem solving generally then, the move is away from plans, drawings, scale models 'mock-ups', and directed instead towards the formulation of computer based models which allow a much more rigorous interrogation of the problem structure.

It is possible to classify most computer based models into groups of either simulation, generation, or optimisation:

(i) In simulation the computer is used to predict the consequences of a set of decisions by manipulating a mathematical model which describes the problem structure. All decision making is external to the model.

(ii) In generation the computer is used to explore the consequences of the recursive application of an ordered set of decision rules. Thus, some decision making is internal to the model but it is not purposeful: all decisions which conform to the rules are equally acceptable.

(iii) In optimisation the computer is used to prescribe a set of decisions in order to achieve a specified goal as closely as possible. Some decision making is internal to the model and is purposeful: decisions are chosen according to their ranking on an explicit measure of effectiveness.

3.2.1 Simulation models

The formulation of a simulation model can be based on one of two premises:

(i) A stochastic simulation - in which differing outputs trial by trial can be achieved without changing the inputs (ignoring random numbers as inputs). Specifically, this means that for identical starting conditions, the outputs from trial to trial and run to run may vary. Experimenting with the model includes sampling stochastic variates from a probability distribution (12): stochastic simulation is actually a statistical sampling experiment with the model. This sampling involves the use of random numbers and is therefore sometimes called Monte Carlo simulation.

(ii) A non-stochastic simulation - in which the inputs or the structure of the model must be changed to obtain changed outputs. This means that for identical inputs, the model will produce identical outputs, run to run, and the experimenter is then forced to operate by trial and error.

The great strength of simulation is that by fixing all the variables their consequences can be examined in great detail and on as many different aspects of the problem as there are prediction methods available. However, to obtain any qualitative information, a solution must first be presented; the use of such a model therefore involves a cyclical procedure of postulation - evaluation - modification.

A simulation study will consist basically of a parametric model where the values of the parameters need not be specified, and a particular parameter set (the proposed solution) which consists of the values of the parameters of the model. The specification of an experiment will then have two components: an experimental frame (or frames) and a simulation run (or runs). An experimental frame defines the limited set of circumstances under which a system (or the model) is to be observed or subjected to experimentation. It requires a specification of the variables to be observed, a schedule of inputs, the initialisation conditions, termination conditions, and a means of collecting and displaying data (13). A simulation run is then an observation of the behaviour of the model, under a specific experimental frame.

Thus, while the main disadvantage with simulation is the lack of explicit information on the overall problem structure and interrelationships, it can be argued (14) that repeated simulation runs are necessarily educational in developing an awareness of the essential complexity and multivariate nature of particular problems.

3.2.2 Generation models

A generative model applies a prescribed set of decision rules to the range of possible system states. In so doing, it produces an unranked catalogue of solutions which satisfy this given set of rules. The technique is therefore suited to situations where a range of feasible solutions are required, as might be the case where efficient, non-standard problem solutions are sought.

The approach assumes that a set of rules can be suitably defined, and the lack of purpose behind the decisions means that the set of solutions generated may be large and partly superfluous. There is nothing more conveyed about the performance or relative merit of respective solutions in the generated set, other than the satisfaction of performance objectives ensured by the rules themselves.

3.2.3 Optimisation models

The philosophy of optimisation essentially is that a prefered state of a system exists (the global 'optimum') and that a choice of values for the system variables must also exist which will yield this optimum.

Historically optimisation has been treated as a mathematical problem in which the interest lay only in the extreme value of the objective and some means of obtaining that value. What those means were, the actual set of decisions required, were not considered particularly significant. Neither was any suboptimal solution. Optimisation techniques were designed to search the whole field of feasible solutions in an attempt to identify those best suited to stated goals. However in many systems, particularly humanistic (i.e. those whose behaviour is strongly influenced by human judgement, perception or emotions), both the decisions and suboptimal solutions are very important because it is not always possible to completely state the goals: other, especially subjective, factors may come into play; some assumptions may change in the course of problem solving; etc.

Any technique adopted therefore should be able to produce field or range of solutions which can be examined both in terms of their relative merit (the values of the objective function) and in terms of the sets of decisions they represent.

In optimisation, the formulation of a single objective is particularly critical (15).

It is apparent, however, that not all problems have a singular, distinct objective. Problems, especially in humanistic systems, usually have a number of disparate objectives which are important to a greater or lesser degree. Radford (16) has classified objectives as being:

(i) single criterion,

(ii) multi-attribute single criterion,

(iii) multi criterion, or

(iv) multi-attribute multi criterion.

The term 'criterion' denotes a non-commensurable measure of performance. The term 'attribute' denotes a commensurable component of a criterion. In building design for example, a criterion might be the total cost or net energy, while the attributes of total cost might be initial capital cost, finance cost and costs-in-use.

In a single criterion problem the criterion space reduces to a one dimensional vector and each point in the decision space has associated with it a corresponding point in this vector (see Figure 4). The entire set of feasible performances will occupy a segment of this vector and a solution is clearly dominated (bettered by) any solution with a better performance in the criterion. Multi-attribute problems can also be represented this way by combining the attributes in the same terms; i.e. by weighting. In multi criterion problems, again, the objective can be generated in a fashion similar to multi-attribute objectives except that now the attributes become objectives and the weights represent some form of trade-off between objectives. Mathematically the two representations are similar. Such techniques have been termed preference methods since they attempt to determine in advance the needs of the decision maker, and have the advantage of greatly reducing the search space.

Unfortunately preference methods are ill suited to the

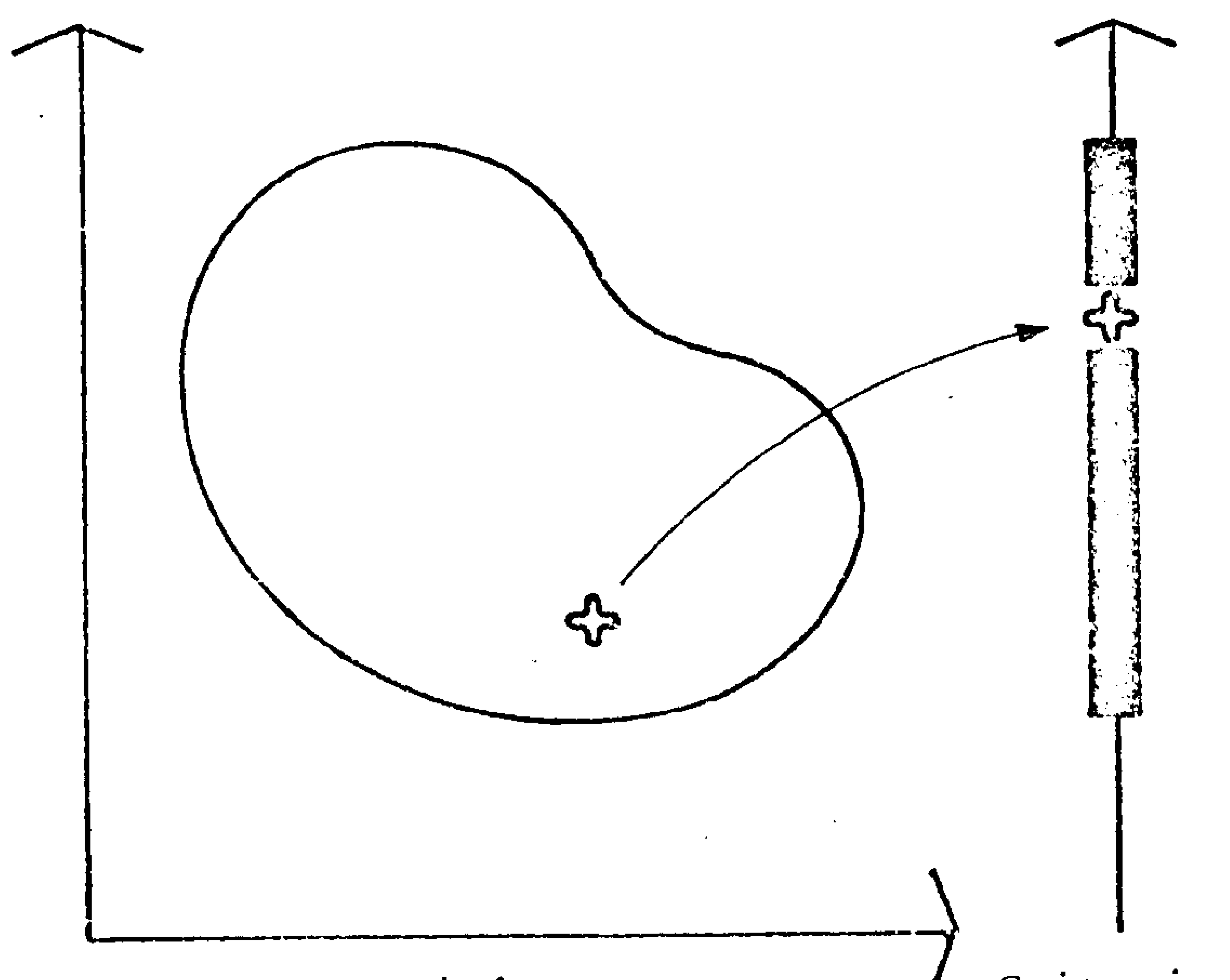


Figure 4: Decision space and single criterion vector

examination of non-quantifiable, subjective criteria, because of the difficulties in measuring, evaluating and expressing a decision makers notion of 'satisfactory performance'. The large number of assumptions necessary suggest that extensive information should be provided on the sensitivity of performance and stability of solution choice given possible changes in the objective function and system parameters. In optimisation, such information is usually obtained by methods of post-optimality analysis (17) after optimal and suboptimal solutions have been identified.

Alternatively, non-preference methods might use the concepts of optimisation to identify the performance options open to the decision maker and leave him to choose between them, based on the information provided and any other information he has available. It may, though, mean the generation of rather a lot of alternatives and would require some ingenuity in the representation of non-dominated sets relating to more than three criteria (i.e. the representation of more than three dimensions) (18).

The basic optimisation methods have all been extended greatly for increasingly more specific problem structures, and in so doing their conceptual base has been locked into the technique itself and is only presentable via a description of that technique. The fundamental concept is generally one in which objectives are evaluated at a given point in the solution space and a direction chosen which has the steepest feasible gradient (i.e. hill climing). Attempts to avoid local optimum vary from slicing through the solution space along a particular variable (19), to using path restriction or state reduction (20), a 'scenario' approach (21), using a grid of starting points (22), or perturbation (23). Many of the optimisation techniques become increasingly unweildy when stochastic, discrete, and non-linear data is used; where the problem is heavily constrained; or where the solution space is non-convex (24).

3.2.4 Summary

The use of symbolic model types has been directed towards the formulation of computer based models which allow a much more rigorous interrogation of the problem structure. Three forms of symbolic models have been considered.

Simulation can produce a great deal of information about many aspects of a systems performance but for only one predefined solution at a time. There is no comparison of that solution with other feasible solutions unless the analysis is repeated in a process of informal optimisation involving a cyclical procedure of postulation - evaluation - modification.

Generation produces a subset of unranked feasible solutions by following a predefined sequence of rules. There is no statement of performance or relative merit of solutions in the generated set other than that they satisfy these prescribed rules.

Optimisation encompasses the whole field of feasible solutions and produces an ordered subset of those solutions which best satisfy the specified performance objectives. Performance in objectives outside this subset is ignored unless further solutions are produced and investigated in a process of simulation. Preference methods require an artifical reduction of objectives to a single criterion by assignment of weights to problem criteria without full knowledge of the trade-off implications. This makes the relevance of optimisation techniques questionable in poorly defined problem situations.

Optimisation usually subsumes generation and simulation: within an optimisation model generation is necessary to create the solution space which is searched, and simulation is necessary to predict the performance which is to be optimised.

3.3 Model Validation

One of the most important steps in the development of a model is determining whether the model is an accurate representation of the system being studied (25). The substantiation that a model possesses a satisfactory range of accuracy within its domain of applicability, consistent with the intended application of the model, is termed model validation (26).

Clearly, if a model is to be validated, it should be developed for a specific purpose or application and its adequacy or validity should be evaluated only in terms of that purpose. Indeed, a model may be valid in one experimental frame (see Section 3.2.1) but invalid in another. Hence, the validity of a model should only be tested with respect to a set of experimental frames determined by the purpose for which the model is intended, and not for all possible experimental frames (or all sets of conditions) (27).

In a very fundamental way, every model is a predictive instrument. It predicts a value of some outcome as a function of the values of a specified set of variables and constants. Testing the validity of a model amounts to testing its ability to predict (28). Since prediction is itself a procedure for estimating future values of a variable, testing consists of determining the principle characteristics of the estimates yielded: bias and reliability. It is therefore generally preferable to use some form of objective analysis for validating the model, a common form being statistical hypothesis testing (29).

In statistical hypothesis testing there are two important wrong decisions involved in testing the validity of a model under a given experimental frame and for an acceptable range of accuracy:

(i) Rejecting the validity of the model when it is actually valid, and

(ii) Accepting the validity of the model when it is actually invalid.

The probabilities of making these two wrong decisions are the risks involved in the validation process. The probability of making the first type of wrong decision is called model builders risk, and the probability of making the second type of wrong decision is called model users risk. The consequences of the first type of wrong decision are that the model will be revised and retested and the 'cost' of the model building process will be increased unnecessarily. The consequences of the second type of wrong decision are that an invalid model will be accepted and incorrect actions may be taken by the model users. This can be serious, especially when decisions involving expensive resources are made on the basis of the results of the model. Thus, the model user's risk is extremely important and should be kept small in the validation of a model.

A significant influence on the validity of a model is the reliability and the variability of the data it uses, there being two types of data (i.e. real system data and simulated data). The acceptability of data has therefore to be discussed as the acceptability of real system data and the acceptability of simulated data. Acceptability of real system data can be considered with respect to the goal of the study or with respect to the norms of experimentation techniques (30). Variables not readily quantifiable such as ones representing human feelings should be treated particularly carefully. An important problem is distinguishing inaccuracies in measurement (measurement 'noise') from data representing an unkown event or an event with a low probability of occurrence.

The acceptability of simulated data has to be considered with respect to real system data collected under similar conditions.

Finally, the evaluation of a model is not always concerned solely with the validity of a model, but consists also of the acceptability, applicability, and utility of the recommendations. Indeed Elzas (31) points out that validation itself is not always applicable. Different types of systems must be considered spearately; repeatable systems, recurrent systems, unique systems.

"Repeatable systems can be the subject of controlled experiments (e.g. chemical reactions, industrial processes, technical objects). Recurrent systems can generally not be experimented with, but at least present themselves to us with some repetition frequency in their discernable states (e.g. weather changes, stellar formations, specimens of a species). Unique systems can be characterised by a state history that occurs only once (e.g. a climate, the world, evolution). It is clear that validation is readily feasible for the first class of systems, can be considered for the second kind of systems (if enough time and data are available) and is out of the question for unique systems. So models of unique systems can only be speculative, cannot be verified or validated, but only "trusted" to some extent if the modelling techniques used have led to useful results when applied to repeatable or recurrent systems. The main dilemma in the simulation field today is that we can provide some reliable information about a growing number of repeatable and recurrent systems while the society demands trustworthy predictive data on the development trends of unique systems (e.g. demography, energy, politics, etc.)(32)".

4. Comment

The systems approach has proved immensely useful in describing an otherwise complex problem structure economically. A system is not so much an object in itself, as a particular way of viewing an object. By considering the system as a hierarchical set of interconnected components it is possible to decompose the problem into simpler sub-problems; to remove from the problem any redundant and, for the particular context, superfluous detail.

Unfortunately, the ease with which a system can be decomposed is influenced greatly by the depth of the problem hierarchy. Where a particular system is partitioned into a large number of components, this will create a large number of interactions which are difficult to aggregate. It is apparent that a poorly defined problem is similarly difficult to decompose and might therefore be better considered at some higher system level.

The beauty of the systems approach is that it provides a means of selectively isolating the level at which a problem is considered and thereby, itself, is generating the intermediate forms which deepen and stabalise the problem hierarchy for future investigations.

The representation of a system, the precursory of any interrogation of that system, is called modelling.

The advent of computer technology has directed model formulation towards the more readily manipulable, symbolic model types. It would appear that the additional effort involved in formulating, interpreting and understanding these more rigorous models is well justified despite the fact that many still suffer serious drawbacks.

Computer-based simulation models can produce a great deal of information about many aspects of a systems performance, but for only one predefined solution at a time. Generation models allow for the exploration of a range of system states by prescribing a set of decision rules. Some decision making is therefore internal to the model but is not purposeful because all feasible solutions are equally acceptable. Optimisation models select an ordered subset of those solutions which best satisfy the performance objectives, the objectives being artificially reduced to a single criterion state.

There emerges a trade-off between the degree of formalised optimisation and the acceptable tolerance level of the system definition: the more formalised the optimisation process, the less variation allowed in performance objectives (see Figure 5).

The choice between these particular model forms will therefore be influenced by how accurately the performance objectives can be defined. While the utility of a model will

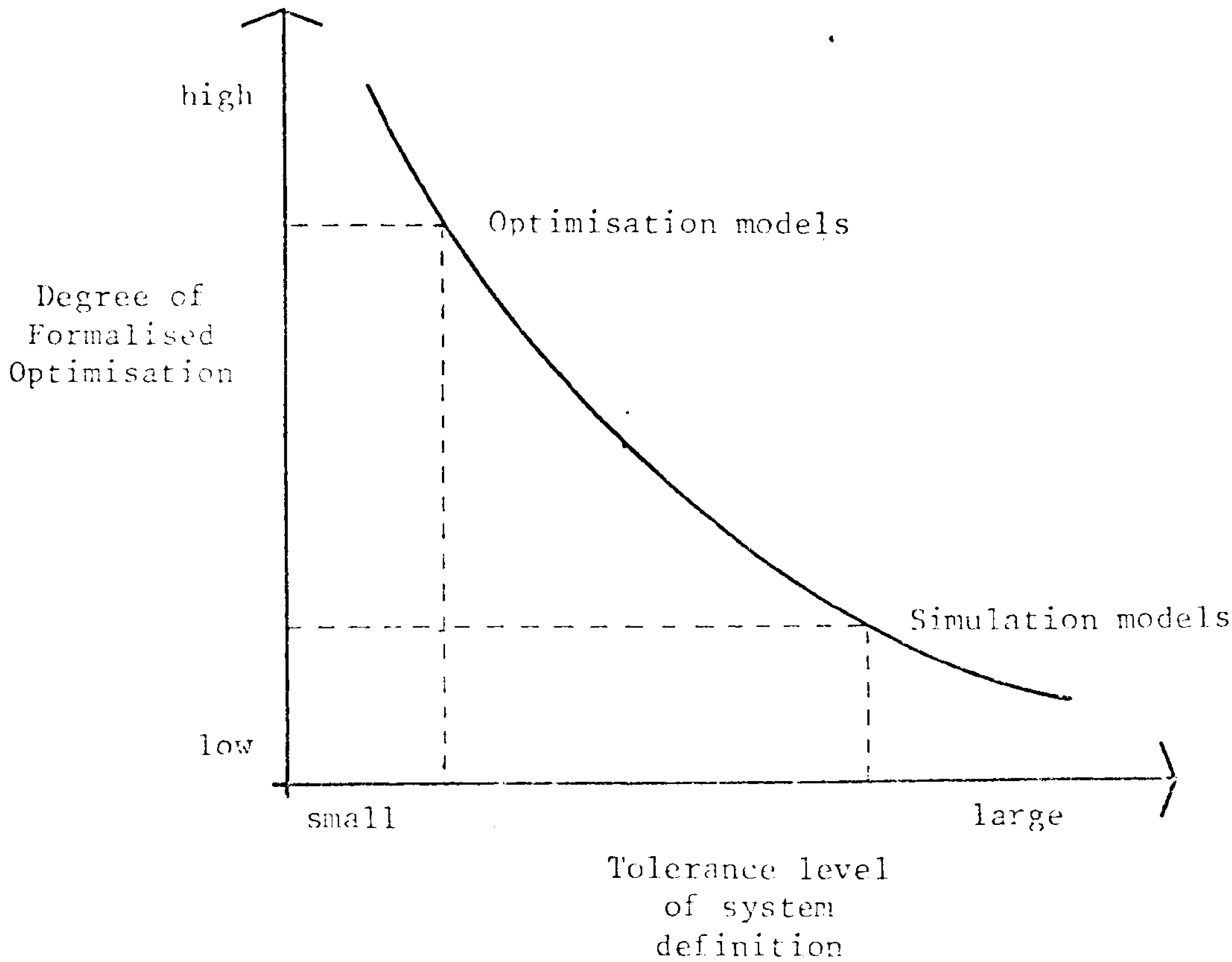


Figure 5: The trade-all between formalised optimisation and system definition

increase the more formalised an optimisation process it achieves, this trend will be reversed if an ability to deal with multiple and ill-defined objectives becomes paramount (see Figure 6).

This disturbance of previously static trends is the concomitant of applying systems and models to increasingly humanistic problem structures. This effect extends also into the realms of model validation where even the general application of statistical hypothesis testing is now questioned.

It is apparent that while immensely successful to date, the use of systems and models to investigate problems whose behaviour is influenced strongly by human judgement, perception or emotions, should be more carefully considered. Given due consideration, however, there is little to suggest that the two approaches should not continue to compliment and extend significantly the processes of human cognition.

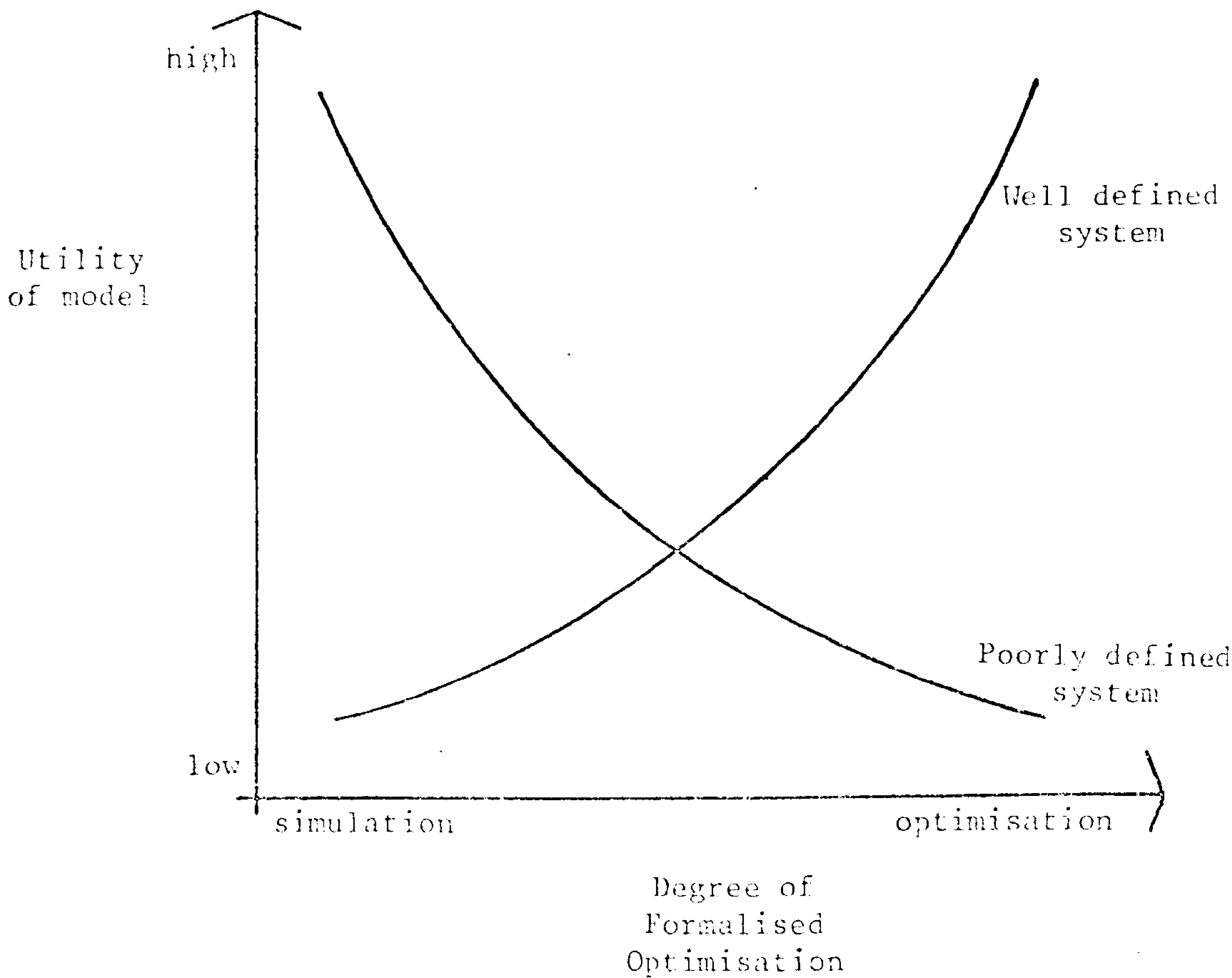


Figure 6: The effect of system definition on the utility of a model

REFERENCES

1. MINSKY M
"A framework for representing knowledge" in "The psychology of computer vision" by P H WINSTON (Editor), McGraw-Hill, 1975, p.212.

2. NEWELL A and SIMON H
"Human Problem Solving", Prentice-Hall, 1972.

3. ABELSON R P
"The structure of belief systems" in "Complete models of thought and language" by R C SCHANK and K M COLBY (Editors), W H Freeman, 1973.

4. KLEINMUNTZ B
"Problem solving: Research, method, and theory", John Wiley and Sons, 1966, p.18.

5. ARBIB M A
"The metaphorical brain", John Wiley & Sons, 1972, p.58.

6. THE OPEN UNIVERSITY
"Systems" Technology Foundation Course Unit 1, The Open University Press, 1971, p.15.

7. SIMON H A
"The sciences of the artificial", MIT Press, 1969, pp.84-118.

8. RITTEL H
"The Universe of design" Faculty seminar - College of environmental design, University of California, Spring 1964, p.28.

9. LINZEY M P T
"That a computer can be intelligent without having a mind" in Design Methods and Theories, Volume 12, No. 1, January - March 1978, pp.60-64.

10. THE OPEN UNIVERSITY
"Systems, Models and Decisions", Technology third level course units 1/2, The Open University Press, 1975, section 2.3.

11. THE OPEN UNIVERSITY
ibid, p.19.

12. KLEINEN J P C
"Statistical techniques in simulation" Part 1, Marcel Decker, 1974.

13. OREN T I and ZEIGLER B P
"Concepts for advanced simulation methodologies" in Simulation, Vol. 32, No. 3, March 1979, pp.69-82.

14. LAWSON B
"How designers think", The Architectural Press, 1980.

15. GERO J S
"Computer-aided design by optimisation in architecture" in Design Studies, Vol. 1, No. 4, April 1980, pp.227-230.

16. RADFORD A D and GERO J S
"On optimisation in computer-aided architectural design", Computer Report CR34, Department of Architectural Science, University of Sydney, 1980.

17. ROSENMAN M A, RADFORD A D and GERO J S
"Postoptimality analysis in dynamic programming" in Engineering Optimisation, Vol. 4, No. 4, 1980, pp.207-214.

18. MEISEL W S
"Trade-off decisions in multiple criteria decision making" in "Multiple criteria decision making" by J L COCHRANE and M ZELENY (Editors), University of South Carolina Press, 1973, pp.461-476.

19. WILDE D J
"A review of optimisation theory" in Industrial and Engineering Chemistry, Vol. 57, No. 8, August 1965.

20. NORMAN J M
"Heuristic procedures in dynamic programming", Manchester University Press, 1972.

21. SALVADORI M G
"Is automated architectural design possible?" in "Basic questions of design theory" by W R SPILLERS (Editor), North Holland, 1974, pp.95-102.

22. WILDE D J
"Optimum seeking methods", Prentice-Hall, 1964.

23. BASTIN C R W
"Notes on AIM: a process for solving quantitative problems of arranging spaces during building design", Department of Architecture, University of Bristol, December 1974.

24. WILSON A J
"Cost modelling in building design" in Chartered Surveyor Building and Quantity Surveying Quarterly, Vol. 5, No. 4, Summer 1978, pp.64-65.

25. BALCI O and SARGENT R G
"A methodology for cost-risk analysis in the statistical validation of simulation models" in Communications of the ACM, Vol. 24, No. 4, April 1981, pp.190-197.

26. SCHLESIGNER S et al
"Terminology for model credibility" in Simulation, Vol.32, No. 3, March 1979, pp.103-104.

27. SARGENT R G
"Verification and validation of simulation models" in "Progress in modelling and simulation" by F E CELLIER (Editor), Academic Press, 1981.

28. ACKOFF R L
"Scientific Method", John Wiley & Sons, 1962, p.392.

29. SCHRUBEN L W
"Establishing the credibility of simulations" in Simulation, Vol.34, No. 3, March 1980, pp.101-105.

30. OREN T I
"Concepts and criteria to assess acceptability of simulation studies: A frame of reference" in Communications of the ACM, Vol. 24, No. 4, April 1981, pp.180-189.

31. ELZAS M S
"Results of a simulation: Can they be trusted?" in Proc. Seminar on Modelling in Business of IFIP Applied Information Processing Group, Amsterdam, January 1978, pp.170-183.

32. ELZAS M S
ibid, p.82.

APPENDIX II : A REVIEW OF CURRENT COST ESTIMATING PRACTICE AND APPROACHES TO COST MODELLING

APPENDIX II: A REVIEW OF CURRENT COST ESTIMATING PRACTICE AND APPROACHES TO COST MODELLING.

1. Introduction

The purpose of this review is to describe the 'state of the art' in cost modelling. This, not by any detailed description of a particular model, but by an evaluation of the comparative performances of the various model types in respect to the requirements of design. The review is considered a necessary adjunct to the thesis for two reasons:

(i) It describes the existing practice; the foundation of any subsequent cost modelling technique.

(ii) It identifies current attempts to improve existing techniques; a source of possible building blocks for subsequent cost modelling techniques.

The reportage will not instance every application encountered in the survey because;

(i) some models are intended to be applied too late in the design process to have any significant effect,

(ii) certain models are very similar in terms of their advantages and disadvantages, and generally

(iii) reportage in the field is not good.

The intention of the review, rather, is to exemplify the range of approaches and related techniques in the following classes:

(i) Current practice

(ii) Automated costing processes

(iii) Statistical analyses

(iv) Parametric studies

(v) Theoretical analyses

(vi) Simulation

(vii) Optimisation.

2. Current Practice

The function of a cost model in current building design practice is usually associated with a process of cost planning. Until the 1950's cost planning was not generally practiced since the methods of estimating cost at an early stage of design were crude and inaccurate in many situations.

The methods consisted of multiplying a cost per cube or superficial unit of building by the volume or area of the proposed project. The unit rates were based on experience of similar, previous projects but were difficult to apply since two buildings having the same volume, or same area, may be constructed entirely differently, and differently designed.

Figure 1 shows three such buildings; A, B and C. A and B have identical volumes, A and C have identical gross floor areas, and yet clearly none are even remotely comparable.

A first attempt to produce realistic cost estimates early in the design process was the storey-enclosure method (1). It introduced factors to account for the number of storeys, storey heights, basements, and areas of enclosing walls, which when multiplied by the area of each gave a total number of Storey Enclosure Units. The method had gained very limited attention when, in the 1960's, elemental cost planning was developed.

This was the first real planning technique, because it allowed control of costs. Control achieved by:

(i) Setting a cost target or plan
(ii) Providing a mechanism to check the achieved performance against the agreed target or cost plan
(iii) Identifying prefered remedial action.

Unfortunately most 'text book' descriptions of cost planning relate to the 1960's, sequential-type model of design (2) as illustrated in Figure 2. (The distinction between 'text book' descriptions and what happens in practice is evidenced later).

The five processes identified in 'text book' descriptions

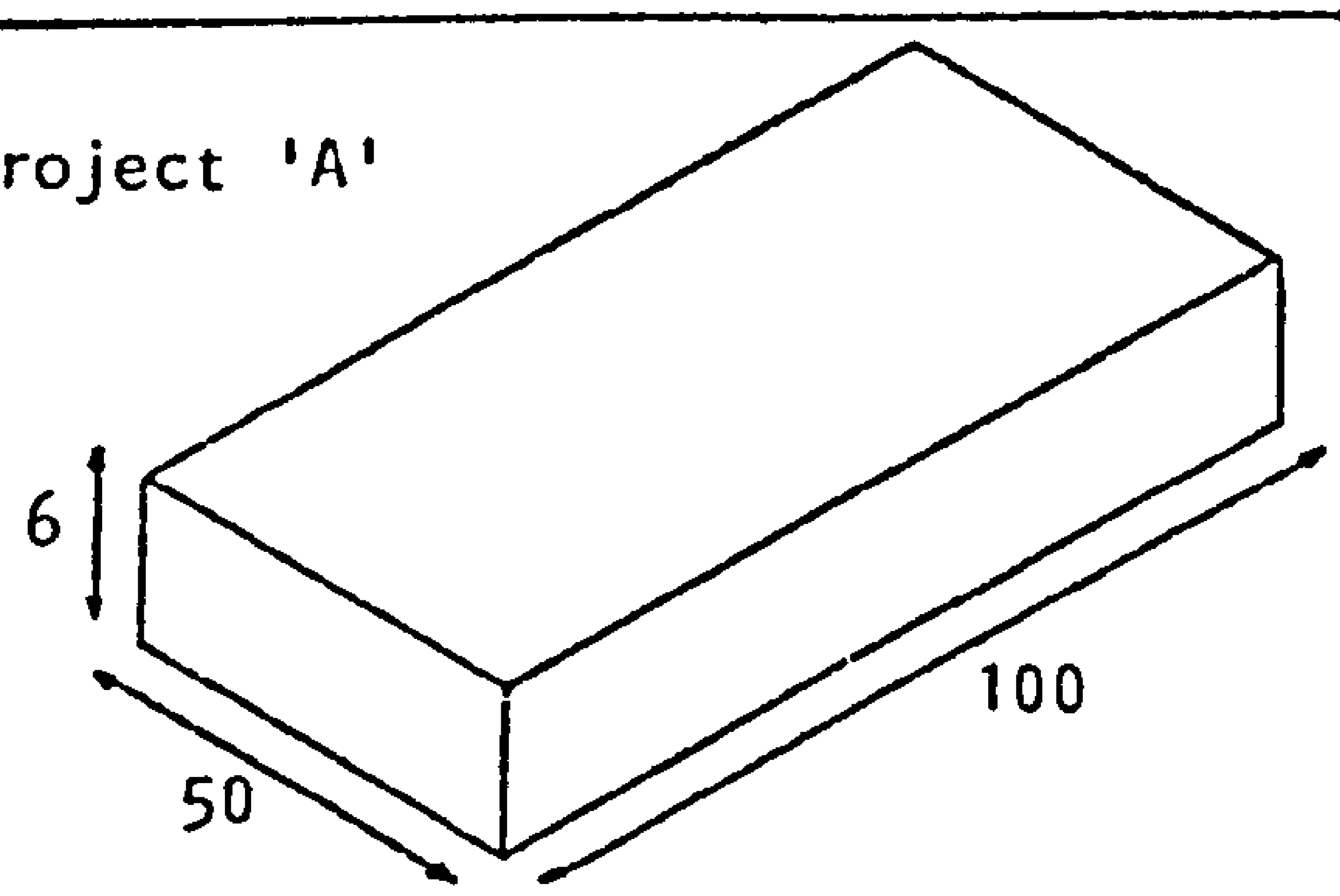
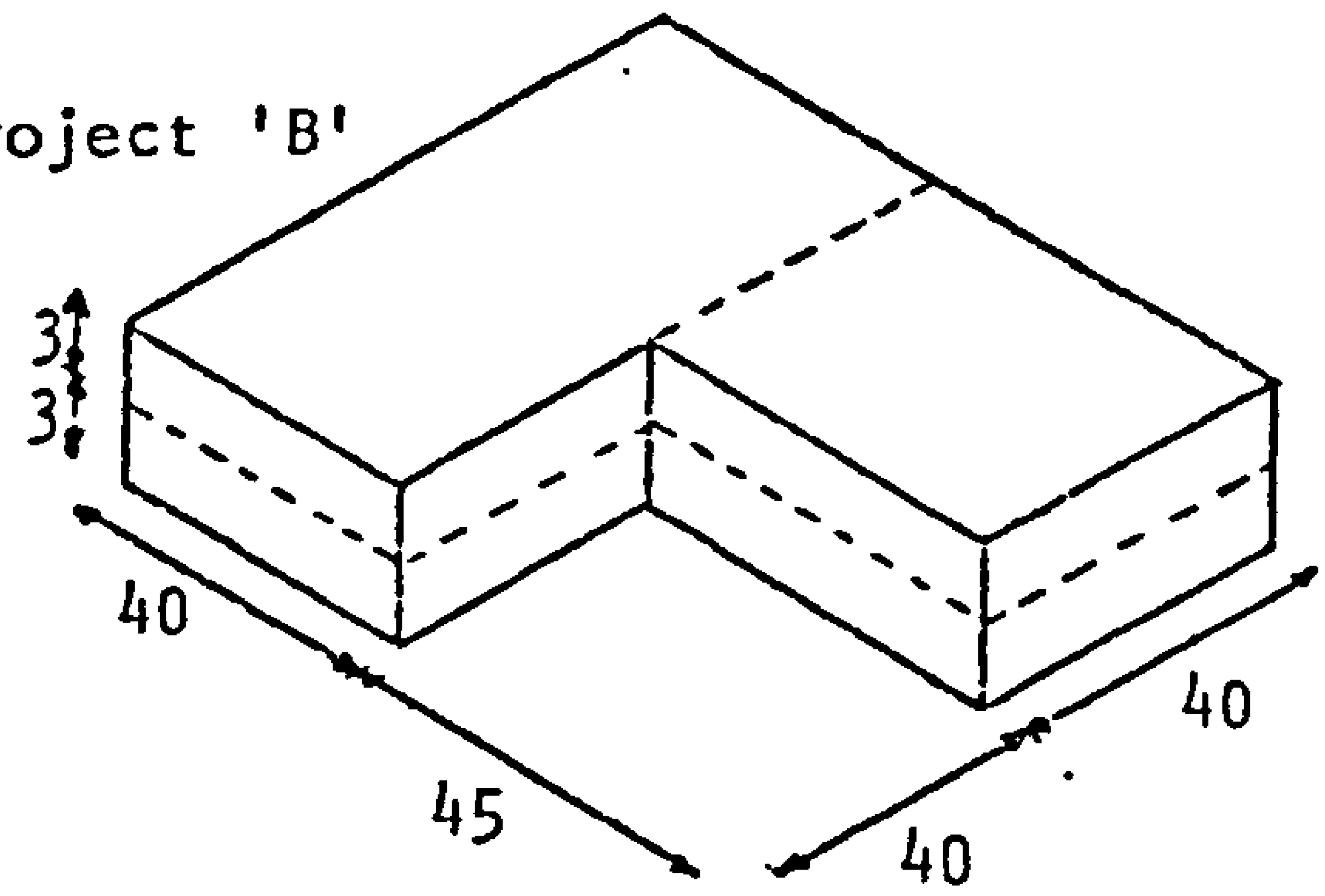
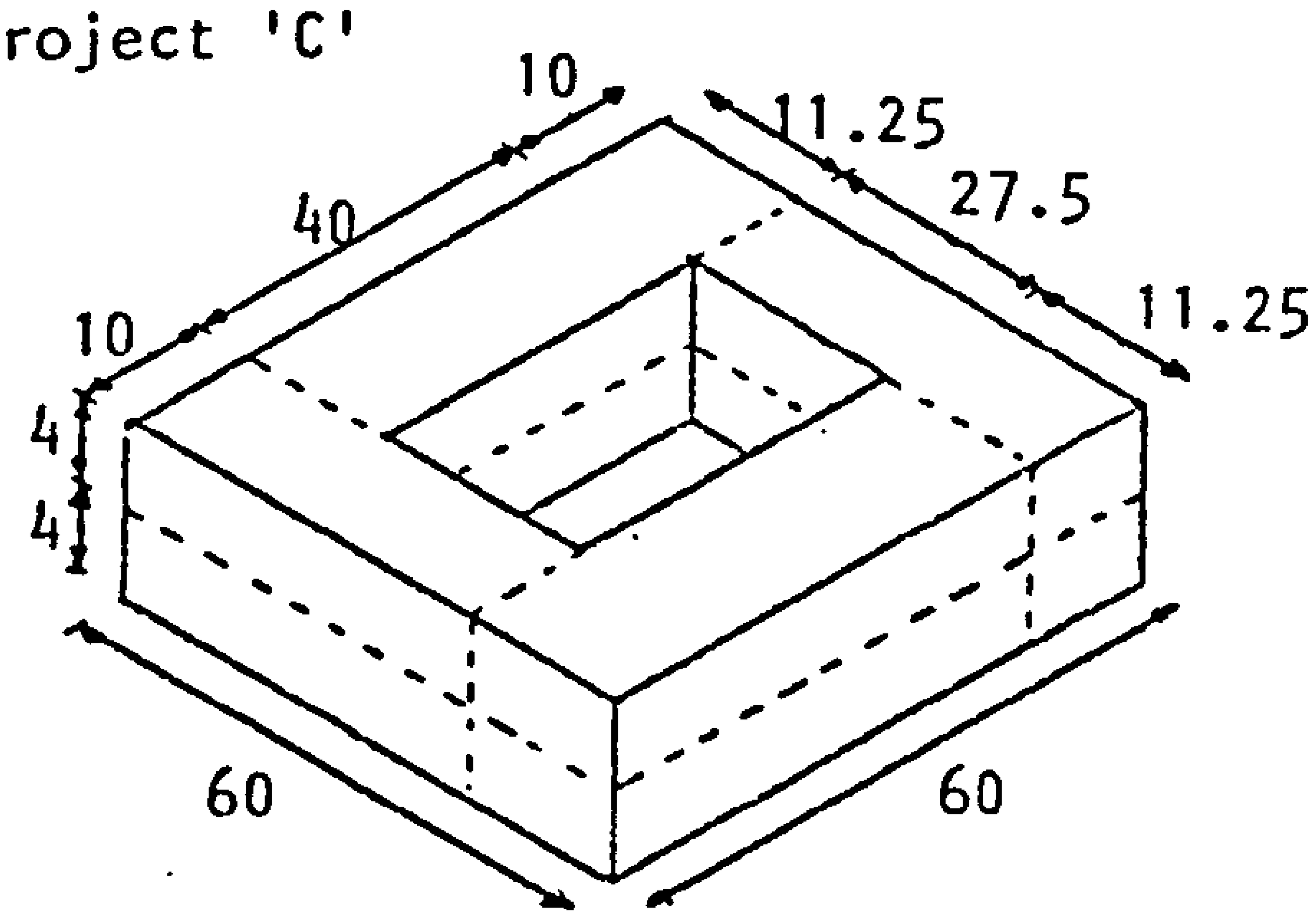
	VOLUME (m3)	G.F.A. (m2)	EXT.WALL (m2)	INT.WALL (m2)
Project 'A' 	30,000	5,000	1,800	0
Project 'B' 	30,000	10,000	1,980	240
Project 'C' 	20,000	5,000	3,000	340

Figure 1: Example geometries for three projects

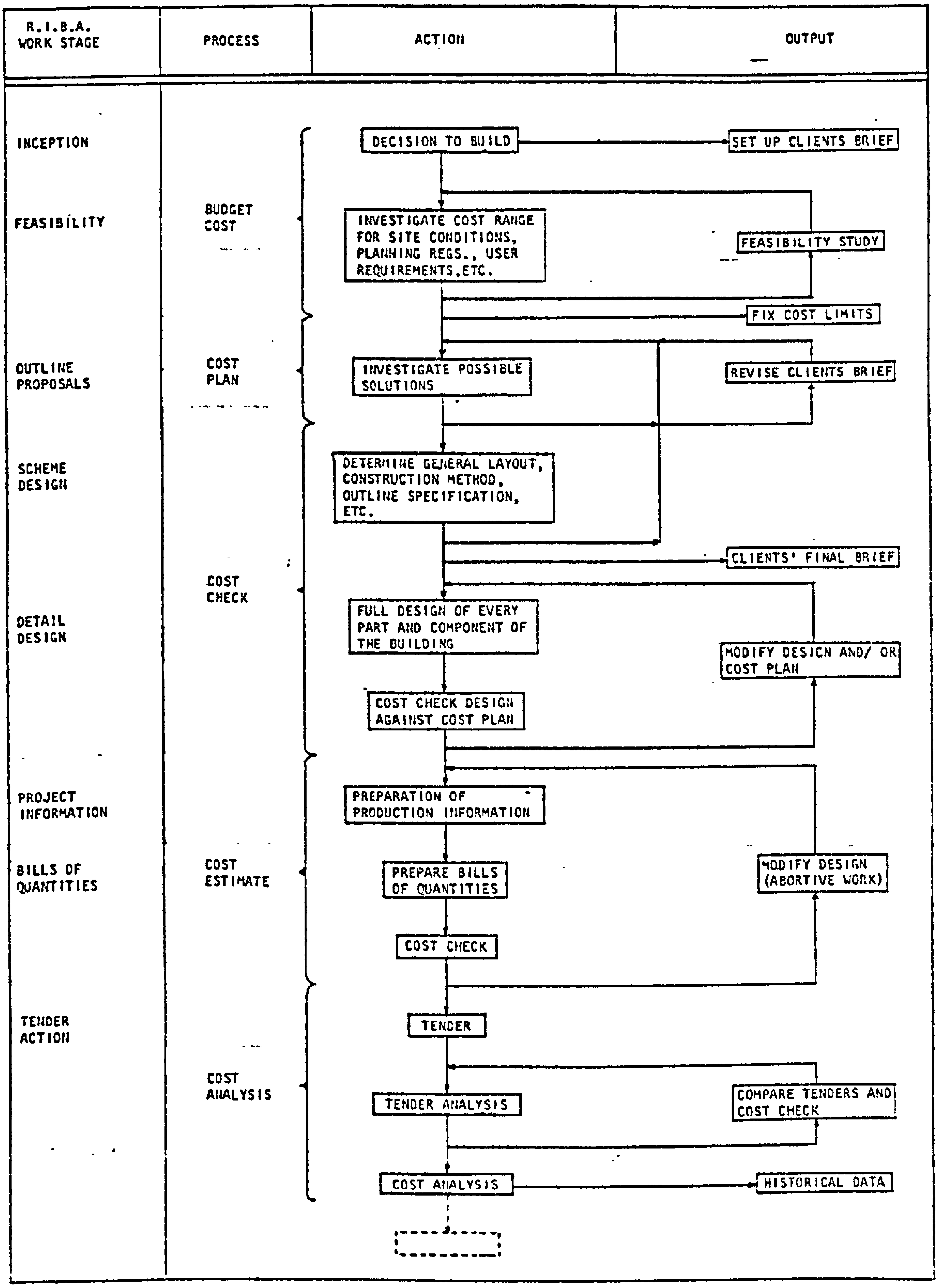


Figure 2: The cost planning process in relation to a sequential type model of design

are defined as:

(i) Budget cost - The intention is to consider the feasibility of providing the clients requirements within a given cost limit, or to establish the sum of money that would be necessary to fulfil the brief. Estimates at this stage are usually prepared before any drawings are available and are therefore based on quite coarse information.

(ii) Cost plan - The designer is expected to investigate a number of solutions through various block and sketch plans. Once a particular scheme and budget are approved, the budget is broken down into a cost plan. Amounts are deducted from the budget cost to be held in reserve for design and pricing risk. (The 'design risk' is a sum of money to cover unforseen problems which may arise during detailing. The 'price risk' is an amount to cover fluctuations in price before tender date which have not been allowed for in the unit rates), the remainder being allocated between the various elements; namely substructures, superstructures, services, etc.

(iii) Cost check - During the development of the detailed design, the proposals are continuously checked against the cost plan. As each element is designed, its effect on total cost is apparent and indicates when savings must be made in subsequent elements or, conversely, when additional money is made available.

(iv) Cost estimate - Once the detailed design has been completed a final cost check is undertaken before going out to tender.

This is also used as a basis for comparing submitted tenders.

(v) Cost analysis - This is a feedback process used to increase the accuracy of estimates for future projects.

A recent survey of cost planning in practice concluded that "the design process is more complex than portrayed by the conventional model" (3). The survey found that the categories produced by budget cost, cost plan, cost check, cost estimate and cost analysis were unsatisfactory, as techniques bearing no relation to each other were being grouped together. Using instead seven categories, a pattern emerged as Figure 3 and revealed cost planning as a flexible system, tailored to suit individual projects by choosing alternative routes from brief through to tender.

The survey also identified eight different estimating techniques which, it purports, represent all approaches to

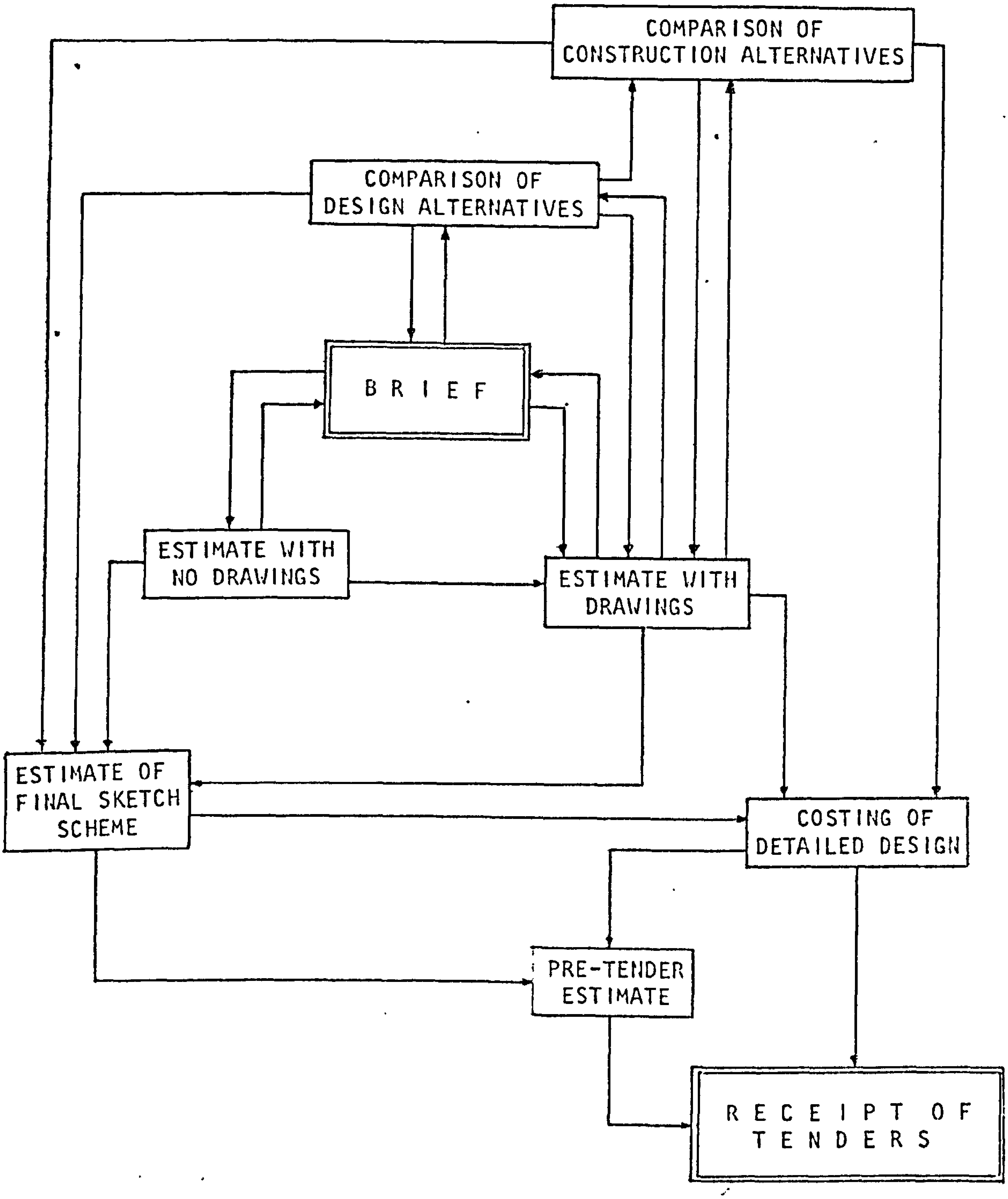


Figure 3: Cost planning as the dynamic process identified in practice (After, 'A construction Cost Data Base', PSA, 1980)

estimating employed in current practice (4).

(i) Cost limit calculation - Some public sector building has a published cost limit which is determined by given formulae. These cost limits are treated as a budget cost within which the building must be designed.

(ii) Floor area method - The improved feedback of regular cost analysis has increased the cost data available for comparable buildings. The accuracy of multiplying a rate per superficial area by the gross floor area of a proposed building has therefore also been improved.

(iii) Functional unit method - When the requirements of a building can be expressed in terms of user units, such as bed spaces, school places, car spaces etc., then an estimate of cost can be determined by multiplying the desired number of units by a cost per unit.

(iv) Elemental cost estimating - Using historic analyses and adjusting for changes in quality, quantity, and pricing levels, a cost per unit of gross floor area for each element or sub-element is produced.

(v) Lump sum estimate - A single figure which is essentially an informed guess with little supporting calculations.

(vi) Cost per square metre for functional use - The gross floor area is sub-divided into various functional types. The area of each functional type is them multiplied by a rate per superficial area for that particular function.

(vii) Approximate quantities - Major items of work are identified, and quantities of each calculated. A price per unit of each item is composed, usually combining several minor items into the one rate. Each item is then multiplied by its corresponding unit rate, and summed to give the cost estimate.

(viii) Pricing the Bills of Quantities - All items are priced and multiplied by the respective quantities. The sum of these totals gives an estimate of cost.

Although all eight techniques were observed, there was a clear preference for using approximate quantities (see Figure 4). The figures also showed a greater variety of techniques being used during the early stages of design, but with no technique being applied to all processes.

2.1 Comment

(i) Current practice has evolved over many years, and is therefore very familiar to designers. The cost information is well filtered by the cost adviser so

Process	Number of different techniques observed being used	Preferred technique	Approximate percentage of total usage	Other significant techniques
Estimate with no drawings	6	A	50	B
Estimate with drawings	5	G	40	B & D
Comparison of design alternatives	4	D	40	G
Comparison of construction alternatives	3	G	90	-
Estimate of final sketch scheme	3	G	85	-
Costing of detailed design	2	G	80	D
Pre-tender estimate	2	H	90	-

where A = Cost limit calculation
B = Floor area method
C = Functional unit method
D = Elemental cost estimating
E = Lump sum estimate
F = Cost per square metre for functional use
G = Approximate quantities
H = Pricing Bills of Quantities

Figure 4: The usage of cost estimating techniques, as observed in practice (From: 'A Construction Cost Data Base', PSA, 1980)

as to be as consistent as possible, but the amount of information presented at any one time is unlikely to exceed the bare minimum. In addition, the current methods of estimating cost during the early stages of design are highly inaccurate (5) and fundamentally inconsistent with the preferred technique of approximate quantities.

(ii) Although in certain instances the cost adviser is appointed at the beginning of the design process, his knowledge of building economics is limited and invariably intuitive. The multifarious nature of building design has meant that published cost relationships are either invalid in the vast majority of situations, or so general as to be of no use. Few investigations have gone to some level of detail as the Wilderness Report (6), in which the cost implications of various steel column spacings were examined, because of the time and cost involved in developing a design tool of such a limited useful life - the assumptions inherent in the Wilderness Report would already be partially invalid by the time it reached publication. The predictive and prescriptive capacity of the cost adviser will continue to be severly limited if current, manual-dependent techniques are not superseded.

(iii) The number of statistical investigations of cost analysis provide an increasingly refined source of information on comparative projects (Building Cost Information Service (7), Property Services Agency, etc.) Unfortunately the cost adviser appears reluctant to phrase a current projects cost information in similar terms (8). For instance, it is rare for an estimate to be qualified by an expression of its statistical accuracy, or by giving a description of the population characteristics (means, standard deviation, etc.) for that building type.

(iv) The gravest short comings of current practice already exist in the early stages of design, when information is most needed. The techniques used are very dependent on human manipulation which makes them slow and cumbersome to relate to the design activity. Cost information from such a passive system will fail increasingly to satisfy the immediate requirements of a designer, and directly limit the number and range of design options considered.

(v) The staging effect of changing from one costing technique to another has created a costing system which tends to be uni-directional with poor review procedures: cost estimates determined by statistical analyses are often incompatible with estimates based on human judgements. Further, as the costing process becomes more distinct from the design process, a designer can lose touch with the dynamics of cost - he can lose his 'feel' for cost. Current practice does not encourage an interrogation of cost during design because of time restrictions. The trend, unfortunately, is towards a 'black-box' treatment where the output is considered in terms of the input required to achieve it and not as a means of determining why a particular input gives a particular output: too much emphasis has been placed on considering the effect, rather than analysing the factors that cause price differences for building work (9).

3. Automated Costing Processes

While traditional costing techniques are themselves cost models, they were not generally considered as such until the processes were automated. The initial automation was commensurate with advances in computer-aided architectural design (CAAD) which demanded a computable, and thereby mechanised, costing system.

GOAL (General Outline Appraisal of Layouts) (10) is a computer package which allows the designer to appraise and modify a sketch design in terms of a number of performance criteria including capital cost. The user inputs typical unit costs for selected elements (substructures, external walls, roof, etc.) depending upon their construction type. A choice of 'quantity' is then made to correspond with the units costed (total upper floor area, total external wall area, total roof light area, etc.) The various unit quantities for a particular design are then calculated automatically and mulitplied by the corresponding cost, outputting an elemental cost plan for the given configuration.

Most CAAD packages of this ilk use a single element unit cost, multiplied by an element unit quantity, to cost the design.

3.1 Comment

(i) The validity of the technique is limited to a range of solutions close to the original, both in form and in timing. They are, however, consistent with existing practice, easy and cheap to use.

(ii) The capacity iteratively to perturbate, is the only assistance such a model can give to solution generation - and this is mainly a reflection of the speed of the computer.

(iii) The technique does not relate the cost of a proposed design directly to other projects, but the unit rates used are often 'average' costs and imply 'average' quality.

(iv) The mechanisms are quite static and relatively inflexible, making them even less applicable to innovative design.

4. Statistical Analyses

The successes of statistical techniques in the pure sciences, has led many to apply their rigour to the study of building cost. Typically, regression analysis has been applied to whole building analysis, as well as the various building elements individually.

The basic technique is to choose a number of raw variables (preferably less than a third of the number of variables available), and record values for each in a series of different projects (Beeston (11) maintains that up to 500 different projects are required to give a realistic spread, but most investigations have been on data sets of well less than 50 projects). A line of 'best fit' through the scattered points is computed using the 'least squares' method and a linear equation derived. Consideration is then given to the significance of each variable in turn with those statistically insignificant being discarded, provided that the square of the correlation coefficient retains an acceptable value. Various checks can be initiated to ensure that what the regression analysis has been unable to explain is due entirely to chance. (Most basic statistical text books consider regression analysis in more detail than has been possible here - especially in respect to non-linear regression. The limitations of the technique are strict, and further reading is recommended before any application is considered (12)).

McCaffer (13) used a regression technique to analyse the total cost of residential flats, and derived the equation:

$$T = 36001.75 + 169.84A + 137.38B + 2553.80C + 3049.53D + 139.85E + 395.88F + 13335.43G$$

where
- T = total cost per residential flat
- A = area of a single unit
- B = area of a double unit
- C = number of storeys
- D = number of lifts x number of storeys
- E = total access area
- F = common room areas
- G = number of garages

Gould (14) has also applied regression to the heating, ventilation, and air conditioning installations of a building, while Buchanan (15) and Bowen (16) have each analysed the structural frame only.

Kouskoulas and Koehn (17) constructed a cost function for whole buildings in the form:

$$T = f(A + B + C + D + E + F)$$

where
- T = cost per superficial unit
- A = a value for location based on indices
- B = a value for a price index utilising historical data
- C = a value for the average superficial unit rate of a particular building type
- D = a value for the building height (the number of storeys)
- E = a value for building quality. To define a value for such a variable, let Xj, j=1, 2, ...k, denote the average cost portions of the total building cost destributed among the 'k' building components. Assign an integer index, Y, from 1 to 4 to each component (corresponding to fair, average, good, excellent) and compute the value of the variable from:

$$E = \frac{1}{k} \sum_{j=1}^{k} Yj\ Xj$$

F = A value for building technology, from:
- F = 1 for normal
- F > 1 for extra costs of special features
- F < 1 for savings through new technology

Solving for all six variables simultaneously on a number of projects, and conducting regression analysis, produced the cost estimate function:

$$T = 23.93A + 10.97B + 6.23C + 0.167D + 5.26E + 30.90F - 81.49$$

where T = cost per square foot

A = location
B = price index
C = building type
D = building height
E = quality
F = technology.

A review of the estimating function showed that the most subjective variables, quality (E) and technology (F), were also the ones with the highest correlation coefficient: the elimination of 'E' and 'F' increased uncertainty to an unacceptable level.

An alternative use of statistics has recently been undertaken by Zahry (18). Using the computer program MAGIC (Multivariate Analysis by Graphical Interative Computing) (19) a series of cost analyses from the Building Cost Information Service (BCIS) were systematically clustered in multi-dimensional space, by applying a number of selected building descriptors (examples of a building 'descriptor' would be the length to breadth ratio, if the building is framed, if a basement is required, etc.) The cluster of data sets to which the proposed building is allocated are then considered to be directly comparable. A simple process of interpolation can then determine the elemental unit rates for the proposed building.

4.1 Comment

(i) Derived from a given range of data, and therefore likely to be valid for only that limited range, the accuracy of a statistical analysis is reduced when applied to a different data set and deteriorates rapidly over time. Most models can be updated using indices, but recent developments suggest that re-computation at each instance may now be practicable.

(ii) Requiring only outline information, the models provide useful predictions during the early stages of a design process. However, being incompatible with subsequent techniques, the later decisions are impaired.

(iii) The technique, by definition, relates directly to historical data and is in fact often restricted by the lack of suitable data.

(iv) Most models are 'stand-alone', but although quick and easy to use, are static and relatively inflexible.

(v) Because all decisions must be related to total cost and a reduced number of variables may promote multi-colinearity, models will often give conflicting output.

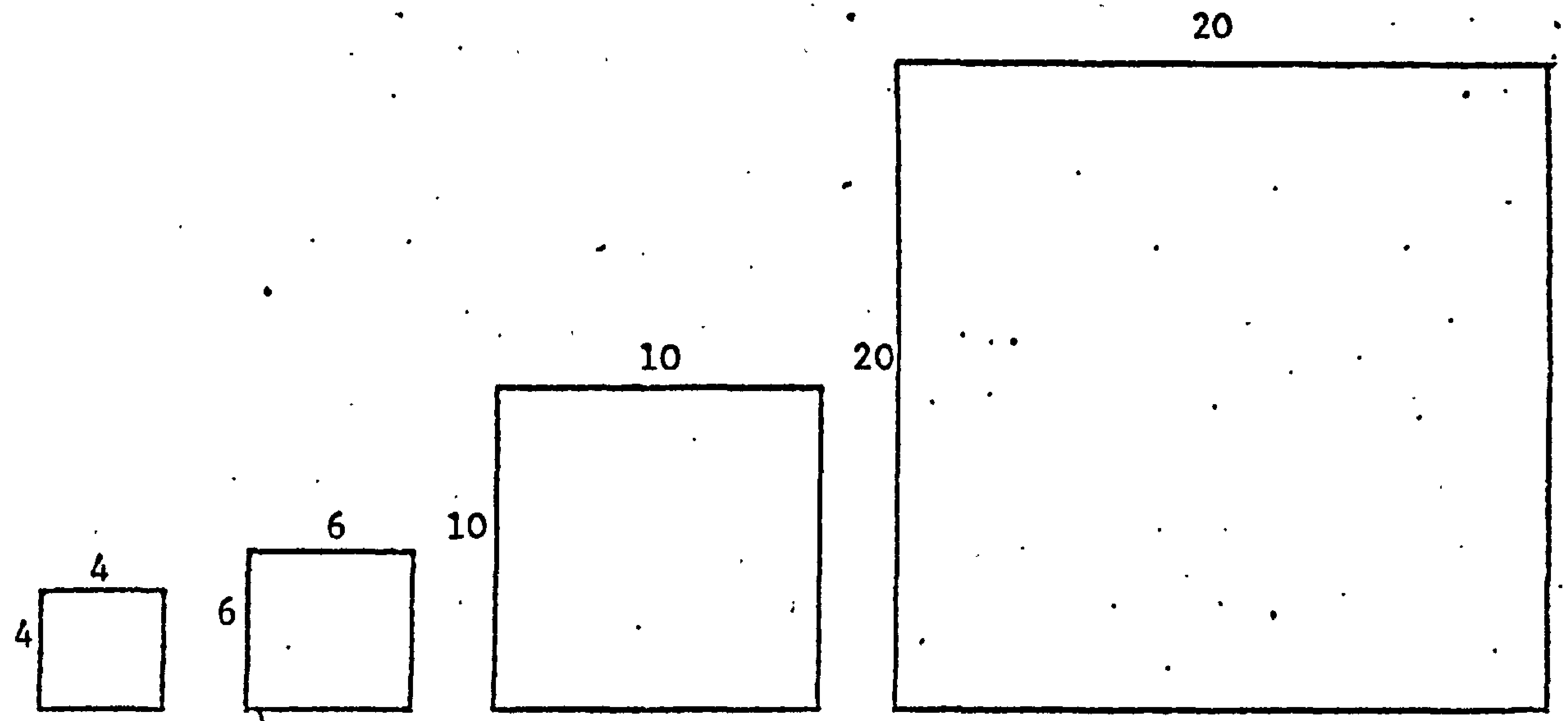
5. Parametric Studies

The basic procedure in any parametric study is to consider each variable individually, and to then record the effect of a change in that variable on another chosen variable (most often overall cost).

A typical study was that undertaken by Pugh (20) in which simple hypothetical buildings of various shapes and sizes were costed and parametric relationships examined. A classic illustration is the effect of plan size on the cost of the enclosing wall element, as shown in Figure 5.

Perhaps the most adventurous parametric study using hypothetical buildings was undertaken by Meyrat (21), in which several hundred plans of dwellings with a certain number of characteristics in common (such as their usable floor areas, services elemental unit rates, etc.) were drafted and costed. The costs of each project were then compared to each other, the work in question being grouped according to the parameter to be studied. From this work was formulated an algebraic method of examining different geometric parameters separately (the ARC method). The cost per dwelling consisted of the cost per dwelling alone, plus the cost of associated out buildings, infrastructure, etc. - for example the cost of the dwelling alone, was based on the formula:

$$T = (\sqrt{A} \times B \times C \times D) + (A \times E) + F$$



	A	B	C	D
Perimeter (m)	16	24	40	80
Area (m2) of enclosing walls* at £25 per m2	56	84	140	280
Cost of enclosing wall	1400	2100	3500	7000
Floor area (m2)	16	36	100	400
Cost of enclosing wall per m2 of floor area	87.50	58.33	35.00	17.50

*Assume building height of 3.50 m

Figure 5: The effect of plan size on the cost of the enclosing wall element per square metre of gross floor area

where T = cost of the dwelling
A = ratio of usable to gross floor area
B = the perimeter coefficient (total room perimeter divided by the square root of 'A').
C = floor to ceiling height
D = cost per square metre of vertical walls (facades, partitions, etc.)
E = cost per square metre of horizontal works (floors, coverings, etc.)
F = price of services per dwelling.

ARC was subsequently used to study the effects on cost of structural design, a marginal square metre, habitable floor area, number of floors, and length of facades. However, the limitations of time in preparing suitable projects in this way (i.e. by hand) has meant that most investigations are based on existing buildings.

Regdon (22), for example, was able to examine 1785 dwellings in buildings up to 20 storeys high. On investigation it was indicated that the costs of future dwellings could be determined on the basis of eight parameters. Diagrams representing the influence of each parameter on building cost were scaled and the parameters ranked in order of importance.

More extensive studies of building cost have also been made. Steyert (23) describes a parameterisation model consisting of over five hundred pages of formulae, tables and curves.

Flanagan (24), extending the previous work of Tregenza (25), chose to consider only two parameters: capital cost, and the number of storeys. Analysis of 15 projects identified a U-shaped curved relationship of the form:

$$T = (A \times B) + (C \times \frac{1}{B})$$

where T = cost per square metre
A & C = constants
B = number of storeys

Of course many of the other forms of cost model, especially the simulation model, may also be used for parametric studies. The flexibility of a parametric approach is exemplified by the use of what is essentially a resource management model called Project Cost Model, which has been used to analyse the complex relationships of time and money (26).

5.1 Comment

(i) Very similar to statistical analysis in terms of its validity, but with an even more restricted range and further reduced number of variables, the parametric model is usually related to early design decisions and is of little use except where the provision is well defined and relatively static. Given favourable conditions however, speed and simplicity help to make it quite a useful technique in predicting general cost relationships.

(ii) A parametric model does not enable the user to compare previous projects directly.

6. Theoretical Analyses

A theoretical model of cost is a prerequisite of any practical application of cost modelling, though not all will state the theoretical base as formally as Brandon (27).

Despite the excellent work of Myer et al (28) in the mid-1960's there is still a distinct lack of generally accepted laws and principles governing cost. The problem may well be that no one individual has a sufficiently comprehensive knowledge of both design and construction to be usefully objective. For example, the theoretical base of the Operational Bill (29) failed to recognise fundamental requirements of the design process (30) while, conversely, Swinburne (31), in dealing with design requirements, fails to recognise that independent functional entities are often interdependent in terms of construction activities. The Joint Working Party on Measurement Conventions, under the auspices of the Royal Institution of Chartered Surveyors and the National Federation of Building Trade Employers, typifies attempts to gain objectivity by having a number of representatives from the various disciplines (32). Unfortunately these have often tended, as much through selfprotectionism as anything else, towards an inevitable 'compromise'.

Much interesting information did emerge from work done in the data processing field, especially during the 1970's (33, 34).

6.1 Comment

(i) There is no generally accepted theoretical model of cost, and yet a theoretical base is inherent in all cost models.

(ii) If all bias could be eliminated, a theoretical model would contribute substantially to the quality of cost information available. Unfortunately many theoretical models are bias, and, perhaps even more importantly, most depend upon a utopean design process radically different from current practice. If the costing process 'tail' is not to wag the design process 'dog', perhaps an adage from the field of data processing should be applied: "Accept the data requirements of the industry in terms of 'what' information is communicated, and coordinate instead 'how' the information might be transferred". That is to forget about optimising cost estimating in respect to some utopian design process and to concentrate instead on rationalising the costing process in respect to current, existing design practice.

7. Simulation

Simulation attempts to mimic the structure of the system to be modelled.

Smith (35) describes a very simple model in which the 'simulation' is merely to replicate knock-on effects of certain variables by using given variables to derive others. For example, by inputing gross floor area, a square index, the density of vertical division, number of storeys, and floor to ceiling height, the model calculates external wall area and the area of internal vertical division: as,

$$S = A \times B \times (4 \times C \times \frac{\sqrt{D}}{B})$$

$$\text{and } T = A \times \left[(D \times E) - (2 \times B \times C \times \frac{\sqrt{D}}{B})\right]$$

where S = area of external wall
T = area of vertical divisions
A = floor to ceiling height
B = number of storeys
C = square index
D = gross floor area
E = density of vertical division

A slightly more sophisticated approach is that of Powell and Chisnall (36) who attempted to simulate the estimating process using the program BECON. The program is structured around a 'typical' elemental cost estimating process, as in Figure 6. Where required inputs to BECON are not yet known by the user default values are calculated from a minimum of basic information.

Townsend (37) has extended the automatic generation of quantities quite considerably. By investigating Codes of Practice, Building Regulations, minimum specifications, etc., it has been possible crudely to simulate the entire design decision-making process for an office building. A choice of basic construction types are available which can be varied so that the consequences of each action may be evaluated.

Moore and Brandon have also attempted to simulate the design deision process, but only for insitu reinforced concrete frames (38). This approach has the added sophistication of a program which is linked directly to a costing mechanism: rather than having to input unit rates, each project is individually evaluated from basic resource costs of labour, plant and material. The program can then compute unit rates specific to the proposed building characteristics automatically.

Flanagan (39) recognises the importance of relating design to construction if the 'true' cost consequences of a design decision are to be considered. A network of about 100 activities

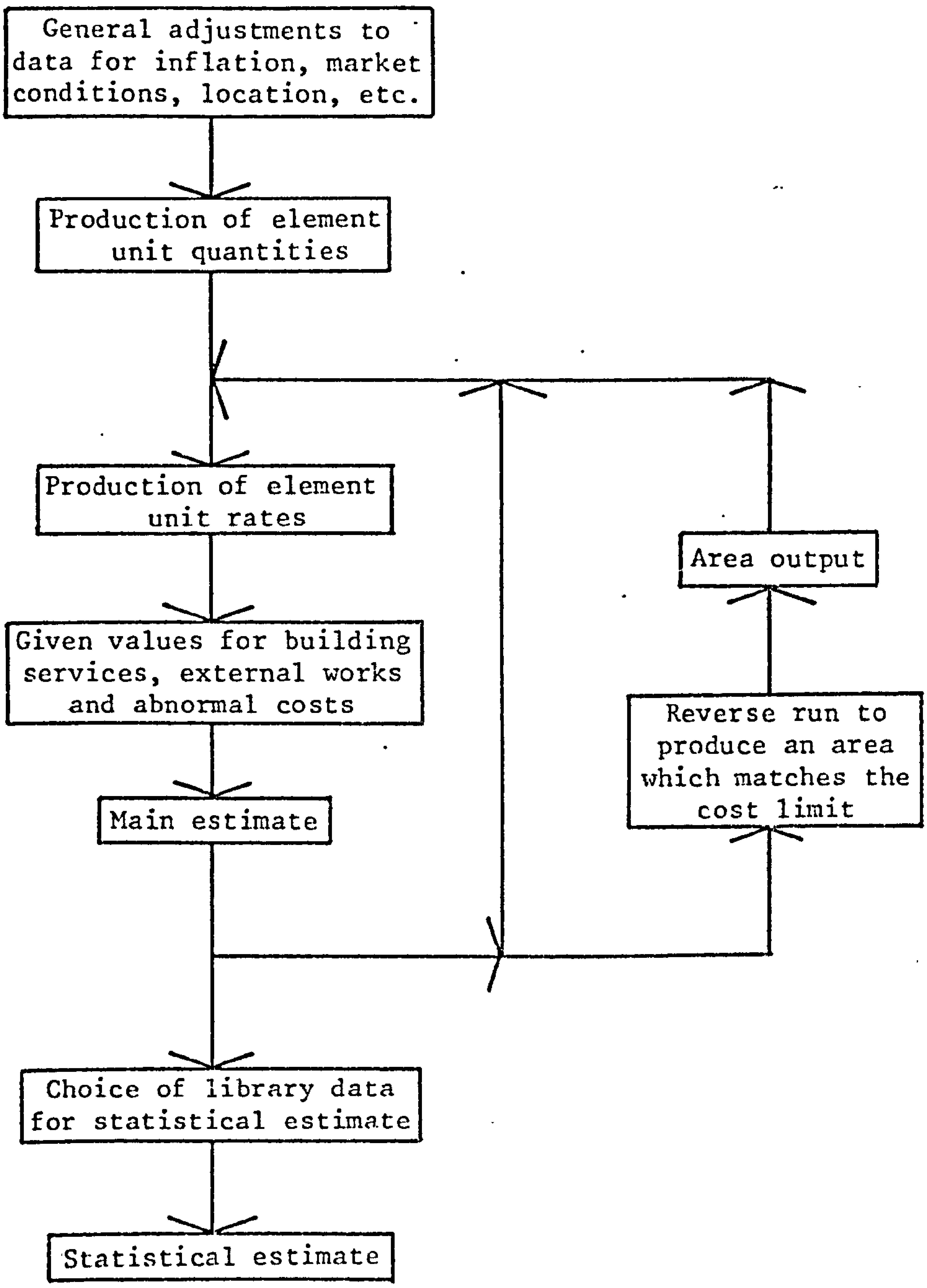


Figure 6: The elemental cost estimating process embodied in BECON

for a square plan, 10 storey office block of brickwork panel and concrete frame, was developed and used to simulate the impact of alternative designs upon construction duration.

The impact of design decisions on construction method was also the main concern of Beeston. The model COCO (40) was developed during the early 1970's based on a survey of the planning and estimating departments of various contracting firms. COCO evaluates a proposed design in terms of the efficiency with which the weight lifting or shifting device is utilised, the location of plant, the frame erection time, and consideration of the constraints imposed by the site.

An alternative technique was outlined recently by the Property Services Agency (41), in which a stochastic model was used to simulate the design, cost analysis, estimating and tendering processes of the building industry. The model is based on a hypothetical client who accounts for approximately 5.5% of the construction projects undertaken within a fictitious geographical area. The simulation is of weekly units, in which a number of projects have to be let to the 30 firms who collectively form the contracting industry in the area. The number of contracts let per week, the number of projects allocated to be handled by the 'client', and the order in which contracts are let, are all randomly generated within certain constraints. The cost and duration of those projects not allocated to the 'client' are also randomly generated, along with the choice of contractors in competition for them. Each project then let by the 'client' is also randomised, but in greater detail. The level of detail is intended to be comparable with the sketch design stage of an actual project, but may be at a coarser level for the purposes of testing a range of estimating techniques. This is a simple application of the Monte Carlo gaming technique, and is useful, in that it allows a more objective evaluation of estimating techniques, far more rapidly than a similar exercise based on 'real' information.

7.1 Comment

(i) Notwithstanding stochastic techniques, most simulation models are compatible with the costing methods prefered in practice, but require some form of sketch plan to be developed and are therefore of only limited use during the very early stages of a design.

(ii) Little assistance is given to generating a design solution except through the users trial and error.

(iii) Existing models fail to relate a proposed design to other, previous projects.

(iv) The models do however facilitate the use of a central data base, are rapid (subject to the extent of data capture needed) and consistent.

(v) Current simulation models allow the user to investigate many relationships in great detail, but are inflexible and invariably empirical.

8. Optimisation

Optimisation models search a field, or space, of feasible solutions to identify those best suited to stated goals (the objective function). The sophistication of the search is greatly influenced by the complexity of the problem definition.

Bathurst and Butler (42) grossly simplified the problem to one of minimising cost. A series of equations with cost related to only one other variable were differentiated against a minimum cost. For example, consider a rectangular building of dimensions X and Y in which a single partition divides the internal space into two equal areas, W: clearly;

$$Y = 2 \times W \times X^{-1}$$

Bathurst and Butler then took the general relationship of plan length to the cost of external walls and partitions, as being:

$$T = (2 \times X \times Z \times A) + (4 \times W \times Z \times A \times X^{-1}) + (2 \times W \times Z \times B \times X^{-1})$$

where T = cost of external walls and partitions

A = cost per unit area of external wall
B = cost per unit area of partition
W = area of each internal space
X = plan length
Z = storey height

To optimise plan length against an objective function of minimum cost, the relationship is differentiated and equated to zero. Therefore:

$$T_{min} = \sqrt{\frac{W \times [(2 \times Z \times A) + (Z \times B)]}{Z \times A}}$$

where Tmin = minimum cost of external walls and partition
A = cost per unit area of external wall
B = cost per unit area of partition
W = area of each internal space
Z = storey height

Wilson and Templeman (43) recognised a more complex problem involving non-linear relationships. Using the program BALANCE that combination of boiler capacity, preheat time and thermal insulation which minimised both capital and amortised running cost was determined. In this case the objective function was composed of three major components; fuel costs, plant costs, and insulation costs. Each component was appraised and given a cost function in terms of system variables. For example, total plant cost was described by the following relationship:

$$T = A + B(C \times D) + (E \times F^{-1} \times C \times G)$$

where T = total plant cost
A and B = boiler regression coefficients
C = preheat power margin
D = output for a continuous regime
E = average radiator cost in pounds per square metre
F = average output rating of radiator surface in w/m2
G = steady state heat loss

Gero (44) however, has observed that buildings and their component systems are rarely designed with a single aim, such as minimum cost in mind. Multi-attribute, multi-criterion problems have been solved using trade-off diagrams (45), provided that attributes can be measured and that the number of criterion is not much more than three. Also, because the technique solves a problem at each decision stage, it indicates how such an optimal, or near optimal, solution might be achieved. However, these problems have been highly constrained and specially formulated to suit dynamic programming; the technique is not as applicable (in any practical sense) to total design. Indeed the whole concept of optimisation is falsified when sub-optimisiation is applied to the inter-related, and inter-dependent, sub-systems which typify building design.

8.1 Comment

(i) Although optimisation is based on conflict resolution, the explicit expression of an objective function is alien to many designers and will create a conflict, most especially, when objectives change during the course of a project.

(ii) The models do describe optimal, and sometimes near optimal, solutions even though these may be optimal for the model only. Projects are not related to good or bad, but merely best.

(iii) The complexity of the models is such that they rapidly become unweildy and difficult to incorporate into a flexible design process.

9. A General Critique

It is clear even from this limited review that the range of approaches to cost modelling is great, in terms both of technique and of level of sophistication. But it is also apparent also that variations between individual approaches within this range are often subtle, and to criticise each separately would be verbose. The intention is therefore, to follow the guidelines set out in Chapter 3 of the thesis to judge the performance of the seven broad categories already outlined.

(i) Does it minimise confict?

The most obvious deviants are the stochastic techniques, for if the user is presented with different answers from run to run, from identical inputs, then this can only increase conflict. Similarly with current practice, where the staging effect of changing from one costing technique to another can often give conflicting results. On the other hand, current practice has evolved over many years, the cost information being filtered by the cost adviser so as to be as consistent as possible.

Another source of conflict is uncertainty. Automated costing processes, parametric studies, and statistical analyses, are only valid for a range of solutions close to the original. This problem can be overcome by having numerous versions for discrete ranges of situations, but conflict still remains where the ranges overlap.

Accuracy for all techniques will depreciate over time, but those relating directly to costs at a particular date do so far quicker than those dealing only with processes. Thus, an automated costing process will have an acceptable degree of accuracy for far longer than, for example, a statistical analysis of building cost: An alarming majority of the models cited in this appendix are already too inaccurate for any practical use. It is possible to extend the period of validity, either by applying the technique to a more general case, or by basing the model on a process. Current practice avoids this problem by evaluating the 'model' continuously.

Other problems arise when a technique is only intended for use at a specific stage in design. Parametric studies and statistical analyses are both related specifically to early design decisions and are inconsistent with later costing techniques. Simulation techniques invariably require some form of sketch plan before evaluation can be achieved, which limits their use during early design stages.

If current practice is taken as the 'norm', then most other models are inconsistent with it, and great care must be taken to ensure that the advantages of such models are not negated by the inconvenience of their use. Consideration should, however, be given to the fact that parametric and statistical models are usually very simple to apply and to understand, and also that theoretical analyses or simulation models may be structured closely with reality which makes them less conspicuous.

Finally, it would appear that the same techniques applied to the same problems are still giving conflicting results, and that even optimisation, which is based on conflict resolution, creates a certain amount of conflict; but then without conflict, where is the design problem?

(ii) Does it assist in solution generation?

The optimisation models are clearly geared to the prescription of the best, or near best, solutions and how to achieve them. The danger is that the solutions generated as optimal may be optimal for the model only. If an optimisation model is inaccurate then it can be very misleading, being more of a hindrance than a help.

Parametric and statistical models both indicate the cost consequences of a range of design decisions, but limit the designer to perhaps 10 or 20 parameters. Statistical models have the additional problem of multi-colinearity, in which some of the 'independent' variables are highly inter-correlated and 'blur' the predictive capability.

A theoretical analysis will provide a number of insights into cost relationships and therefore be of great assistance in solution generation. The paucity of knowledge relating to building economics, in some respects, is a reflection of the lack of just such a theoretical base.

Automated costing and simulation models are unable to predict cost consequences, except by iterative trial and error or perturbation. Few existing models provide such facilities.

(iii) Does it relate to other projects?

The whole basis of statistical analysis is to relate a proposed project to the trends observed in historical data. Any new project is therefore compared to other, previous projects, directly and explicitly.

Automated costing, parametric studies and current practice relate projects implicity, through either the experience of the cost adviser or the historical data used in the study. A theoretical analysis is often too abstract to allow any practical comparison of projects.

Very few of the simulation and optimisation models provided a mechanism by which the scheme under consideration is related explicitly to other projects: Stating that a project is the best, does not determine if it is good or bad.

(iv) Does it link the user to a central data base?

Most automated costing processes are part of a more general computer-aided architectural design package, and therefore provide an excellent link to the central, or common data base.

Conversely, parametric studies and statistical analyses are very much 'stand-alone' systems, and tend to discourage the use of common data bases.

None of the simulation or optimisation models studied make use of centralised data, although being computer-based such a link is usually possible and some models are specifically structured for easy incorporation into such a coordinated system.

Most theoretical models will also recognise the need for a centralised information base, but the choices of data structure are many and varied.

Despite the findings of the Working Party on Data Coordination (46), no data base central to the construction industry has yet been adopted generally.

(v) Is it quick?

A great advantage of the graph, or of a computer based model, is the speed of its execution. Unfortunately, data capture is very often a time consuming process. The static models created by an automated costing process, a statistical analysis, or parametric study, are intended for use at an early stage in design and invariable require less data input than other approaches. Where extensive information is required by the model, data capture is greatly assisted by utilising some of the more sophisticated input and output devices now available.

Significant improvements could be made if more attention was paid to the interfacing of user and model.

The gravest shortcoming of current practice is that the techniques used are very dependent on human manipulation which makes them slow and cumbersome to relate to the design activity.

(vi) Is it adaptable?

Although generally based on the norm, few (if any) of the models reviewed are capable of dealing directly with either innovative costing techniques, nor the complete range of possible design solutions. In the past, little emphasis has been placed on the capacity to adapt to a variation in requirements and the failings of current models are quite marked in this respect.

Human ingenuity has enabled current practice to satisfy most requirements so far. Manual methods are unlikely to prove as resilient in future.

(vii) Is it dynamic?

Obviously those models which are applicable only to part of the design process and inconsistent with the remainder do not contribute to a dynamic system. Statistical analyses and parametric studies are different fundamentally to the prefered technique of approximate quantities.

An optimisation model must assume a consistent objective function if it is to apply to all stage of the design process. The fact that such models are relegated to dealing with well defined sub-problems, clearly illustrates their failure to match the variability of design.

It would appear that only the most sophisiticated of simulation models are even remotely close to reflecting the true dynamics of design.

This critique is further summarised in Figure 7; clearly, none of the cost models have satisfied all criteria.

	Current Practice	Automated Costing Process	Statistical Analysis	Parametric Study	Theoretical Analysis	Simulation	Optimisation
1. Does it minimise conflict ?	S	LS	F	F	F	S	LS
2. Does it assist in solution generation ?	F	S	S	LS	LS	LS	S
3. Does it relate project to other comparable projects ?	F	F	S	F	F	F	F
4. Does it link the user to a central data base ?	F	S	F	F	LS	LS	LS
5. Is it quick ?	F	S	S	S	F	S	S
6. Is it adaptable ?	S	F	F	F	F	F	F
7. Is it dynamic ?	F	F	F	F	F	LS	F

Where: S - satisfactory
LS - limited satisfaction
F - failure to satisfy

Figure 7: The performance of current cost estimating practice and approaches to cost modelling

REFERENCES

1. SEELEY I H
"Building economics: Appraisal and control of building design cost and efficiency", MacMillan, 1972.

2. RIBA
"Handbook of Architectural practice and management", 4th edition, RIBA Publications.

3. PROPERTY SERVICES AGENCY
"Construction cost data base", Vol. 1, PSA, 1980, p.59.

4. PROPERTY SERVICES AGENCY
ibid, pp.20-22.

5. BEESTON D T
"Cost models", in B and QS Quarterly, Vol. 5, Summer 1978, pp.56-59.

6. THE WILDERNESS COST OF BUILDING STUDY GROUP
"An investigation into building cost relationships", RICS, 1964.

7. BUILDING COST INFORMATION SERVICE
"Section F: Cost studies and research and development papers", RICS.

8. LIDDLE C
"Process engineering - the QS role" in Chartered QS, October 1979, pp.58-60.

9. FLANAGAN R
"Tender price and times prediction in construction work", Ph.D. thesis (unpublished), University of Aston, 1980, p.73.

10. SUSSOCK H
"GOAL - General Outline Appraisal of Layouts", ABACUS Occasional Paper no. 62, (revised), 1981.

11. BEESTON D T
op cit.

12. EDWARDS A L
"Statistical methods", 2nd edition, Holt Rinehart & Wilson, 1967.

13. McCAFFER R
"Some examples of the use of regression analysis as an estimating tool", QS, December 1975, pp.81-86.

14. GOULD P R
"The development of a cost model for H & V & AC. installations in buildings", M.Sc. Project Report, (unpublished), University of Loughborough, 1970.

15. BUCHANAN J S
"Cost models for estimating: Oultine of the development of a cost model for the reinforced concrete frame of a building", RICS, 1972.

16. BOWEN P
"An alternative estimating approach" in Chartered QS, February 1982, pp.191-194.

17. KOUSKOULAS V and KOEHN E
"Predesign cost estimate function for buildings", ASCEP, Journal of the Construction Division, 100 (CO4), 1974, pp.589-604.

18. ZAHRY M
"Capital cost prediction by multi-variate analysis", M.Sc. thesis (unpublished), University of Strathclyde, 1982.

19. BRIDGES A
"MAGIC-Multivariate analysis by graphical interactive computing", ABACUS Occasional Paper No. 65, 1978.

20. PUGH B
"Cost considerations", in AJ, 18th August 1971, pp.375-383.

21. MEYRAT R F
"Algebraic calculation of cost price", in Build International, November 1969, pp.27-36.

22. REGDON G
"Pre-determination of housing cost", in Build International, March 1972, pp.94-99.

23. STEYERT R S
"The economics of high rise apartment buildings of alternative design construction", ASCE, Construction Research Council, 1972.

24. FLANAGAN R and NORMAN G
"The relationship between construction price and height" in B and QS Quarterly, Vol. 5, Summer 1978, pp.69-71.

25. TREGENZA P
"Association between building height and cost", in AJ, 1st November 1972, pp.1031-1032.

26. PERRY J G et al
"Cost modelling is theory and in practice", in Proceedings, 5th INTERNET congress, 1976, pp.240-248.

27. BRANDON P S
"A framework for cost exploration and strategic cost planning", M.Sc. thesis (unpublished), University of Bristol, 1977.

28. MYER T H et al
"Computer-aided cost estimating techniques for architects", MIT, 1966.

29. BISHOP D
"Operational bills and cost communication" in Architectural Review, February 1966, pp.158-162.

30. SKOYLES E R and FLETCHER L
"Bills of quantities, or the operational bill?" in AJ, 28th January 1970, pp.233-240.

31. SWINBURNE H
"Design cost analysis for architects and engineers", McGraw Hill, 1980.

32. RICS and NFBTE
"Report of the joint working party on measurement conventions", RICS, 1972.

33. DIRECTOR GENERAL OF DEVELOPMENT, DOE
"Structuring project information", HMSO, 1972.

34. PROJECT INFORMATION GROUP
"Project Information - its content and arrangement", DOE, 1976.

35. SMITH G
"Cost Planning the design process" in Chartered QS, August 1980, pp. 13-16.

36. POWELL J and CHISNALL J
"Getting early estimates right" in Chartered QS, March 1981, pp.279-281.

37. TOWNSEND P R F
"The effect of design decisions on the cost of office developments", in B and QS Quarterly, Vol. 5, Summer 1978, pp.53-56.

38. MOORE G and BRANDON P S
"A cost model for reinforced concrete frame design" in Chartered QS, October 1979, pp.40-44.

39. FLANAGAN R
op cit, 1980.

40. BEESTON D T
"COCO - Cost of Contractors operation: Cost consequences of design decisions", DOE, 1973.

41. PROPERTY SERVICES AGENCY
op cit.

42. BATHURST P E and BUTLER D A
"Building cost control techniquės and economics", Heinemann, 1973, pp.21-28.

43. WILSON A J and TEMPLEMAN A B
"An approach to the optimal thermal design of office buildings", Build and Env., Vol. 11, No. 1, 1976, pp.39-50.

44. GERO J S
"Computer-aided design by optimisation in architecture", Design Studies, Vol.1, April 1980, pp.227-230.

45. RADFORD A D and GERO J S
"Trade-off diagrams for the integrated design of the physical environment in buildings", in Build. and Env., Vol. 15, January 1980, pp.3-15.

46. PROJECT INFORMATION GROUP
op cit, 1976.

APPENDIX III: 'FUZZY' TREATMENT OF COST UNCERTAINTY - AN EXEMPLIFICATION

APPENDIX III: 'FUZZY' TREATMENT OF COST UNCERTAINTY - AN EXEMPLICATION

1. Introduction

It was never the intention of this thesis to consider possibility theory and its various applications at length. In concluding that a possibilistic treatment of the uncertainty in cost generation should be attempted, however, it is necessary to evidence how that theory might conceivably be applied. The applications considered here illustrate very simple examples of how fuzzy sets can be used to deal with imprecision: nevertheless it is hoped they give a useful indication of the potential.

It was considered that the fuzzy sets used in the examples, although subjective in nature, should as far as possible be based on 'real' data. A recent study by Wilson (1) determined for each of seventeen identified constituent items in the cost synthesis of a concrete floor slab, the minimum, probable and maximum values from eight individual estimators. In what is one of the first studies of its kind, Wilson makes an interesting comment:

> "...it does appear that estimators are constrained by the traditional practice of single figure estimating, and when the opportunity is presented to them of expressing the uncertainties in their estimates they rise to the occasion".

Wilson relates this expression of uncertainty to the probabilistic estimating approach of Spooner (2), but it is apparent that it corresponds even more closely to an expression of imprecision in the sense of possibility theory. Figure 1 illustrates how several of the so-called maximum values for ready mix concrete are LESS than some of the so-called minimum values. The transition from membership of 'minimum' to membership of 'maximum' is patently gradual rather than abrupt.

2. Preliminary Definitions

The general definition of a fuzzy set has already been given in Section 4.2.3.2 of the main text. Several other important concepts now need to be defined, with the point of departure being a collection of objects referred to as the kernel space.

A kernel space, K = {w}, with generic elements denoted by w; can be any prescribed set of objects or constraints. For example:

(i) K = set of moving objects in a room

(ii) K = the set of possible ages for individuals in a group

(iii) K = a set of smells

Consider A to be a fuzzy subset of K; in the case of (ii) perhaps, the subset of individuals who are middle-aged. Such a

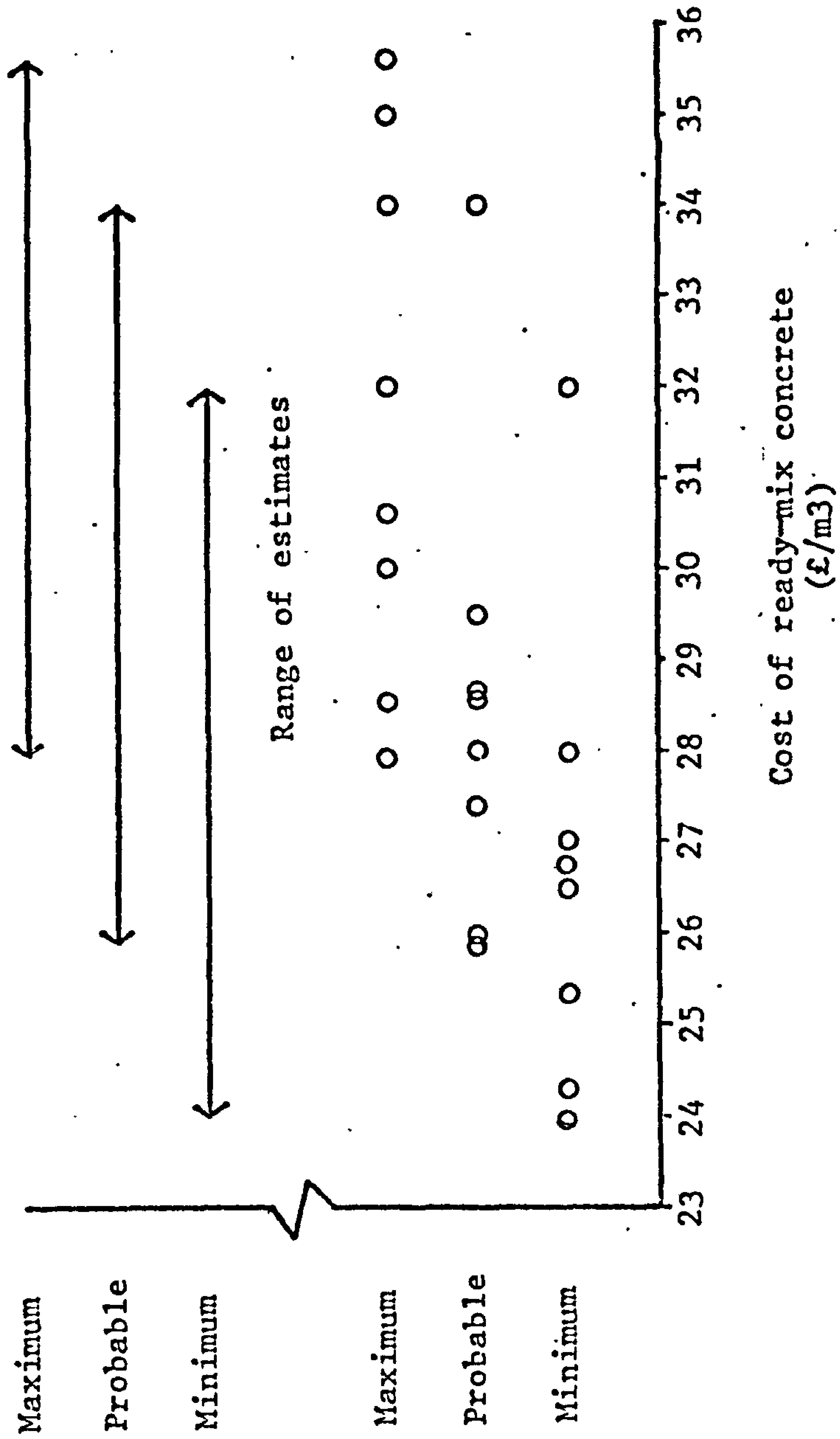


Figure 1: The range of estimates for the cost of ready mix concrete (From A J WILSON "Experiments in probabilistic cost modelling" in "Building cost techniques : new directions" by P S BRANDON (ed), Spons, 1982, p175)

subset can be characterised by its membership function μ_A which associates with each element w of K its grade of membership, $\mu_A(w)$, in K. See Table 1, where only those pairs (w, $\mu_A(w)$) in which $\mu_A(w)$ is positive are tabulated.

Table 1

w(=age)	40	41	42	43	44	45	46	47	48	49	50	51	52	53
$\mu_A(w)$	0.3	0.5	0.8	0.9	1	1	1	1	1	0.9	0.8	0.7	0.5	0.3

Note that μ_A can be defined in a variety of ways; in particular,

(i) by a formula

(ii) by a table

(iii) by an algorithm (recursively)

(iv) in terms of other membership functions (as in a dictionary)

In general the total collection of objects, E, has to be richer than K, because the concepts to be defined may involve n-tuples of elements of K and, more generally, collections of fuzzy subsets of K. For example in the case of K being the set of possible ages, the relation of 'much older than' requires a two dimensional relationship $E = K^2$.

Informally, the universe of discourse is a collection of objects, U, that is rich enough to make it possible to identify any concept, within a specified set of concepts, with a fuzzy subset of U.

The set expressed by E will, in general, contain all subsets of K many of which are of no interest; thus U will be a subset of E.

Let K be the set of integers from 1-100 representing the possible rates for ready mixed concrete in pounds per cubic metre. Let E = K and let U be the subset of E in which K is restricted to the range 20-40. Three fuzzy subsets in the range of possible rates correspond to labels of 'cheap', 'average' and 'expensive', on the linguistic variable 'Cost'. The membership functions detailed in Table 2 were subjectively determined from the data in Figure 1.

Table 2

w(=rate)	20	21	22	23	24	25	26	27	28	29	30	31	32	33	34	35	36	37	38	39	40
μ_{Cost}(cheap)	0	0	0	0.1	0.6	0.9	1	1	0.9	0.8	0.5	0.3	0.1	0	0	0	0	0	0	0	0
μ_{Cost}(average)	0	0	0	0	0	0.1	0.9	1	1	0.9	0.8	0.6	0.4	0.2	0.1	0	0	0	0	0	0
μ_{Cost}(expensive)	0	0	0	0	0	0	0	0.1	0.6	0.8	1	1	1	1	1	0.9	0.6	0.3	0.1	0	0

These membership functions are not probability distributions, but merely a subjective indication of the extent to which a particular rate 'w' fits one's conception of the

'Cost' label 'cheap', say. Thus a rate of £28.00 per cubic metre might be assigned the grade of membership 0.9 in the fuzzy set labelled 'cheap'; 1.0 in the fuzzy set labelled 'average'; and 0.6 in the fuzzy set labelled 'expensive'. The meaning of each label is illustrated graphically in Figure 2 by plotting the membership functions with respect to the base variable 'rate'.

A statement "concrete is cheap" is then interpreted as an assignment equation which assigns the value 'cheap' to the linguistic variable 'Cost'. In turn, the value 'cheap' is interpreted as a label for a fuzzy restriction on the base variable 'rate', with the meaning of this fuzzy restriction defined by its membership function. As an aid to the understanding of the concept of a linguistic variable, Figure 3 shows the hierarchical structure of the relation between the linguistic variable 'Cost', the fuzzy restrictions which represent the meaning of its values, and the values of the base variable 'rate'.

3. Linguistic Connectives, Negations and Hedges

The totality of values of a linguistic variable constitute its term-set, T, which in principle could have an infinite number of elements. For example;

T(Cost) = cheap + not cheap + very cheap + ... + average + ... + expensive + ... + not very cheap and not very expensive+ ...+ extremely expensive + ...

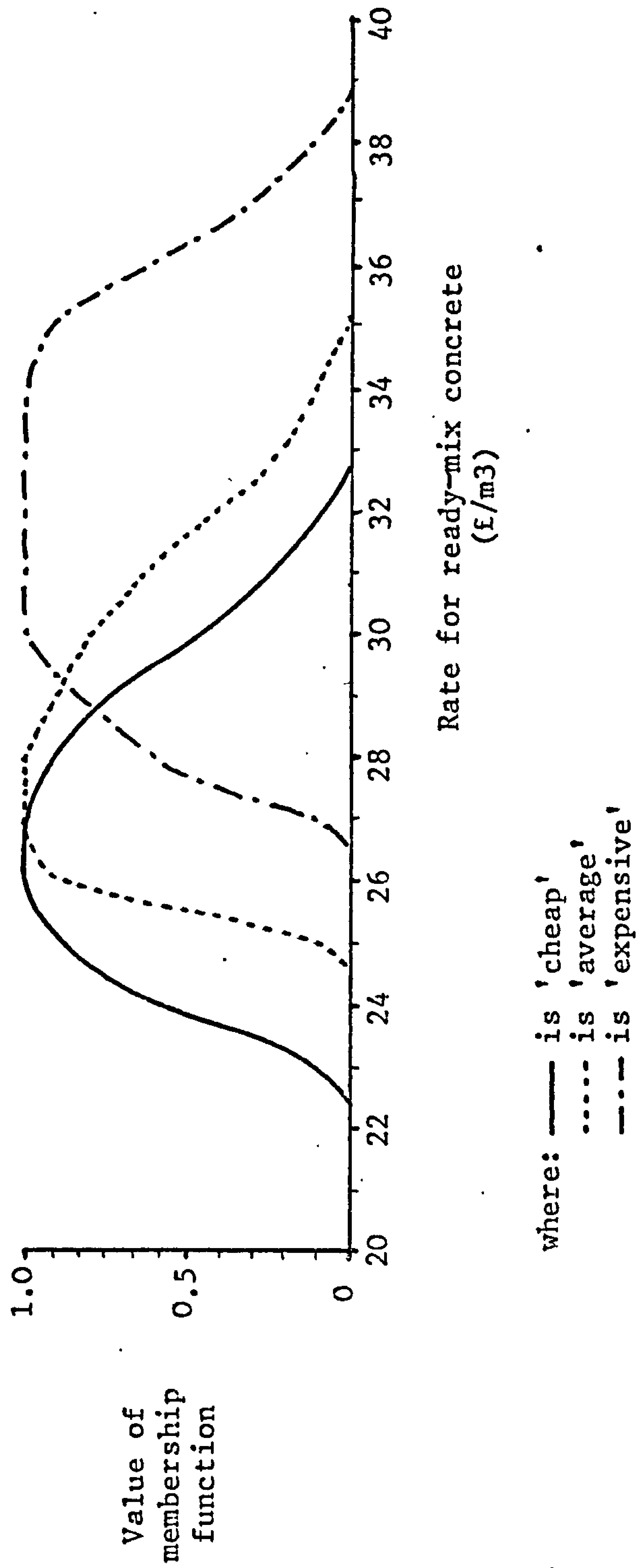


Figure 2: The membership functions of fuzzy subsets of the linguistic variable 'Cost' plotted against the base variable 'rate'.

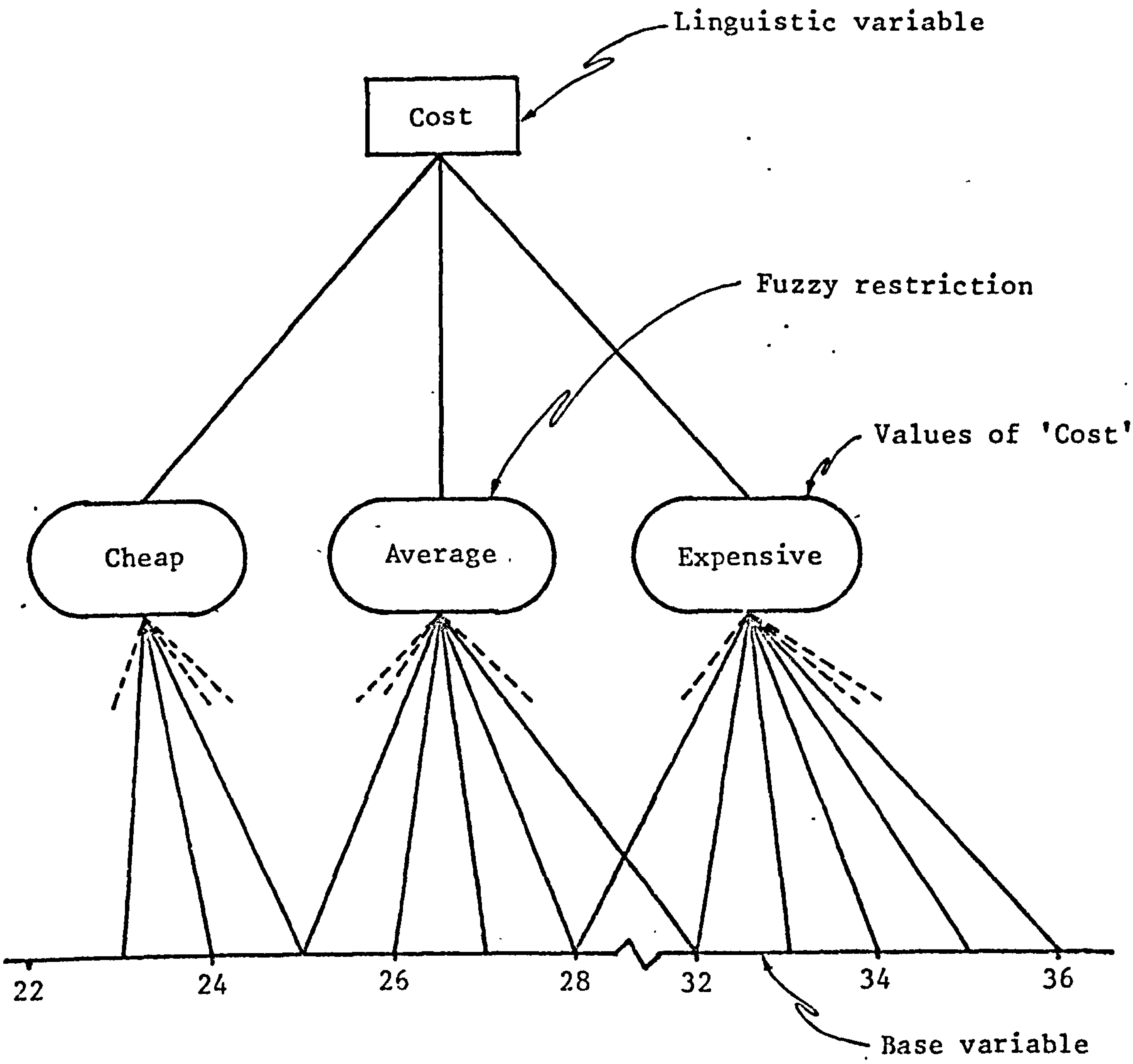


Figure 3: Hierarchical structure of a linguistic variable

in which '+' is used to denote the union rather than the arithmetic sum.

In fuzzy-set theory it is not possible to define terms such as 'not', 'very', 'and', etc. in respect of the kernel space, K (or more precisely the values which constitute the kernel space, namely w), because the terms are operators on the fuzzy subsets of K. That is, for example, the term 'very' is an operation which transforms a fuzzy subset ('cheap') into a fuzzy subset of itself ('very cheap') : it can only be equated with functions of K, not of K itself. Figure 4 represents the operator 'very' as a function from 'cheap' to 'very cheap'.

In fact, given the membership functions of 'cheap', 'average' and 'expensive' the meaning of all the remaining elements of T can be defined in terms of 'cheap', 'average' and 'expensive' by interpreting 'not' as an operation of complementation (or equivalently, negation), 'and' as the operation of intersection, and 'or' as the operation of union in U. More specifically,

$$\mu(\text{w/not cheap}) = 1 - \mu(\text{cheap})$$
$$\mu(\text{w/average or expensive}) = \mu(\text{average}) \vee \mu(\text{expensive})$$
$$\mu(\text{w/not cheap and not expensive}) = (1 - \mu(\text{cheap})) \wedge (1 - \mu(\text{expensive}))$$

where the symbols $\wedge$ and $\vee$ stand for minimum and maximum

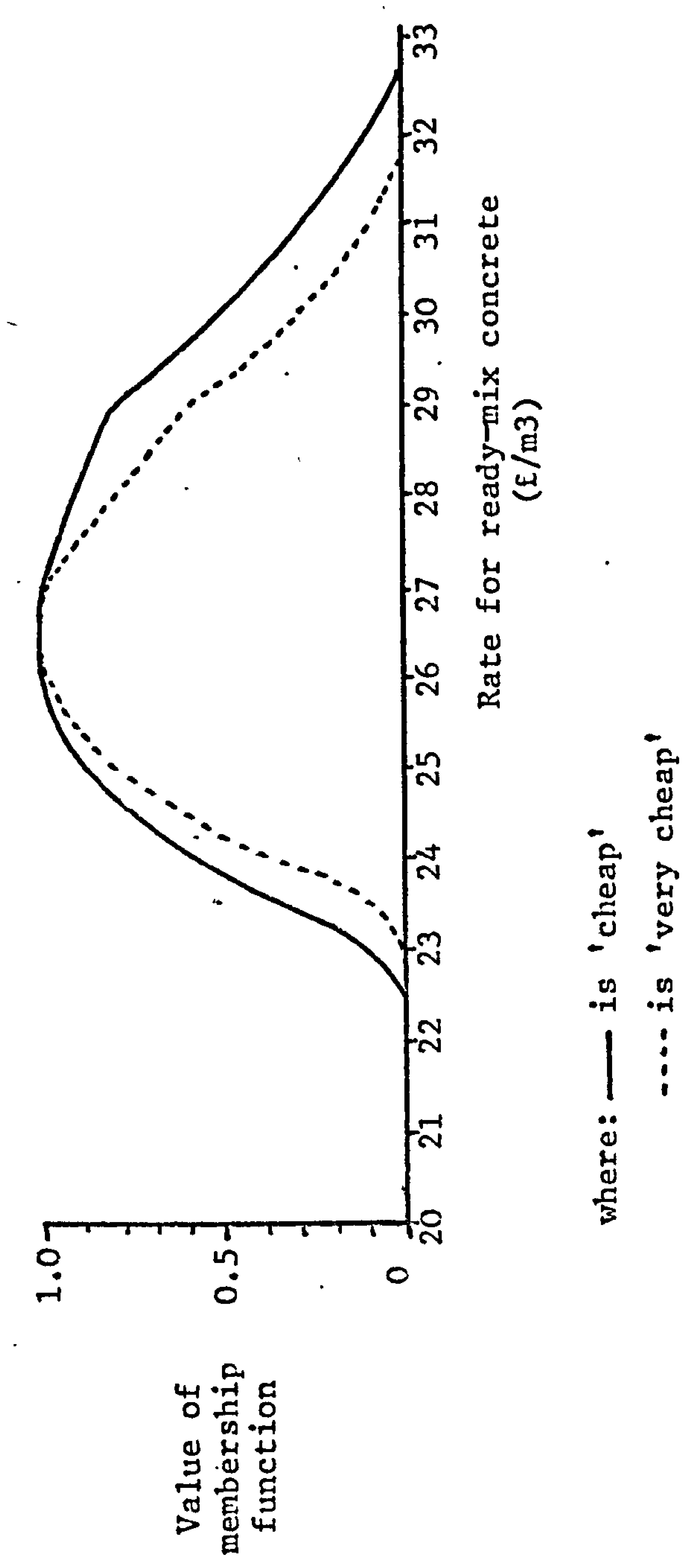


Figure 4: Representation of 'very' as an operation on the function 'cheap'

respectively. Thus for a rate w = 31 (refer to Table 2),

$$\mu(31/\text{not cheap}) = 1 - 0.3 = 0.7$$

$$\mu(31/\text{average or expensive}) = 0.6 \vee 1.0 = 1.0$$

$$\mu(31/\text{not cheap and not expensive}) = (1 - 0.3) \wedge (1 - 1.0)$$

$$= 0.7 \wedge 0.0 = 0.0$$

An alternative visual representation is to construct Venn-Euler diagrams. Figures 5(a), (b) and (c) illustrate complementation. The properties of intersection and union are shown in Figures 6(a), (b), (c) and (d). In Figures 7(a) - (h) are represented the properties of difference and the disjunctive sum.

In general then, the value of a linguistic variable is a composite term made up of four types of atomic terms:

(i) primary terms, which are labels of specified fuzzy subsets of the universe of discourse (for example, 'cheap', 'expensive', etc.)

(ii) the negation 'not' and the connectives 'and' and 'or'

(iii) hedges, such as 'very', 'much', 'slightly', 'more or less', etc.

(iv) markers, such as parentheses.

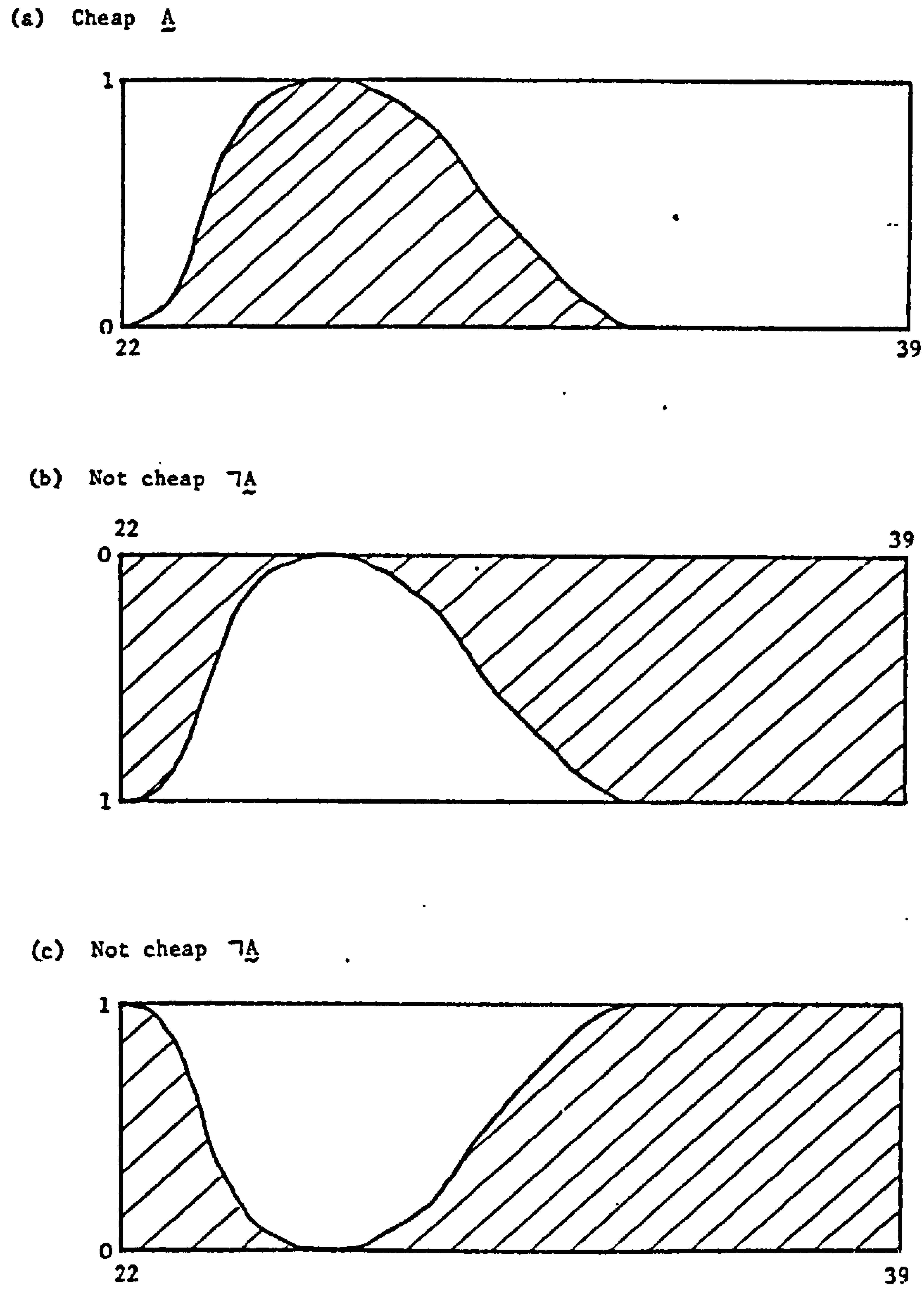


Figure 5: Complementation

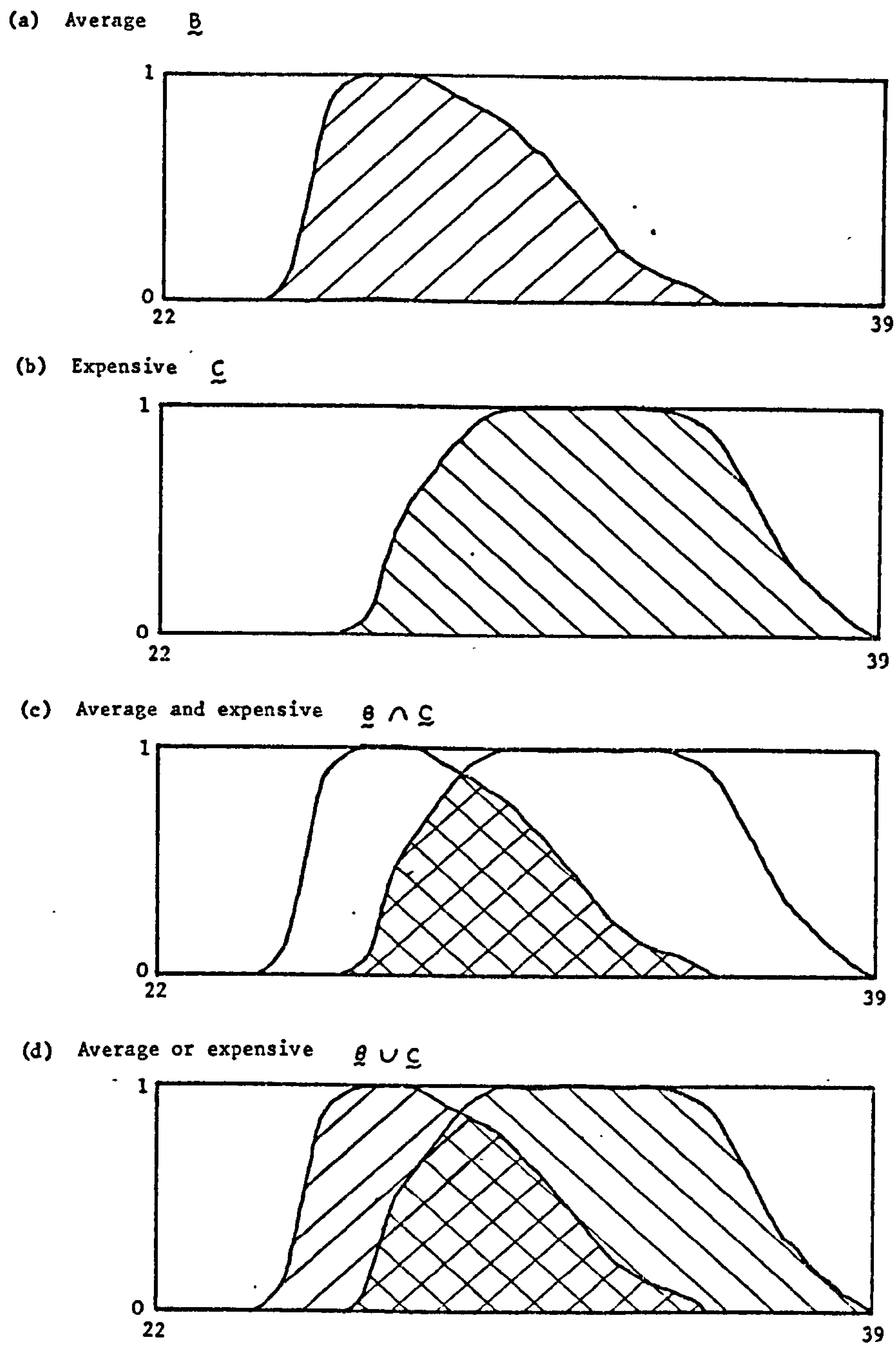


Figure 6: Intersection and union

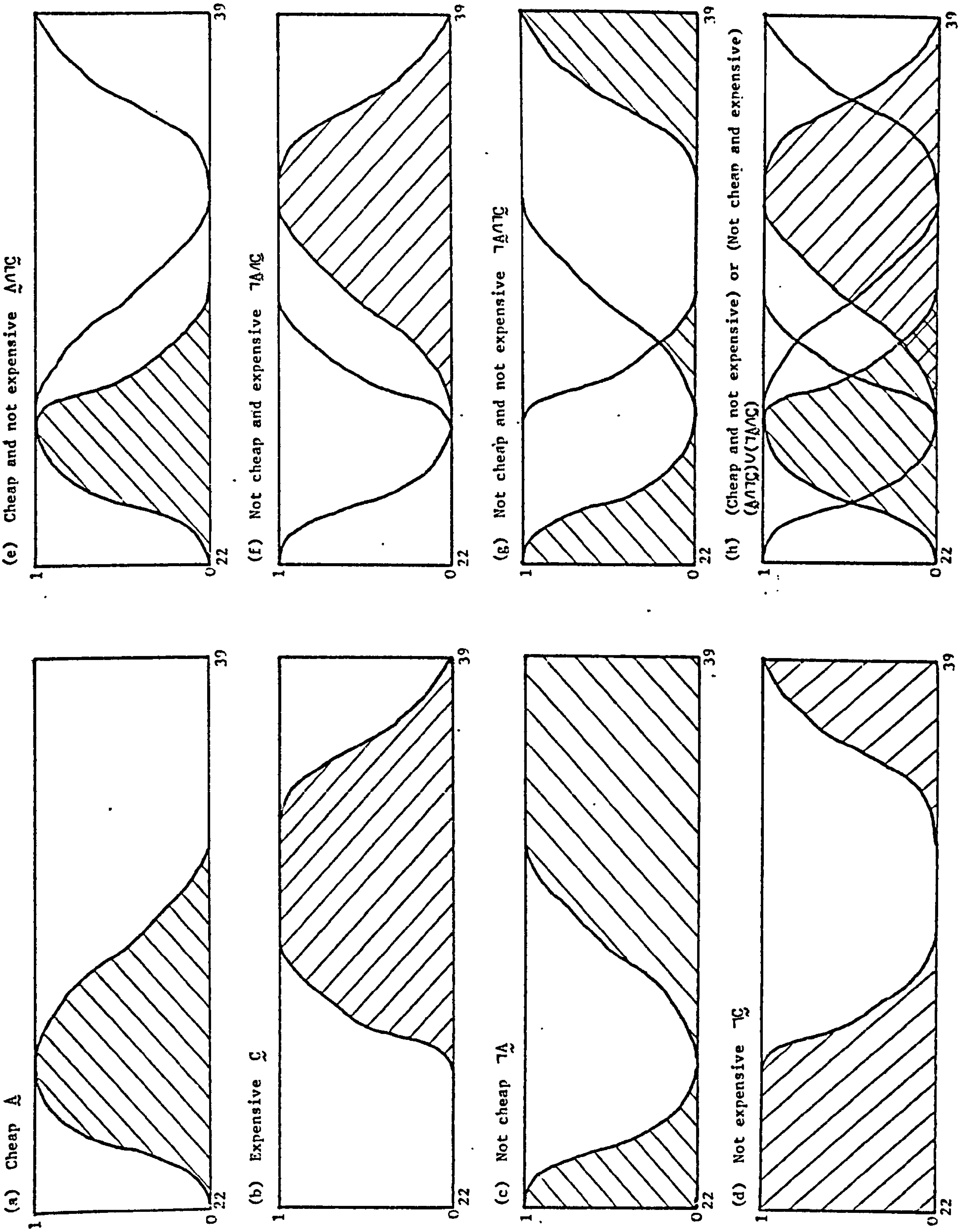


Figure 7: Difference and the disjunctive sum

4. Linguistic Truth Variables and Fuzzy Logics

In everyday discourse, the degree of truth of a statement is frequently characterised by expressions such as very true, quite true, more or less true, false, completely false, etc. The similarity between these expressions and the values of a linguistic variable suggests that in situations in which the truth or falsity of an assertion is not well defined, it may well be appropriate to treat 'Truth' as a linguistic variable for which 'true' and 'false' are merely two of the primary terms in its term-set rather than a pair of extreme points in the universe of truth-values.

It follows that a proposition such as "u is A", where 'u' is a name of an object and 'A' is the name of a possibly fuzzy subset of a universe of discourse U (for example, "concrete is expensive", "labour is cheap", etc.), must be associated with two fuzzy subsets:

(i) the meaning of A, represented by the membership function μ_A

(ii) the 'truth-value' of "u is A", which is denoted by v(A) and is defined to be a possibly fuzzy subset of a universe of truth values, V.

The notion of a fuzzy truth-value operating upon a fuzzy set implicates two things:

(i) that fuzziness pervades all of fuzzy-set theory; meaning that if concepts are fuzzy then so also are truths, labels, membership functions, rules of inference, etc.

(ii) that truth taken as a linguistic variable, leads to a fuzzy linguistic logic, termed approximate reasoning, which is quite different from the conventional two-valued or even n-valued logic because it employs truth-values and rules of inference which are fuzzy rather than precise (3).

4.1 Comment

It would appear to be at about this point where the current understanding of fuzzy-set theory begins to break down. Having identified the notion of 'fuzziness' as an inexactitude, it is apparent that the notion translates into an infinite hierarchy of fuzzy operations on fuzzy sets at previous levels. In many ways, this is akin to the reasoning structure used by humans in ill-defined or unquantifiable situations; indeed, it may well be the case that much - perhaps most - of human reasoning is approximate rather than precise in nature. However in practice the human being can 'side-step' the inherent complexity of such imprecision by adopting the principle of abstraction, through which approximate reasoning is simplified greatly. Certainly the concepts of fuzzy-set theory have reached a level of complexity beyond which no practical application will be realistic without an overt method of modelling the human process of abstraction (4). For the present, such complexities have merely to be ignored.

5. Fuzzy Algorithms

Any application of fuzzy-sets to 'real-world' problem solving is likely to involve a fuzzy algorithm. Roughly speaking, a fuzzy algorithm is an ordered set of fuzzy instructions which upon execution yield an approximate solution to a specified problem (5).

The instructions in a fuzzy algorithm, while not themselves necessarily fuzzy, fall into the following three classes:

(i) assignment statements - e.g. x is expensive, y nearly equals x.

(ii) fuzzy conditional statements - e.g. IF x is cheap THEN decrease y slightly, IF x is expensive THEN go to 7.

(iii) unconditional action statements - e.g. increase x quite a lot, multiply y by itself a few times, go to 7.

Example One:

Consider a universe of discourse in which the primary term 'small' is defined as

$$\mu(small) = 1/1 + 0.8/2 + 0.6/3 + 0.4/4 + 0.2/5$$

Consider also the 'Cost' of plywood formwork in pounds per square metre, in which the primary term 'cheap' is defined (again from Wilson (1)) as

$$\mu(cheap) = 0.1/2 + 1/3 + 1/4 + 0.5/5 + 0.2/6$$

If at some point in the execution of a fuzzy algorithm the following instructions are encountered:

(1) x is very small

(2) IF x is small THEN y is cheap ELSE y is not very cheap.

The result of execution of (1) and (2) will be the following:

x acquires the membership function for 'very small'

$$\mu(x) = 1/1 + 0.64/2 + 0.36/3 + 0.16/4 + 0.04/5$$

This membership function is mapped against the relation matrix, R, for the fuzzy conditional statement; where

$$R = (A \times B) + (\neg A \times C)$$
$$A = \mu(\text{small})$$
$$B = \mu(\text{cheap})$$
$$C = \mu(\text{very cheap})$$

Thus $$R = \begin{bmatrix} 0.1 & 1 & 1 & 0.5 & 0.2 \\ 0.1 & 0.8 & 0.8 & 0.5 & 0.2 \\ 0.1 & 0.6 & 0.6 & 0.5 & 0.2 \\ 0.1 & 0.4 & 0.4 & 0.4 & 0.2 \\ 0.1 & 0.2 & 0.2 & 0.2 & 0.2 \end{bmatrix} + \begin{bmatrix} 0.99 & 0 & 0 & 0.75 & 0.96 \\ 0.80 & 0 & 0 & 0.75 & 0.80 \\ 0.60 & 0 & 0 & 0.60 & 0.60 \\ 0.40 & 0 & 0 & 0.40 & 0.40 \\ 0.20 & 0 & 0 & 0.20 & 0.20 \end{bmatrix}$$

$$R = \begin{bmatrix} 0.99 & 1 & 1 & 0.75 & 0.96 \\ 0.80 & 0.80 & 0.80 & 0.75 & 0.80 \\ 0.60 & 0.60 & 0.60 & 0.60 & 0.60 \\ 0.40 & 0.40 & 0.40 & 0.40 & 0.40 \\ 0.20 & 0.20 & 0.20 & 0.20 & 0.20 \end{bmatrix}$$

y = max-min product (6) of x and R, denoted by $x \circ R$

$$y = x \circ R$$

$$y = \begin{bmatrix} 1 & 0.64 & 0.36 & 0.16 & 0.40 \end{bmatrix} \circ \begin{bmatrix} 0.99 & 1 & 1 & 0.75 & 0.96 \\ 0.80 & 0.80 & 0.80 & 0.75 & 0.80 \\ 0.60 & 0.60 & 0.60 & 0.60 & 0.60 \\ 0.40 & 0.40 & 0.40 & 0.40 & 0.40 \\ 0.20 & 0.20 & 0.20 & 0.20 & 0.20 \end{bmatrix}$$

$$y = 0.99/2 + 1/3 + 1/4 + 0.75/5 + 0.96/6$$

It is important to observe that as a result of executing the two instructions both x and y are fuzzy sets rather than single numbers. How then can such a definition be reconciled with the patent need for a quantity surveyor to commit only one rate in the bill of quantities?

An immediate response of course is that a single rate is not the most realistic interpretation of the cost of work involved. Current practice may produce an absolute and precise, single figure for the total tender amount, but it would be naive indeed ever to interpret such a figure as being 'absolute and precise', because it is so very variable (see for example Section 4.2.2.1 of the main text). The more rational approach would surely be to accept the imprecision and adopt 'fuzzy' rates, which produce 'fuzzy' tenders.

In accordance with the basic philosophy of this thesis however (to accept current practice as fixed in the short term), it is a necessary requirement to have some means of producing a single figure, or single response, from a fuzzy-set of figures or possible responses. Two alternatives are proposed:

(i) Zadeh (7) argues that it is reasonable to assume that the single result of an execution producing a fuzzy set of possible results, will be that element of the fuzzy set which has the highest grade of membership in it. However in Example One, above, from the fuzzy-set produced, y, it is apparent that such an element is not always unique, and Zadeh suggests then that a random or arbitrary choice can be made among the elements having the highest grade of membership. Alternatively, an external criterion can be introduced which linearly orders those elements of the fuzzy set which have the highest membership, and this generates a unique greatest element. For example, if the external criterion is to minimise cost, then the rate used for plywood formwork would be £3.00 per m2.

While the interpretation of a fuzzy-set in terms of some unique value is still very much at the frontiers of current research, this particular treatment does seem to be something of a sham. The sudden reversal from imprecision to randomness could be construed as an abandonment of the basic tenets of fuzzy-set theory, and so an alternative argument is proffered.

(ii) It has been argued that much of human thought involves manipulating imprecise concepts, and yet humans have little difficulty in interpreting a fuzzy set as a unique value. Consider the following documentary on the thought processes of an estimator:

thinks -the cost of aggregate is very high at the moment, perhaps I should increase the rate for ready mix concrete a little.

action - change x (rate for concrete) from £26 to £30.

thinks -£30, that seems rather excessive, perhaps I should reduce it very slightly.

action - change x from £30 to £29.

thinks - that's better.

action - enter £29 in the bill of quantities.

The question to be answered is whether in actual fact £26, £29 and £30 are each unique values. On the contrary, rather than translating a fuzzy-set into a unique value, might it not be the case that the estimator is simply labelling a fuzzy-set with a number rather than a word, i.e. '26' rather than 'cheap' - say.

Example Two:

Consider a universe of discourse in which the following primary terms are defined:

$$\mu(\text{little}) = 1/0 + 1/1 + 1/2 + 1/3 + 0.8/4 + 0.3/5$$

$$\mu(\text{very slightly}) = 1/0 + 1/1 + 0.5/2$$

Consider also the 'Cost' of ready mix concrete as detailed in Table 2, except instead of 'cheap', read '26'. Then

$$\mu(26) = 0.1/23 + 0.6/24 + 0.9/25 + 1/26 + 1/27 + 0.9/28 + 0.8/29 + 0.5/30 + 0.3.31 + 0.1/32$$

say, $$\mu(29) = 0.3/23 + 0.6/24 + 0.9/25 + 1/26 + 1/27 + 1/28 + 1/29 + 1/30 + 0.9/31 + 0.7/32 + 0.5/33 + 0.2/34$$

say, $\mu(30) = 0.5/24 + 0.8/25 + 0.9/26 + 1/27 + 1/28 + 1/29 + 1/30 + 0.9/31 + 0.8/32 + 0.7/33 + 0.5/34 + 0.3/35 + 0.2/36 + 0.1/37$

$$\mu(26) \text{ plus } \mu(\text{little}) = \begin{bmatrix} 0.1 & 0.6 & 0.9 & 1 & 1 & 0.9 & 0.8 & 0.5 & 0.3 & 0.1 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0.1 & 0.6 & 0.9 & 1 & 1 & 0.9 & 0.8 & 0.5 & 0.3 & 0.1 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0.1 & 0.6 & 0.9 & 1 & 1 & 0.9 & 0.8 & 0.5 & 0.3 & 0.1 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0.1 & 0.6 & 0.9 & 1 & 1 & 0.9 & 0.8 & 0.5 & 0.3 & 0.1 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0.1 & 0.6 & 0.8 & 0.8 & 0.8 & 0.8 & 0.8 & 0.5 & 0.3 & 0.1 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0.1 & 0.3 & 0.3 & 0.3 & 0.3 & 0.3 & 0.3 & 0.3 & 0.3 & 0.1 \end{bmatrix}$$

$= 0.1/23 + 0.6/24 + 0.9/25 + 1/26 + 1/27 + 1/28 + 1/29 + 1/30 + 0.9/31 + 0.8/32 + 0.8/33 + 0.5/34 + 0.3/35 + 0.3/36 + 0.1/37$

Linguistic approximation (8) can then be used to map the given membership function against available fuzzy sets. In this case the function might map best with the fuzzy-set labelled '30'.

x (the rate for concrete) now equals '30'

where $\mu(30) = 0.5/24 + 0.8/25 + 0.9/26 + 1/27 + 1/28 + 1/29 + 1/30 + 0.9/31 + 0.8/32 + 0.7/33 + 0.5/34 + 0.3/35 + 0.1/37$

Reduce the rate for concrete very slightly.

$$\mu(30) \text{ minus } \mu(\text{very slightly}) = \begin{bmatrix} 0 & 0 & 0.5 & 0.8 & 0.9 & 1 & 1 & 1 & 1 & 0.9 & 0.8 & 0.7 & 0.5 & 0.3 & 0.1 \\ 0 & 0.5 & 0.8 & 0.9 & 1 & 1 & 1 & 1 & 0.9 & 0.8 & 0.7 & 0.5 & 0.3 & 0.1 & 0 \\ 0.5 & 0.5 & 0.5 & 0.5 & 0.5 & 0.5 & 0.5 & 0.5 & 0.5 & 0.5 & 0.5 & 0.3 & 0.1 & 0 & 0 \end{bmatrix}$$

$$= 0.5/22 + 0.5/23 + 0.8/24 + 0.9/25 + 1/26 + 1/27 + 1/28 + 1/29 + 1/30 + 0.9/31 + 0.8/32 + 0.7/33 + 0.5/34 + 0.3/35 + 0.1/36$$

Linguistic approximation gives the answer as '29'.

It is only at the point of entry into the bill of quantities that the label loses its imprecision. Even then, the loss is only in abstract terms since the quantity surveyor will still view the figure '29' with some sceptisism, and intutively map onto it some fuzzy-set of possible values.

An analogous question to how a single figure might be obtained from a fuzzy-set, arises in situations in which a 'yes' or 'no' answer has to be given to a fuzzy question.

Example Three:

Suppose that the following instruction occurs in a fuzzy algorithm

IF x is small THEN stop ELSE go to 7

in which small is defined as in example one

$$\mu(\text{small}) = 1/1 + 0.8/2 + 0.6/3 + 0.4/4 + 0.2/5$$

If x has a value of 3, which has a grade of membership of 0.6 in μ(small), should the process 'stop' or 'go to 7'? Again it is possible to assume the alternative which is most true (namely 'stop'), or where both alternatives have more or less equal truth values, the choice can be made arbitrarily. Naturally what should really happen is that for x = 3 there should result the fuzzy set:

0.6/stop + 0.4/go to 7

which implies that the execution is carried out in parallel. The assumption of parallelism is implicit in the compositional rule of inference and is basic to the understanding of fuzzy algorithms and their execution by humans and machines.

6. Concluding Remarks

The foregoing discussion has addressed but a few of the many basic issues involved in the development of a conceptual framework for dealing with systems such as cost generation, in which the human decision-making is too complex or too ill-defined to admit of precise quantitative analysis. The limited aim has been to suggest the possibility of treating this complexity in terms of fuzzy-set theory, which equates human reasoning with fuzzy logics.

The main concern has centered on what may be called a linguistic approach, but there are many basic as well as detailed aspects of the approach which have been treated incompletely, if at all. Among these are questions relating to the execution of fuzzy algorithms; the conjunction of fuzzy instructions; the assessment of goodness of fuzzy algorithms, membership functions, etc., the implications of the compositional rule of inference; the principle of linguistic approximation; non-numerical base variables; representation of linguistic hedges; fuzzy flow charts; the fuzzy treatment of probability; and the rule of preponderant alternative.

The linguistic approach has however enabled an alternative treatment to be proffered for how a single value might be extracted from a fuzzy set of possible values. It is suggested that by accepting the pervasiveness of imprecision in much of human thinking and perception, the door has been tentatively unlocked, if not opened slightly, for a whole new approach to the understanding of those systems which are strongly influenced by human decision-making.

REFERENCES

1. WILSON A J
"Experiments in probabilistic cost modelling", in "Building cost techniques: new directions", by P S BRANDON (editor), Spon, 1982, pp.169-180.

2. SPOONER J E
"Probabilistic estimating" in ASCE Journal of Construction Division, March 1974, pp.65-77.

3. ZADEH L A
"The concept of a linguistic variable and its application to approximate reasoning - III" in Information Sciences, Vol.9, 1975, pp.43-80.

4. BELLMAN R E et al
"Abstraction and pattern classification" in Journal Math. Analysis and Application, Vol. 13, 1966, pp.1-7.

5. ZADEH L A
"Outline of a new approach to the analysis of complex systems and decision processes" in IEEE Transactions on Systems, Man., and Cybernetics, Vol. SMC-3, No. 1, January 1973, pp.28-44.

6. GERO J S and OGUNTADE O O
"Fuzzy set evaluators in architecture: preliminary studies", Computer Report CR29, Department of Architectural Science, University of Sydney, 1978.

7. ZADEH L A
"Fuzzy algorithms" in Information Control, Vol.12, 1968, pp.94-102.

8. ZADEH L A
"The concept of a linguistic variable and its application to approximate reasoning - I" in Information Sciences, Vol. 8, 1975, pp.199-249.

APPENDIX IV: A GLOBAL CONCEPTUAL MODEL OF THE DATA FLOWS WITHIN A COSTING FUNCTION

APPENDIX IV: A GLOBAL CONCEPTUAL MODEL OF THE DATA FLOWS WITHIN A COSTING FUNCTION

A significant aspect of the systems approach to a problem concerns the identification of information flows within and between each system, the processing of such flows being paramount in system control. Although information is a difficult concept to define usefully, it is undoubtedly an important agent in increasing the synergy of a system, and much research has therefore been applied to the structuring of information (arguably any structured information can be termed a 'database').

Chapter 6, Section 6.2.4 considered the need to generate some form of 'database', and prompted this analysis of the data flow within a costing function.

The transformation of the 'real world' information flow to a conceptual model, can be described as being a process of analysing the real world data into a series of entities associated by relationships, which can then be further manipulated into the 'third normal form' - the conceptual model. The third normal form (abbreviated to 3NF) is a state in which for each entity (1):

(i) there are no repeating groups of attributes,

(ii) non-key attributes are functionally dependent upon the whole of the key, and

(iii) all non-key attributes are mutually independent.

A number of techniques have been developed to achieve a 3NF state, one such being 'normalisation' (2). The local conceptual models which result from this process are merged into a global conceptual model.

1. A Functional Analysis

It is necessary, initially, to try to anticipate a comprehensive list of functional requirements. These can be changed and supplemented later, but form the foundation of a tentative model.

* create and modify environmental specification
* create and modify construction specification
* create and modify geometry
* create and modify unit rates
* create and modify design details
* determine physical properties
* determine quantities
* predict cost
* predict cost relationships
* create and modify heuristics and all modes of calculation.

2. The Necessary Processes

Each function in turn, is associated with a series of processes which collectively will make up the activities of that function. For example, the processes associated with 'creating and modifying an environmental specification' can be listed as:

* list choices available
* change selection
* display selection
* locate regime
* alter scope of regime
* change properties
* retrieve properties

3. The Local Data Set

The group of processes associated with each function can then be analysed and their data requirements specified. Thus, for each function a 'local data set' is produced which describes fully the data used by that function. Taking the environmental specification again as an example, the resulting local data set is:

* location

for each location

* environment

for each environment

* regime

* environment properties

for each regime

* heating strategy

* lighting strategy

4. First Normal Form

Each local data set is arranged into entities with no repeating groups of attributes.

PROJECT (nr. regimes, nr. spaces)

REGIME (regime #, heating strat, lighting strat, property 1, property 2, ...property N)

ENVIRONMENT SPEC (space #, regime #)

5. Second Normal Form

Check that all non-key attributes are functionally dependent upon the whole of the key.

HEADER (database name, number of regimes)

PROJECT (project name, number of spaces)

REGIME (regime #, heating strat., lighting strat., property 1, property 2, ...property N)

ENVIRONMENT SPEC (space #, regime #)

6. Third Normal Form

Check that all non-key attributes are mutually independent

HEADER (database name, number of regimes)

PROJECT (project name, number of spaces, number of environments)

REGIME (regime , heating strat., lighting strat.)

ENVIRONMENT TYPE (environment , regime , property 1, property 2, ... property N)

ENVIRONMENT SPEC (space#, environment)

All of the local conceptual models which resulted from this process, were merged to produce the global conceptual model illustrated in Figure 1.

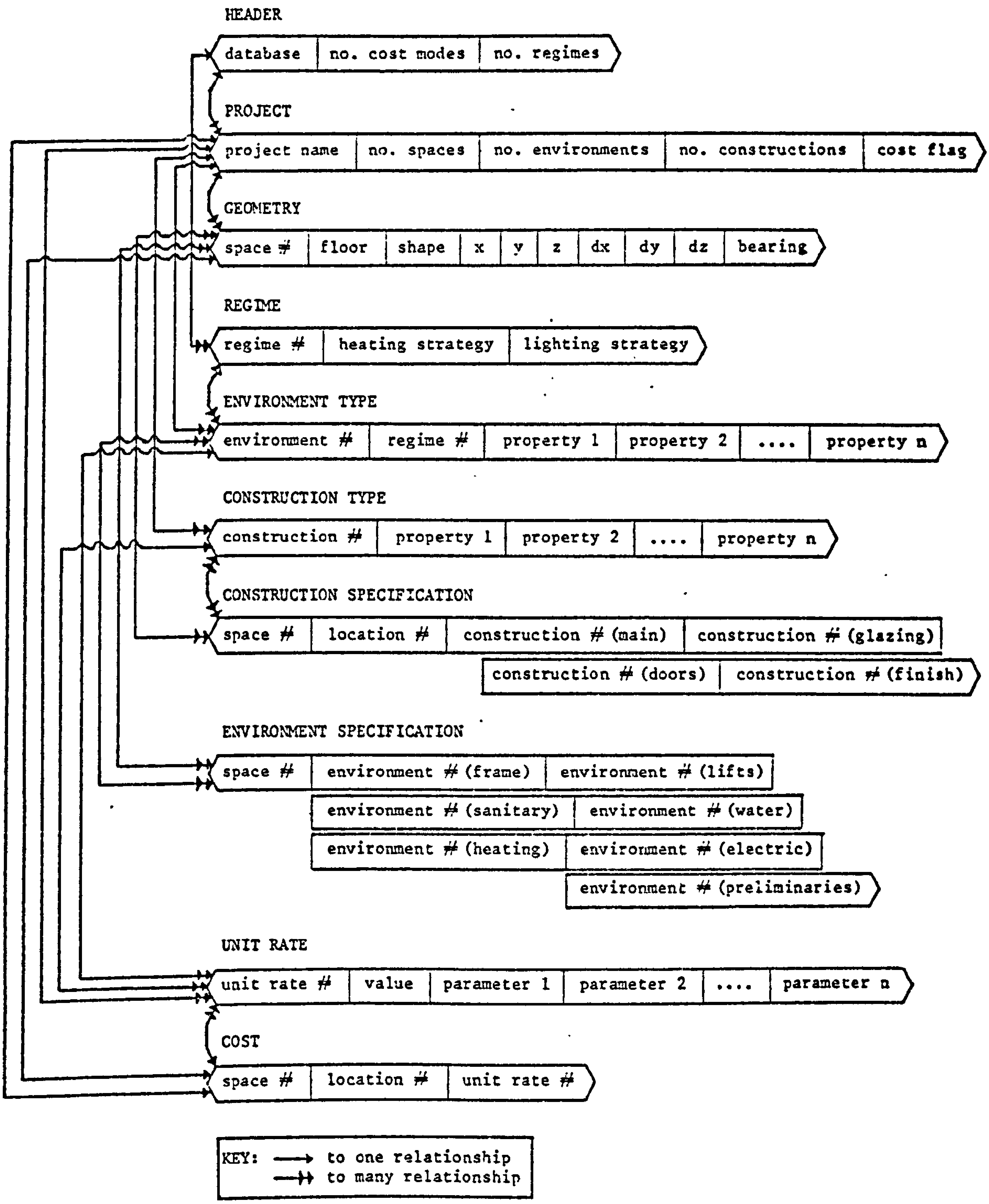


Figure 1: A global conceptual model for the costing function

REFERENCES

1. BERNSTEIN P A
"Synthesizing third normal form relations from functional dependencies" in ACM TODS, Vol. 1, No. 4, December 1976, pp.277-298.

2. THE OPEN UNIVERSITY
"Mathematics: A third level course", Block II, The Open University Press, 1980.

APPENDIX V: THE INGRES DATABASE MANAGEMENT SYSTEM – A TECHNICAL NOTE

1. Introduction
2. Basic Concepts and Definitions
3. The INGRES Process Structure
4. QUEL (QUEry Language)
5. EQUEL (Embedded QUEL)
6. Protection
7. Decompositions and Query Processing

REFERENCES

APPENDIX V: THE INGRES DATABASE MANAGEMENT SYSTEM - A TECHNICAL NOTE

1. Introduction

INGRES (Interactive Graphics and Retrieval System) (1) is a relational data base and graphics system running as a normal process under the UNIX (2) operating system. The implementation of INGRES is programmed primarily in C, a high level language in which UNIX itself is written. Parsing is done with the assistance of YACC (3), a compiler-compiler available under UNIX.

This appendix is intended only to gloss over the mechanics of actually formulating a query, concentrating instead on some of the fundamental principles underlying INGRES (For an explanation of the mechanics see the tutorial (4)). It will address the following aspects in some technical detail:

(i) basic concepts and definitions

(ii) the INGRES process structure

(iii) QUEL (QUEry Language)

(iv) EQUEL (Embedded QUEL)

(v) protection

(vi) decomposition and query processing

2. Basic Concepts and Definitions

Let D1, D2,..., Dn be non-empty sets, not necessarily distinct. A subset, R, of the product D1 x D2 x ... x Dn is called a relation, and Di are called the domains of R (i.e. the attributes). Let r be an element of R, then r is an n-tuple (r1, r2, ..., rn) where ri belongs to Di: that is, if R simply is a table with its elements appearing as rows, then R(Di) is just the column corresponding to Di.

3. The INGRES Process Structure

It is possible to invoke INGRES in two ways (5):

(i) by invoking the system directly from UNIX, using 'ingres' as a UNIX command. In that situation the process structure is as illustrated in Figure 1.

From standard input and output (which allows any terminal, line printer, file, etc. to be used) 'Process 1' maintains a work space with which the user interacts; formulating, printing, editing and executing a variety of high level non-procedural QUEL commands. When the user is satisfied with the query, the workspace contents are passed down 'pipe-A' as a string of ASCII characters.

'Process 2' contains a lexical analyser, parser, concurrency routines, and query modification routines. The parser provides a

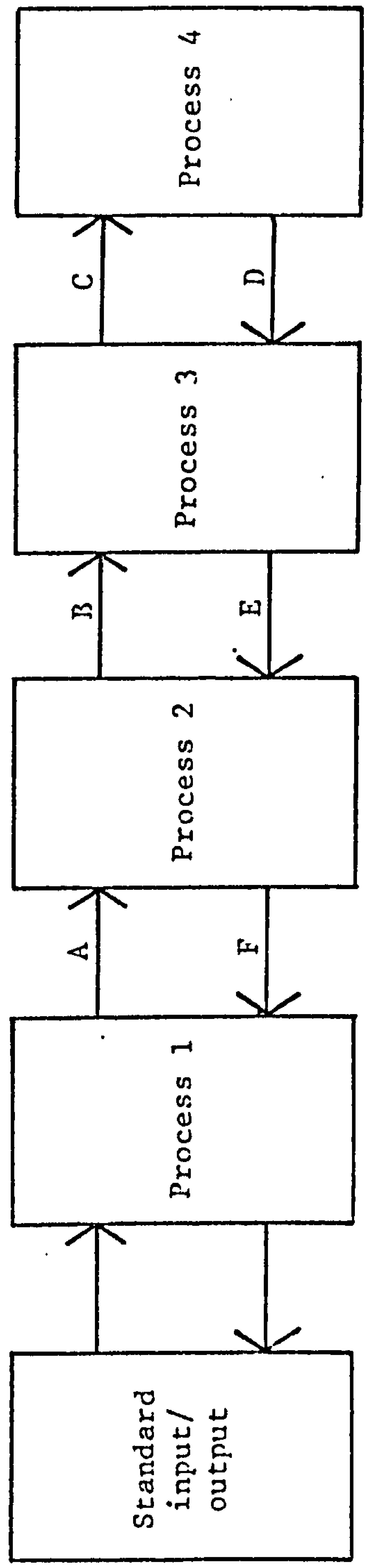


Figure 1: The INGRES process structure

tree-structured representation of the input query - the qualification portion of the query being converted to an equivalent Boolean expression in conjunctive normal form. Query modification includes adding integrity and protection predicates to the original query, and changing references to virtual references into references to the appropriate physical relations.

'Process 3' accepts a string of tokens from 'pipe--B' and first decomposes a multivariate query into a series of interactions involving only a single variable, and secondly executes a one variable query processor which accesses tuples from a single relation given a particular one variable query (6).

'Process 3' simply passes through 'pipe--C' any commands which 'Process 4' can execute.

'Process 4' is organised into several overlay programs, bringing the required overlay into core as required. 'pipe--D', 'pipe--E' and 'pipe-F' pass back error messages to 'Process 1', which returns them to the user: 'Process 3' may also pass certain retrives directly to standard output.

(ii) by invoking INGRES by code from the pre-compiler EQUEL (Embedded QUEL). The translator (pre-compiler) turns an EQUEL program into a valid C program by converting the QUEL statements into appropriate C code and calls to INGRES. The resulting C program is compiled as normal and its executable module replaces the front end process as illustrated in Figure 2, replicating the unparsed ASCII strings down 'pipe-A'.

A condition code is also returned through 'pipe--F' to indicate success, or the type of error encountered.

4. QUEL (QUEry Language)

QUEL is a calculus based language using keyword deliminators (7). Each query in QUEL contains one or more 'range-statements' of the form

RANGE of (variable) IS relation

and one or more 'retrieve-statements' of the form:

RETRIEVE INTO result-name (target list of 'result-domains' = function)

WHERE qualification

The goal of a query is to create a new relation called 'result-name', with the domains defined in 'target-list' for each

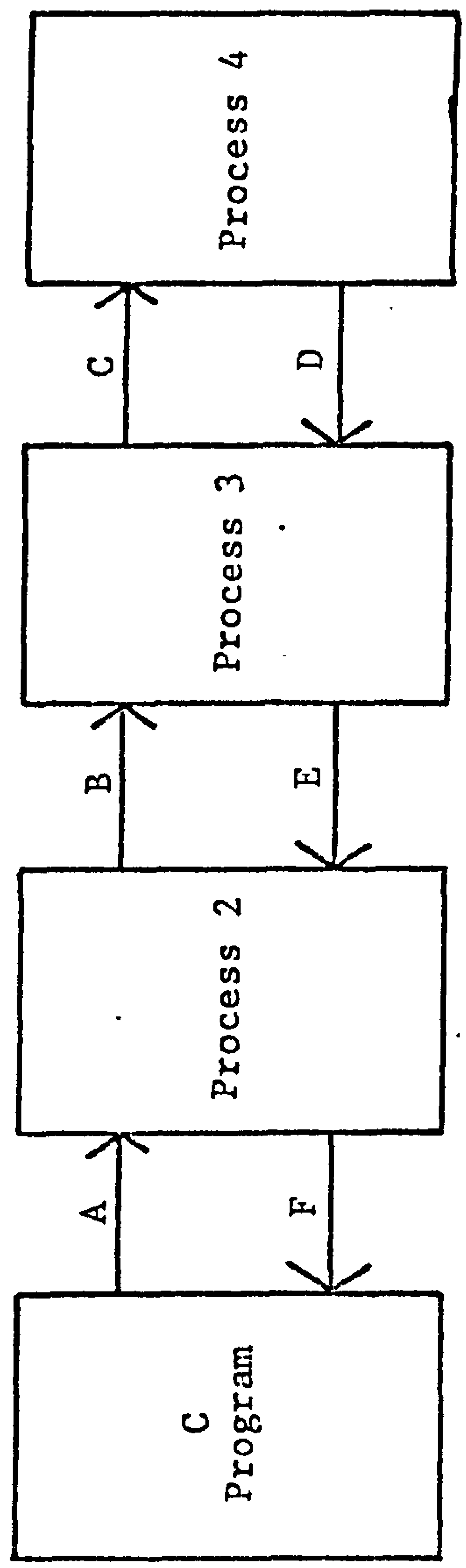


Figure 2: The INGRES process structure 'forked' to accommodate a C program

'retrieve-statement'. For example:

```
Env-Space   (Funct_type_name,   Funct_type_ele,  Heat_input,
             Heat_loss)

RANGE OF 'es' IS Env_Space

RETRIEVE INTO C_Gains (es.Funct_type_name,
                       Energy  =  es.Heat_loss -
                       es.Heat_input)

WHERE es.Funct_type_name = 'Bedrooms'
      AND es.Heat_input G.T. 5000.00
```

gives a new relation C_Gains (Funct_type_name, Energy).

It is apparent that by accommodating functions on products of relations, QUEL queries can be exceedingly complex. The allowable functions fall into three categories:

(i) functions resulting from arithmetical combinations of attributes: allowed operators are +, -, /, x, exponent, absolute value, and module division.

(ii) set valued functions such as "the set of elements for each function type".

(iii) aggregate functions obtained by aggregating set functions, such as "average heat loss for all function types". Allowable aggregates are 'count', 'count unique values only', 'minimum', 'maximum', 'average', 'average of the unique values', 'sum', 'sum of the unique values'.

5. EQUEL (Embedded QUEL)

EQUEL (8) is a programming language which embeds the relational data sub-language QUEL into the general programming language C. It is defined as follows:

(i) any C language statement is a valid EQUEL statement

(ii) any QUEL statement (or INGRES utility command), is a valid EQUEL statement as long as it is prefixed by two number signs (hash's)

(iii) C-program variables may be used in QUEL statements in place of relation names, domain names, target list elements, or domain values: again prefixed by two number signs.

(iv) retrieve-statements without a result relation have the effect of 'while there is a qualifying tuple', 'execute braced C-code'. For example, the program:

```
where Env_Space (Funct_type_name, Funct_type_ele,
                 Heat_Input, Heat_loss)

main()
{
##      char fname[20];
##      int C_Gain;

##      RANGE OF es IS Env_Space

        while(read(fname))
        {
##              RETRIEVE(C_Gain=es.Heat_loss - es.Heat_input)
##                      WHERE es.Funst_type_name = fname
##              {
                        print("The casual gain for",fname,"is",C_Gain);
##              }
        }
}
```

would calculate the casual gains for whichever functional type was input.

The following problems arise:

(i) Dynamic schemes: because the legality of an INGRES command may not be determinable at the start of a program parsing must be done during execution. This has obvious runtime costs since a RETRIEVE statement in some loop would be parsed on each invocation. The same dilemma applies to the integrity constraints on relations, access control statements for relations, and view definitions.

(ii) Recursion: there is no recursion in INGRES itself since no INGRES commands are implemented by invoking other INGRES commands. Yet many data base applications have natural recursion - for example, to find all employees who work for a particular manager, directly or indirectly. Although recursion is allowed in C, it appears difficult to implement in programming systems which span more than one process.

(iii) Types and type checking: conversion of types between the data base and a C-program acting as the 'front-end' cannot be done at compile time since the pre-compiler cannot know what types various domains will be at run time. INGRES therefore performs all type conversions at run time.

(iv) Syntax: because aggregates may be nested and multivariate, the scope of tuple variables, especially in the BY clauses, is objectionable and cannot easily be resolved.

6. Protection

Although protection of data in a cost model may not be crucial, certain notions should be explained (9).

INGRES manages a collection of data bases, each of which is made up of a set of relations. Each data base is associated with a special user called the Data Base Administrator (DBA). Only a data base's DBA may create shared relations in that data base, relations created by others being guaranteed private. Each data base contains certain relations which are system catalogs containing permissions for specific users and relations. No users, including the DBA, is allowed to update system catalogs using QUEL. This guards the integrity of the catalogs by making them accessible only through INGRES in response to INGRES commands. A directory of DBA's is maintained by the INGRES 'super user', and only he may read or write to them.

Protection of data is obviously very much based on the UNIX file protection system with the DBA given powers which cannot be delegated: namely,

(i) the ability to create shared relations and to specify access control for them, and

(ii) the ability to destroy any relations in his data base (except the system catalogs).

The power to create, destroy, etc., entire data bases (i.e. become a DBA) is authorised by the system 'root' or UNIX 'super user'.

7. Decomposition and Query Processing

With a non-procedural data sublanguage the loss of efficiency for queries spanning several relations can be fearsome. INGRES is therefore equipped to optimise query processing, but the costs of such optimisation may very well outweigh the benefits.

The overall strategy is to break up a query at the joining variables whenever this is possible, and to select a variable for substitution which incurs a 'minimum cost' whenever substitution can no longer be postponed. This 'decomposition' of an arbitrary multivariate query to a sentence of single-variable ones is only really undesirable when interrelational information such as 'links' are available, in which case the desirable atomic units may be two-variable queries.

REFERENCES

1. HELD G D et al
"INGRES - A relational database system" AFIPS Conf. Proc., Vol. 44, National Computer Conference, 1975, pp.409-416.

2. RITCHIE E and THOMPSON K
"The UNIX time-sharing system". CACM, Vol. 17, 1974, pp.365-375.

3. JOHNSON S C
"YACC, yet another compiler-compiler", UNIX Programmer's Manual, Bell Telephones Labs., July 1974.

4. EPSTEIN R
"A tutorial on INGRES", Memorandum No. ERL-M77-25, Elect. Research Lab., University of California, 15th December 1977.

5. STONEBRAKER M et al
"The design and implementation of INGRES", ACM Trans. on Database Systems, Vol. 1, No. 3, September 1976, pp.189-222.

6. WONG E and YOUSSEFI K
"Decomposition - A strategy for query processing" in ACM Trans. on Database Systems, Vol. 1, No. 3, September 1976, pp.223-241.

7. WOODFILL J et al
"INGRES: Version 6.2 - Reference manual", Electronics Research Lab., University of California, January 1982.

8. ALLMAN E et al
"Embedding a relational data sublanguage in a general purpose programming language", Proc. of Conf. on data: abstraction, definition and structure, SIGPLAN Notices, ACM Vol. 11, 1976, pp.25-35.

9. STONEBRAKER M and RUBINSTEIN P
"The INGRES protection system", Annual Conf. of ACM, Texas, October 1976, pp.80-84.

APPENDIX VI: THE ACE SYSTEM - A TYPICAL DIALOGUE BETWEEN USER AND COMPUTER

APPENDIX VI: THE ACE SYSTEM - A TYPICAL DIALOGUE BETWEEN USER AND COMPUTER

The ACE system consists of distinct modules which interact through the general structure described in Chapter 6, Section 6.2 of this thesis. The purpose of this appendix is to illustrate the logical form of the computer program ACE, by demonstrating a typical dialogue between user and computer.

1. Phase One

The first step is to provide a data base, specific to the particular project under consideration.

```
This module concerns the data base to be used.

Do you wish to:
        1.Create a new project data base
        2.Use an existing project data base

Please type number corresponding to choice
>> 1
1: OK ?
-> 1
What do you wish to call the project data base ?
*> oral
oral: OK ?
-> 1
What is the name of the standard data base ?
*> sdb
sdb: OK ?
-> 1

Executing . . .
```

The user may create a new, or access an existing, project data base. If created anew, at this stage the data base will contain only the standard construction types. These provide a palette of alternative window types, roof types, external wall types, heating types, etc. and associated physical properties, from which the proposed project can be composed.

Note the use of prompts to indicate what response the computer expects.

>> integer or real number

*> character string

-> a 'yes'(y,Y,1) or 'no'(n,N,0) response

Each number or string is echoed for the user to confirm before proceeding.

The 'Executing . . .' is usual where a delay between user inputs is likely.

The user would now decide on the application software required

For example:
1.Environment design(ESP)
2.Aesthetics (VISTA)
3.Geometry (BIBLE)
4.Structural design
5.Economics (ACE)
6.Draughting (STAG)
7.Lift design
8.Functional efficiency (MAGIC)
9. . . etc

For now we will take ACE only

The ACE program is intended for use in an integrated computer-aided architectural design environment and is therefore really only one of several options.

2. Phase Two

2.1 Data input

```
At what level of detail do you wish to input information;
        1.Outline (minimum)
        2.Sketch
        3.Detailed

Please type number corresponding to choice
>> 1
1: OK ?
-> 1
Do you have a saved solution file to input ?
-> n
By what name is this project to be known ?
%> orall
orall: OK ?
-> 1
```

ACE can be used throughout the design process. To avoid asking the user for detailed responses at an early stage in design the program allows the user to input information at various levels. Each question in the 'knowledge base' is associated with a particular level of detail, and will not be asked unless the user wishes it so.

It is possible to initialise variables in the knowledge base by inputing a saved solution file. The solution file records the value and status of previous interactions (see later in this appendix).

```
This module deals with the project geometry


How would you like the geometry relationship to be created ?
        1. Program generation
        2. Saved file
        3. GOAL file
        4. BIBLE file
        5. Digitiser
        6. Keyboard

Please type number corresponding to choice
>> 1
1: OK ?
-> 1
Do you wish to choose a general building form from the following:
        1.Cubic
        2.High rise
        3.High rise tower with podium
        4.Low rise square
        5.Low rise linear
        6.Low rise court-yard
        7.Single storey square
        8.Singile storey linear
        9.Unknown

Please type number corresponding to choice
>> 1
1: OK ?
-> 1
```

Having set-up the desired project data base the program knows that it requires the following information

- a geometry
- a construction specification
- an environmental specification

If no such information exists within the project data base the program must generate its own.

Various input formats can be accommadated, and the program will generate a number of standard (though very simple) geometric forms.

The knowledge base then interrogates the user for sufficient information.

```
Do you know the gross floor area of the building ?
-> 400
-> 1
Please enter the area
>> 400
400.000000: OK ?
-> 1
Do you know the length to breadth ratio for the building ?
-> 1
Please enter ratio as a single real number
>> 1
1.000000: OK ?
-> 1
Do you know the average room area ?
-> n
Obviously there is a minimum amount of information required to prov
estimate.
So far you have failed to provide sufficient information.
Would you care to try again ?
-> 1
```

A minimum amount of information is required however. In this case some indication of room size is needed - the first attempt to find a solution being the geometry relationship. As this data does not yet exist, the user is asked if he can supply further information.

```
Do you know the average room area ?
-> 0
Do you know the category of building type ?
-> 1
Building type may be:
         1.Galleries, libraries
         2.Cinemas, concert halls
         3.Factories
         4.Hospitals
         5.Hotels
         6.Offices
         7.Restaurants
         8.Schools-nursery
         9.       -day
        10.       -boarding
        11.Housing
Please type number corresponding to choice
>> 6
6: OK ?
-> 1

Executing . . .
```

As the average room area is still not known, the program uses an alternative mode of calculation, based on gross floor area (already known) and the building type.

The geometry is now recorded in the data base.

```
Do you wish to:
        1.Continue
        2.Change geometry
        3.Save solution file
        0.Exit

Please type number corresponding to choice
>> 1
1: OK ?
-> 1
```

The program then checks the data base for a project construction.

```
This module deals with the project construction


How would you like the construction specification to be created ?
        1.Interactive selection
        2.Saved file
        3.GOAL file

Please type number corresponding to choice
>> 1
1: OK ?
-> 1
```

```
The following information is required.
:The choice of a 'standard' construction
1.SUBSTRUCTURES
                                  -foundations     ?>0
2.SUPERSTRUCTURES
                                  -roof            ?>0
                                  -external walls  ?>0
                                  -windows         ?>0
                                  -perc. glazing   ?>20
                                  -internal walls  ?>0
                                  -internal doors  ?>0
                                  -floors          ?>0
3.FINISHES
                                  -ceilings        ?>0
                                  -walls           ?>0
                                  -floors          ?>0

:The number of spaces which are exceptions to this standard
?>0
Do you wish to list the construction choices made ?
-> 0

Do you wish to change anything ?
-> 0

Do you know how many storeys the proposed building will have ?
-> 0

Do you know if the building is to be framed ?
-> y
Is the building to be framed ?
-> y
```

Interactive selection allows the user to associate a particular construction type (as stored in the data base) with each face in the previously created project geometry. A 'face' is the floor, wall or roof of a geometric 'space', or room. If the user wishes to delay his/her decision on construction specification, a 0 is entered and the program uses its own knowledge base to assume some suitable choice for the given context.

The construction is now recorded in the data base.

```
Do you wish to:
        1.Continue
        2.Change construction chaoices
        3.Save solution file
        0.Exit

Please type number corresponding to choice
>> 1
1: OK ?
-> 1
```

The program then checks the data base for a project environment.

```
This module deals with the project environment

How would you like the environment specification to be created ?
        1.Interactive selection
        2.Saved file

Please type number corresponding to choice
>> 1
1: OK ?
-> 1
```

```
The following information is required.
:The choice of a 'standard' environment
                    Frame                  ?>1
                    Lifts                  ?>0
                    Sanitary installation  ?>1
                    Water                  ?>2
                    Heating                ?>1
                    Electrical             ?>4
                    Preliminaries          ?>0

:The number of spaces which are exceptions to this standard
?>0
Do you wish to list the environment choices made ?
->0

Executing . . .
```

In this case particular choices are associated with each space - a maximum number of 99 different options are available for each of the frame type, lift type, heating type, etc.

The environment is now created in the data base.

```
Do you wish to:
        1.Continue
        2.Change environment choices
        3.Save solution file
        0.Exit

Please type number corresponding to choice
>> 3
3: OK ?
-> 1
Please give the name for your solution file
Σ> orall.1
orall.1: OK ?
-> 1
```

It is also possible to save a solution file containing the value and status of all variables in the knowledge base, for use in subsequent program runs (see previously).

```
This module deals with the project costs


Do you know the plan area ?
-> n

Do you know the site area ?
-> n
Do you know the plot ratio for the proposed development ?
-> n
How would you like the costs to be presented ?
        1. elemental group totals
        2. Elemental breakdown with preliminaries separate
        3. Elemental breakdown with preliminaries included

Please type number corresponding to choice
>> 2
2: OK ?
->
```

A project cost is determined by using the approximate quantities technique. Each unit rate is determined by the program dependent on context and aggregated to give the total cost breakdown.

	TOTAL FOR ELEMENT		% OF TOTAL COST		COST/M2 GFA	
1.SUBSTRUCTURES	1587		0.84		3.97	
1.1.foundations		1587		0.84		3.97
2.SUPERSTRUCTURES	70568		37.29		176.42	
2.1.frame		3797		2.01		9.49
2.2.floors		13977		7.39		34.94
2.3.roof		4528		2.39		11.32
2.4.extl walls		35482		18.75		88.71
2.5.windows		12785		6.76		31.96
2.6.intl walls		0		0.00		0.00
2.7.doors		0		0.00		0.00
3.FINISH	6154		3.25		15.39	
5.SERVICES	82437		43.56		206.09	
5.1.sanitary		1222		0.65		3.05
5.2.water		11120		5.88		27.80
5.3.heating		46688		24.67		116.72
5.4.electric		23407		12.37		58.52
5.5.lift		0		0.00		0.00
6.PRELIMINARIES	28488		15.05		71.22	
TOTAL	189235.44		100.00		473.09	

Note that the program determined that no internal walls or doors were necessary for such a small plan area, and that for three storeys, no lifts were needed.

2.2 Data output

```
This module deals with the interrogation of project solution

Do you wish to:
        1.Retrieve value of particular variable
        2.Change value of particular variable
        3.Calculate costs
        0.Exit

Please type number corresponding to choice
>> 1
1: OK ?
-> 1
Do you want full variable record ?
-> 0
VARIABLE number
>> 34
34: OK ?
-> 1
GETVAR 34
GETVAR 34 = 133.333344
VARIABLE number
>> 100
100: OK ?
-> 1
GETVAR 100
GETVAR VNR = 100
2-GET VNR=100
GETVAR 100 = 48.092125
VARIABLE number
>> 1
1: OK ?
-> 1
GETVAR 1
GETVAR 1 = 62.000000
VARIABLE number
>> 0
0: OK ?
```

The user can then interrogate the solution produced. Each variable in the knowledge base is accorded a number (see Chapter 7, Table 7.3 for further examples):

34 = plan area

100 = surface area of radiator

1 = number of occupants

A zero ends execution.

```
This module deals with the interrogation of project solution


Do you wish to:
        1.Retrieve value of particular variable
        2.Change value of particular variable
        3.Calculate costs
        0.Exit

Please type number corresponding to choice
>> 2
2: OK ?
-> 1
Which variable do you wish to change ? ( 0 to continue )
>> 1
1: OK ?
-> 1
What is the new value ?
>> 75
75.000000: OK ?
-> 1
1,75.000000
Which variable do you wish to change ? ( 0 to continue )
>> 0
0: OK ?
-> 1
```

Alternatively, new values for each variable can be enforced on the knowledge base. In this case the number of occupants is increased from 62 to 75.

```
Are dependencies:
        1.File input
        2.User input
        0.None

Please type number corresponding to choice
>> 1
1: OK ?
-> 1
What is file name ?
*>
```

Associated with each change are a number of dependent variables which must be recalculated before the 'true' effect of that change is expressed (see Appendix VII).

```
This module deals with the interrogation of project solution

Do you wish to:
        1.Retrieve value of particular variable
        2.Change value of particular variable
        3.Calculate costs
        0.Exit

Please type number corresponding to choice
>> 3
3: OK ?
->
```

The cost consequences of each alternative design decision are calculated anew, and can be recorded and stored as a solution file, or further interrogated.

	TOTAL FOR ELEMENT		% OF TOTAL COST		COST/M2 GFA	
1.SUBSTRUCTURES	1587		0.85		3.97	
1.1.foundations		1587		0.85		3.97
2.SUPERSTRUCTURES	70568		37.65		176.42	
2.1.frame		3797		2.03		9.49
2.2.floors		13977		7.46		34.94
2.3.roof		4528		2.42		11.32
2.4.extl walls		35482		18.93		88.71
2.5.windows		12785		6.82		31.96
2.6.intl walls		0		0.00		0.00
2.7.doors		0		0.00		0.00
3.FINISH	6154		3.28		15.39	
5.SERVICES	80656		43.03		201.64	
5.1.sanitary		2045		1.09		5.11
5.2.water		11380		6.07		28.45
5.3.heating		43855		23.40		109.64
5.4.electric		23376		12.47		58.44
5.5.lift		0		0.00		0.00
6.PRELIMINARIES	28488		15.20		71.22	
TOTAL	187454.14		100.00		468.64	

Note the changes in cost over the previous case. Although more sanitary appliances, etc. are needed, the heat output from each person reduces heating costs by a greater amount.

By making a series of such changes in the values of specific variables, cost relationships and cost thresholds are produced which can then be explicitly displayed. At present the solution files are manually sorted into the correct format for the ACE display modules.

```
File name of display data ?
*> occupant.dat
Does data have labels ?
-> y
File name of standard colours ?
*> colour1.dat
How is matrix to be processed:
        1.With respect to absolute value

Please type number corresponding to choice
>> 1
1: OK ?
-> 1
What is the minimum expected value ?
>> 250
250.000000: OK ?
-> 1
What is the expected range of data ?
>> 225
225.000000: OK ?
-> 1
```

Having prepared a suitable display file the data can, for example, be presented in the form of colour matrix where each value in the display file is associated with the relevant colour in a given colour scale.

This same procedure was adopted when undertaking the cost investigations of Chapter 7, and gives some indication of the flexibility and quality of the ACE system.

APPENDIX VII: AN ANALYSIS OF THE DEPENDENCIES BETWEEN VARIABLES AND UNIT RATES WITHIN THE ACE KNOWLEDGE-BASE

APPENDIX VII: AN ANALYSIS OF THE DEPENDENCIES BETWEEN VARIABLES AND UNIT RATES WITHIN THE ACE KNOWLEDGE-BASE

1. Introduction

In Chapter 6, Section 6.1 mention was made of the fact that an investigation of the logical structure within ACE: version 1 revealed it to be extremely complex:

* a large number of routines are recursive in that they are dependent upon other variables, in turn dependent upon the calling routine (see Figure 1(a)).
* the structure is dictated by the context in which each routine is called. That is, in different situations different modes of calculation might be selected which could produce a different set of dependencies (see Figure 1(b)), thus creating an animated logical structure.
* the large number of immediate dependencies (perhaps 6 per variable) and the depth of the overall structure (accentuated by the recursive nature of many dependencies) made the logical diagram unmanageably large, and difficult to reproduce on paper.

This appendix is an equivalent study of the logical structure for ACE: version 2. The structure itself is no less complex than that described above, and this particular analysis will therefore concentrate on a description of the process by which a simple set

```
Var 5.-┬-dependent on Var.7-┬-dependent on Var.5-┬-dependent on Var.7  etc
       │                    │                    └──────── and on Var.26 etc
       │                    └──────── and on Var.26┬dependent on Var.52 etc
       │                                           └──────── and on Var.53 etc
       └──────── and on Var.26┬dependent on Var.52 dependent on Var.26 etc
                              └──────── and on Var.53┬dependent on Var.26 etc
                                                     └──────── and on Var.52 etc
```

(a) The recursive nature of 'variable' dependencies

```
Variable 25 dependent on Variable 92
                  and if Variable 92 is greater than zero
                     on Variable 70
                     on Variable 71
                else on Variable 82
                     on Variable 83
```

(b) The influence of context on 'variable' dependencies

Figure 1: The complexity of the ACE programs' logical structure: Two examples

of dependencies are transformed into a luxuriant source of cost relationships.

2. Formulating the Knowledge-Base - An Example

The total number of variables and unit rates within the ACE knowledge-base currently stands at 206 (meaning that each individual variable might be dependent on upto 205 other variables; or, that the total number of possible dependencies is 206 x 205 = 5330). This example has been simplified greatly, to one containing only 9 variables.

The example concerns the total cost of a roof, which is said to be:

VAR1 = VAR2 x VAR3

where VAR1 = total cost of the roof

VAR2 = area of the roof

VAR3 = unit rate per square metre of roof

Thus VAR1 (the total cost of the roof) is dependent upon VAR2 (the area) and VAR3 (the unit rate).

Considering now VAR2, we might determine that area can be calculated as:

VAR2 = VAR4 x VAR5

where VAR2 = area of roof

VAR4 = length of roof

VAR5 = breadth of roof

Each and every variable is described in this way, as a function of some other variables.

VAR1 = {VAR2, VAR3}

VAR2 = {VAR4, VAR5}

VAR3 = {VAR2, VAR6, VAR7}

VAR4 = {VAR2, VAR5, VAR7, VAR8}

VAR5 = {VAR2, VAR4, VAR7, VAR8}

VAR6 = {VAR9}

VAR7 = {VAR2, VAR4, VAR5}

VAR8 = {VAR4, VAR5}

VAR9 = {VAR6}

where VAR1 = Total cost of roof
VAR2 = Area of roof
VAR3 = Unit rate per square metre of roof
VAR4 = Length of roof
VAR5 = Breadth of roof
VAR6 = Building height
VAR7 = Plan perimeter
VAR8 = Length to breadth ratio
VAR9 = Number of storeys

Note however that each function need not be linear, nor necessarily even deterministic: the terms of the expression simply identify the immediate (or primary) determinants of the variable. These 'primary determinants' form a set which can then be translated into a matrix, as illustrated in Figure 2.

	VAR1	VAR2	VAR3	VAR4	VAR5	VAR6	VAR7	VAR8	VAR9
VAR1	1	1	1						
VAR2		1		1	1				
VAR3		1	1			1	1		
VAR4		1		1	1		1	1	
VAR5		1		1	1		1	1	
VAR6						1			1
VAR7		1		1	1		1		
VAR8				1	1			1	
VAR9						1			1

Figure 2: The dependency matrix or primary determinants for a total roof cost

It is apparent, by implication, that if VAR4 and VAR5 are determinants of VAR2, they must also affect VAR1. These 'secondary determinants' are included in the matrix by replacing each primary determinant with its 'determinant set'. Figure 3 shows a fully resolved matrix for the total cost of a roof. Associated with each variable is a row containing the complete set of all other variables on which it is dependent. For example, a change in any variable (except obviously total cost) might affect the unit rate for the roof (VAR3), but only a change in the number of storeys (VAR9) can affect the building height (VAR6).

In turn, each column associates a variable with the complete set of those variables actually dependent upon it. Thus it is possible to state that a change in the length of the roof (VAR4) might affect, directly or indirectly, the unit rate per m2 of roof (VAR3), the breadth of the roof (VAR5), the length:breadth ratio (VAR8), and the perimeter length (VAR7). These variables should therefore be recalculated each time a change is made to the value for roof length.

Figure 4 shows the hierarchy of dependencies, given some change in the roof length (contrast this with the hierarchy illustrated in Chapter 7, Figure 7.12 - the complexity of a hierarchy will increase substantially as more variables are introduced). Note that the actual relationship between, say, roof length and the unit rate per m2 of roof is never stated explicitly, but is inherent within the actual model implementation. This approach has considerable advantages:

	VAR1	VAR2	VAR3	VAR4	VAR5	VAR6	VAR7	VAR8	VAR9
VAR1	1	1	1	2	2	2	2	2	2
VAR2		1		1	1		2	2	
VAR3		1	1	2	2	1	1	2	2
VAR4		1		1	1		1	1	
VAR5		1		1	1		1	1	
VAR6						1			1
VAR7		1		1	1		1	2	
VAR8		2		1	1		2	1	
VAR9						1			1

Figure 3: The fully resolved matrix for a total roof cost

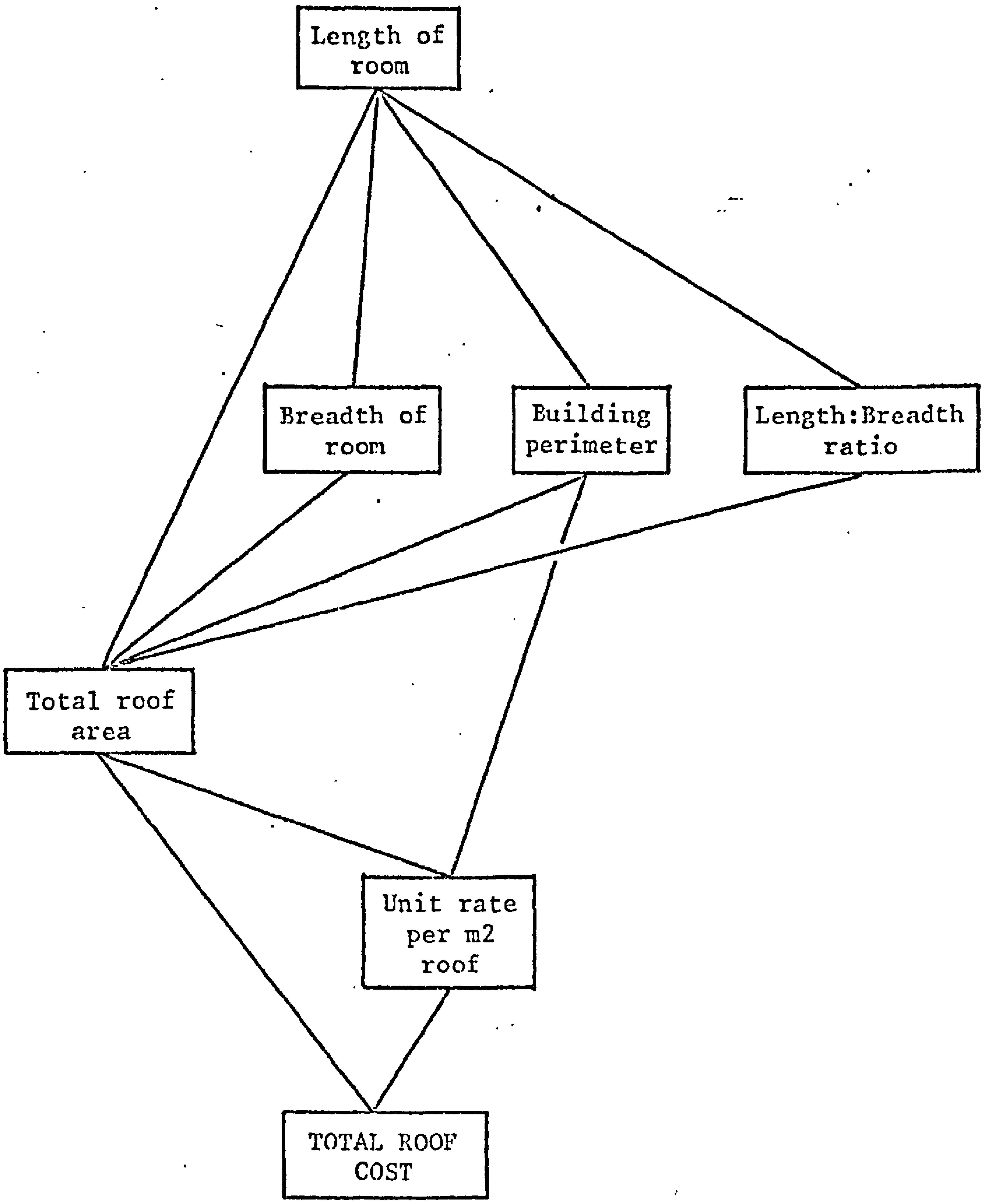


Figure 4: The hierarchy of dependencies for a change in the roof length

(i) The description of each variable can be as complex a function as necessary - in fact even a completely separate program for, say, heat-loss calculations, etc.

(ii) The explicit statements which constitute the knowledge-base need only relate to the primary determinants of each variable. This makes 'knowledge capture' a more straight-forward procedure, as the 'expert' need be less definitive in his/her description.

(iii) From the dependency matrix of primary determinants, a model such as ACE can infer secondary determinants and will therefore take into account the full knock-on effect of any given design decision.

(iv) Most significantly perhaps, with a computer-based model the knowledge structure can be exhaustively interrogated; both formally by generating dependency hierarchy's from the program logic, and informally by investigating cost relationships produced by iterative runs through the program.

3. The ACE Dependency Matrix

The complexity of a dependency matrix is compounded greatly when the number of variables considered increases from 9 to over 200. Simply to resolve a matrix of this size requires the use of a sizeable computer; to produce a dependency hierarchy, some form of sophisticated clustering package is helpful (1).

Figure 5 illustrates the ACE knowledge-base dependency matrix for primary determinants only. Some detail unfortunately is lost during photographic reduction, but essentially each shaded square in the matrix corresponds to a dependency between two variables (the total matrix represents all possible dependencies). The sparseness of points reflects the simplicity of each variables description in the ACE knowledge-base, and a more comprehensive implementation of the model would make the matrix correspondingly more filled.

Resolving the matrix for all dependencies has a quite dramatic effect (see Figure 6). Despite the original sparseness, a very strong dependency is revealed for a few key variables; namely,

variables 5 - gross floor area
7 - number of storeys
17 - plan perimeter
31 - plot ratio
33 - site area
34 - plan area
68 - plan length
69 - plan breadth
89 - length/breadth ratio

It is patently obvious that the significant design decisions (in so far as they are likely to have the greatest impact on total cost) correspond to those which affect the size, shape and general massing of a building.

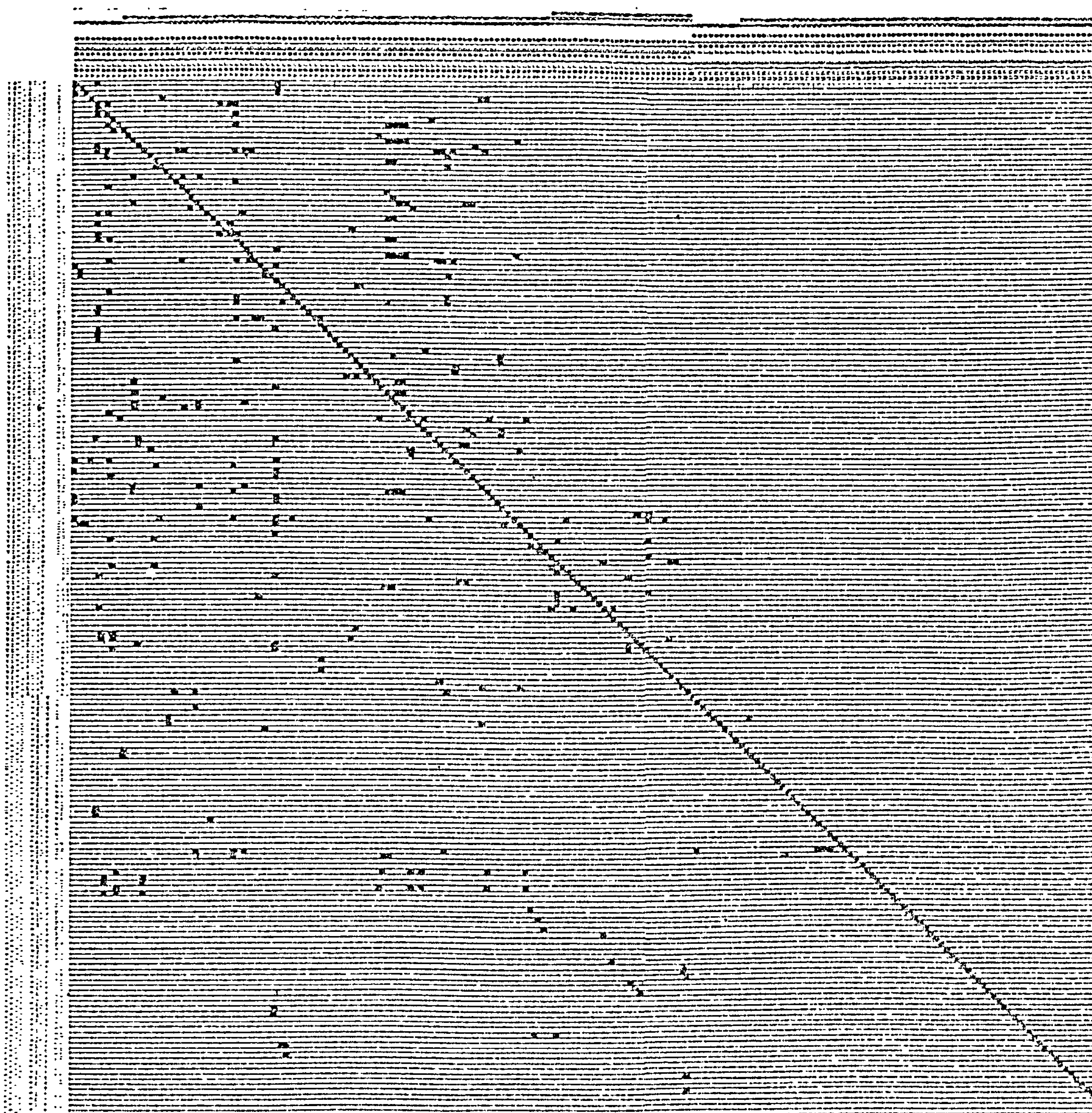


Figure 5: The dependency matrix of primary determinants for ACE

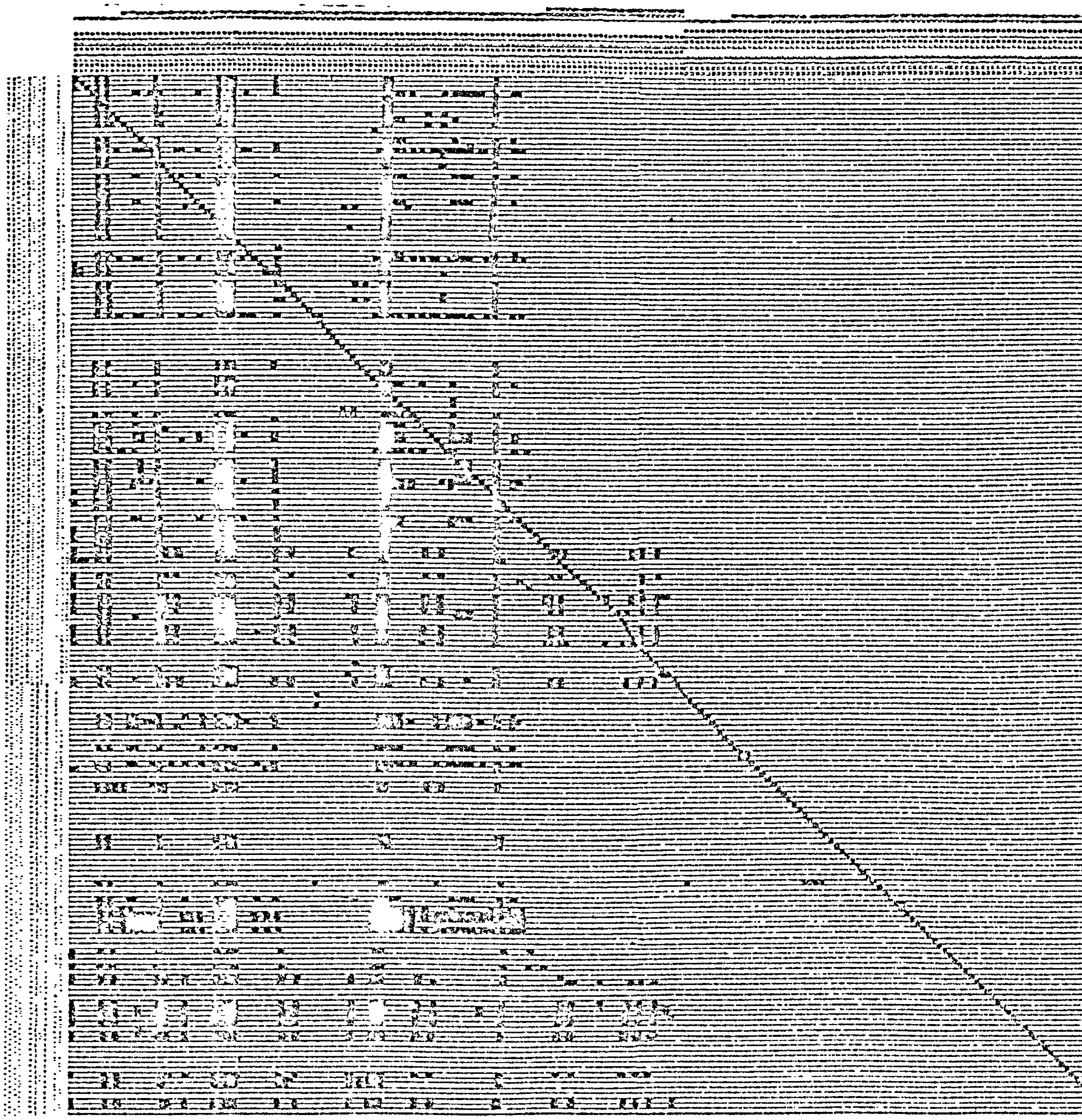


Figure 6: The fully resolved matrix for ACE

Naturally other knowledge-bases might reveal other causal variables - certainly this primary matrix is quit sparse, especially where it describes the unit rates - but the process does highlight causal variables which might otherwise have been ignored, and successfully externalises the complex labyrinth of cost and design inter-dependencies.

REFERENCES

1. BRIDGES A

"MAGIC-Multivariate analysis by graphical interactive computing", ABACUS Occasional Paper No.65, 1978.