COST MODELS FOR
ENGINEERING SERVICES

VALDA ROSALIND ALLENBY

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SUMMARY

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This thesis describes the procedure and results from four years research undertaken through the IHD (Interdisciplinary Higher Degrees) Scheme at Aston University in Birmingham, sponsored by the SERC (Science and Engineering Research Council) and Monk Dunstone Associates, Chartered Quantity Surveyors.

A stochastic networking technique VERT (Venture Evaluation and Review Technique) was used to model the pre-tender costs of public health, heating, ventilating, air-conditioning, fire protection, lifts and electrical installations within office developments. The model enabled the quantity surveyor to analyse, manipulate and explore complex scenarios which previously had defied ready mathematical analysis.

The process involved the examination of historical material costs, labour factors and design performance data. Components and installation types were defined and formatted. Data was updated and adjusted using mechanical and electrical pre-tender cost indices and location, selection of contractor, contract sum, height and site condition factors. Ranges of cost, time and performance data were represented by probability density functions and defined by constant, uniform, normal and beta distributions. These variables and a network of the interrelationships between services components provided the framework for analysis.

The VERT program, in this particular study, relied heavily upon Monte Carlo simulation to model the uncertainties associated with pre-tender estimates of all possible installations. The computer generated output in the form of relative and cumulative frequency distributions of current element and total services costs, critical path analyses and details of statistical parameters. From this data alternative design solutions were compared, the degree of risk associated with estimates was determined, heuristics were tested and redeveloped, and cost significant items were isolated for closer examination. The resultant models successfully combined cost, time and performance factors and provided the quantity surveyor with an appreciation of the cost ranges associated with the various engineering services design options.

Keywords: VERT, Mechanical, Electrical, Estimates, Models.

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1.0 Introduction

The thesis is divided into ten chapters which review the context and requirement for the research, study the relevant literature and previous research, structure the research data based on the proposed probabilistic methodology, examine the VERT programming process, test and discuss the resultant cost models for engineering services. Appendices give a fuller understanding of the subject areas. Prior to each chapter, sections and sub-sections for each subject area are documented for the benefit of the reader.

2.0 PROJECT BACKGROUND

2.1 The Interdisciplinary Higher Degrees (IHD) Scheme

This research was conducted through the Interdisciplinary Higher Degrees Scheme at the University of Aston in Birmingham. The scheme, which was initiated in 1968, encourages students to combine practical research supplied by an external sponsoring organisation with academic respectability. Cochran (1981) explains the methodology behind the system.

David Chelmick, from the sponsoring organisation and Helene Ryding from the university, originally recognised the need for research within the quantity surveying profession. IHD provided the framework. The research was funded by a studentship awarded by the Science and Engineering Research Council (SERC) and sponsored by Monk Dunstone Associates, Chartered Quantity Surveyors.

Approximately two thirds of my time was spent in industry, the remaining one third at the university using the IHD facilities, attending coursework and seminars, researching literature and operating the computer.

The IHD approach provided a balance between the commercial pressures of problem solving and the academic rigour of research.

2.2 Monk Dunstone Associates

2.2.1 Monk Dunstone Associates (MDA) is an independent private practice of Chartered Quantity Surveyors with offices throughout the United Kingdom and in many countries throughout the world. The practice was founded in 1950 by K.W. Monk FRICS, FCI Arb and P.H. Dunstone TD, PhD, FRICS, FIQS, FCI Arb under the name Monk and Dunstone. In 1970 they amalgamated with another UK practice, Mahon and Scears, founded in 1946 by A.F. Mahon FRICS, FCI Arb and R.L. Scears FRICS, FCI Arb, to form Monk and Dunstone Associates (MDA).

During the 1950s, Monk and Dunstone researched into the development of rationalised building, modular and dimensional co-ordination techniques. In the 1960s, they pioneered the introduction of computerised techniques and produced, in 1964, a standard library of descriptions for building works. The preparation of bills of quantities and cost planning by computers was also introduced. Mahon and Scears were the first successful practice to pioneer a construction cost consultancy in Europe. An office in Brussels was opened in 1962. The Engineering Services Division (ESD) was established in 1979, when the need for specialist quantity surveyors was recognised.

Monk Dunstone Associates are generally employed by clients to offer expert advice on the financial, contractural and communication aspects of the construction industry. They act as an impartial link between the client, the architect, the engineers and the builders. The quantity surveyor controls the cost of the construction of a project from the design stage to the final completion of the contract. He is responsible for the contractural negotiations, monitoring the progress of the construction and agreeing the final account. As the economist of the building team, he is often known as the construction cost consultant.

2.2.2 There are problems in defining the role of the quantity surveyor (Wilson, 1985), but the principal services can be outlined - Preliminary cost advice which indicates the likely cost of the proposed project to the client, the recommendation of the most economical layout or design including the materials and method of construction, and the assessment of the project duration. The quantity surveyor may produce estimates of future maintenance and running costs, and compare alternative design solutions. He advises on contractual methods and contractor selection, prepares tender documents, bills of quantities and specifications. He may produce construction schedules, network analyses and cash flow charts. The quantity surveyor analyses tender documents, implements cost control techniques to evaluate site construction work in progress, produces monthly progress payment evaluations and forecasts the final costs. Variations in the design or construction are evaluated and accounts agreed and settled with contractors. Contractual claims may be investigated and expert evidence given at arbitrations and disputes. In general, the quantity surveyor should ensure that the resources of the construction industry are used to their best advantage, and should provide financial management and cost advice to the client and designers during the whole construction process. The RICS (1977) described the work of the quantity surveyor on an international level.

The quantity surveying role has developed over the years from the passive role of accounting for cost to the more active and creative role of predicting costs and advising before the event (Milburn, 1980). Bennett (1977) reviewed the challenges facing the quantity surveying profession whilst Birchall and Newcombe (1985), Newton (1985) and Mathur (1982)[2] advocated new methods which should be developed to secure the future of the profession.

2.3 Engineering Services

2.3.1 Mechanical and Electrical (M&E) engineering services encompasses sanitary installations, the provision of hot and cold water systems, provisions for the control of the internal environment by means of heating, ventilating and air-conditioning, fire protection systems, conveyancing installations, electrical supplies, lighting, power, telephones and lightning protection. Specialist services may include security installations, aerial systems, refuse disposal, rainwater and drainage installations, call and public address systems, clocks, specialist laboratory and hospital services, kitchen equipment, computer provisions and sophisticated communication systems. Engineering services provisions vary widely with building function and design.

2.3.2 With the ever-increasing emphasis on technology, there has been a dramatic increase in the scope and sophistication of engineering services over the last thirty years (Billington & Roberts, 1982). The quantity surveyor can no longer ignor them, as they are assuming a greater significance particularly from the financial viewpoint (Fussell, 1971). If engineering services are cost controlled substantially less effectively than the building elements, the financial outcome of construction projects can be jeopardised (RICS, 1975). An analysis of a typical modern office development shows that services can account for between 20-60% of the total building costs (Cartlidge & Mehrtens, 1982; Chelmick, 1982[3]; Judson, 1985 and Ferry, 1980). Watson (1980)[2] and Cartlidge & Mehrtens (1982) proposed that the proportion of services costs within total building costs had increased partially because of more sophisticated fire protection systems and communication installations, but mainly because of the increased demand for ventilation and air-conditioning elements.

2.3.3 Traditionally, the quantity surveyor had little involvement with engineering services because of their relatively low cost and generally simple nature (Barry, 1985 and Burr, 1972). Engineering contractors and specialist sub-contractors often submitted design solutions, estimated and tendered for projects without the involvement of engineering consultants or quantity surveyors. When the quantity surveyor was involved, prime cost sums were included in bills of quantities for sub-contractor lump sum offers. Bills of quantities were generally disliked within the building services industry. In 1982, the Engineering Services Committee of the RICS released its findings from a 1981 questionnaire which showed that the majority of organisations prepared less than five bills of quantities for M&E services per year. Their analyses also suggested that quantity surveyors were becoming more involved in engineering services, but few were involved in cost research. There is controversy within the building services industry over who (quantity surveyor or consulting engineers) and in what format costings should be prepared (Q.S. Notes, 1978 and Ferry, 1980).

A study of quantity surveying practice and client demand (RICS, 1985)^2 found that clients considered that the quantity surveyor offered inadequate early cost advice and appeared to have little knowledge of the content of engineering services. Ferry (1980) noted that even when a consulting engineer was appointed, the quantity surveyor did not seem to be aware of the design considerations involved. The quantity surveyor may argue that a lack of early detailed design information from the engineers and poor co-ordination of services had contributed to the lack of good cost advice (Venning, 1978). Scant attention to the training of potential engineering services quantity surveyors, the penalties of failure to qualify through the test of professional competence due to specialisation and the lack of technical research seem to have produced apathy within the profession. Milburn (1980) challenged the quantity surveyor to understand the services engineering industry, appreciate its differences, organisation, methods and personalities.

Some would argue that the quantity surveyor is paid a fee to cost control a whole building including the engineering services elements. The Q.S. Engineering Services Committee (Q.S. Notes, 1978) emphasized the advantages of the quantity surveyor being responsible for services costings rather than the engineer. Watson (1980)[3] stated that the less attention paid to M&E services elements at the tender stage, the more that service would be likely to cost at the end of the day. He stated that if the quantity surveyor does not get involved in the more complex technical aspects of M&E design, the more difficult it would be to challenge apparently inexplicable increases in costs. He also showed through his research that the introduction of the quantity surveyors professional expertise into the field of engineering services could lead to more effective cost control and that his involvement was more than justified in terms of cost viability (Turner, 1982). MDA maintain that engineering services work carried out by private practice can be profitable and that it is essential to provide the client with a complete cost control package.

In 1978 the RICS endeavoured to encourage a greater interest into engineering services. Many of the larger quantity surveying practices do appear to have services departments. Only the larger companies have been able to tackle the problem of cost planning the services elements, because of the lack of published cost analyses (Skoyles, 1985) and the large amounts of historical data and expertise required (Edworthy & Chelmick, 1980). Nisbet (1979) claimed that, given the appropriate level of information, quantity surveyors could become sufficiently acquainted with engineering services. There seems to be a movement within the profession to encourage quantity surveyors to obtain both capability and respect within the engineering services field to an extent equal to that in the building elements. If the services elements continue to be ignored, the adverse effect on the finances of a project would increase as the monetary share of the total cost represented by these elements increases. The quantity surveyor should provide effective cost control and should improve his technical knowledge of the services elements. As Edworthy & Chelmick (1980) stated, the quantity surveyor should be prepared to tackle these responsibilities and work in co-operation with the services engineer.

2.4 Problem identification, aims and objectives

> "There is no more urgent research task for the profession to undertake than to discover the determinants of costs both for forecasting and estimating purposes."
>
> Drake (1984)

2.4.1 Since there are a lack of published detailed cost analyses for engineering services, MDA was concerned about the lack of analysis and co-ordinating of cost information and expertise which had accumulated within the Engineering Services Division (ESD). D. Chelmick, the associate in charge of the ESD, was unhappy about what he perceived to be signs of poor estimating performance and the lack of standardised format for the cost control of engineering services. The ESD could not guarantee the client good value for money, achieve a realistic distribution of expenditure amongst the various services elements or keep expenditure within the limits agreed by the client. Few of the quantity surveyors within the division, working on a regular day-to-day basis, had the time available to research into possible solutions, co-ordinate and analyse the valuable cost information which had accumulated since 1979.

> "The profession has, to date, failed to develop in a systematic manner either the techniques or the information necessary to enable them to directly influence the development of the sketch plan."
>
> Bennett (1977)

2.4.2 The aim of this research was therefore to define a systematic procedure and produce sophisticated cost appraisal models for the estimation of mechanical and electrical engineering services, required at the feasibility stage (RIBA Plan of

Work, 1980) of design. The cost models should take account of the quantifiable cost and design determinants and lend themselves to computer programming. They should contribute to the design process by supplying cost information on alternative design options in a precise and unambiguous form. The models should be flexible enough to accommodate changes in design technologies, labour factors, the historical cost data and design trends. Following their completion, the ESD should be able to re-examine, supplement and confirm cost information, outline the design implications of the selected cost range or cost limit, prepare reliable cost plans or elemental costings, note cost significant items, so as to liaise with the engineers and agree specifications at a pre-tender stage when detailed design information is largely lacking.

The cost models were to be designed specifically to suit the requirements of the Engineering Services Division and were presented in a format which reflected closely the estimators' current practice.

3.0 LITERATURE REVIEW

3.1 Cost planning

3.1.1 Originally the use and meaning of the phase 'cost planning' was confined to the process of setting elemental cost targets and of monitoring costs against these budgets. The development of cost planning was well described by Higgen & Jessop (1963). Today its meaning has broadened to describe any system which seeks to count the cost of construction before design decisions have been taken (Morrison, 1981). Cost planning indicates the expenditure commitment through the design process, from the inception stage to the tender period (Brandon, 1977). Willis and Willis (1980) stated that cost planning could be defined as the relationship between the design of buildings and their cost with reference to the quality, utility and appearance. It not only estimates the tender figure but examines the cost implications of each component, ensures that tenders do not exceed estimates and that the design gives the fullest value to the client (Ferry, 1980). Cost planning is not a control mechanism, but it gives a reference point against which later control can be exercised. A cost plan provides a statement of the design issues, isolates the courses of action available to the client and should provide a comprehensive economic picture of the whole. It may include probably user costs (Southwell, 1968), but should not impose a design strait jacket. The RICS (1976) stated that cost planning should provide a consistent and systematic framework for estimating construction costs, without which there would be no scientific basis for comparative analysis. They also stated that whilst all estimates were at risk until proved, there was less chance of error when a cost planning system was used.

3.1.2 Cost planning is a generic term which covers a variety of techniques (Kelly, 1982). Numerous books and reports are available which describe these methods: Ferry (1980); RICS (1976); RICS (1968); Bathurst & Butler (1980);

Harlow (1981); Stewart (1982); Miller (1978); Cartlidge & Mehrtens (1982); Smith (1980); Morrison & Stevens (1980). They define the techniques used in practice and offer their view of the most promising available approaches. The quantity surveyor may either design to a cost or cost a design. The first approach, known as elemental cost planning, has been supported by the Building Cost Information Service (BCIS, 1969) and forms the basis of the Standard Form of Cost Analyses. A budget is fixed for each element and costs are checked against each target as they are incurred in the design. The second approach, comparative cost estimating, involves the costing of the implications of design solutions before they are formalised, for the comparison of alternative solutions. Very little research into cost planning techniques has been undertaken in Britain, therefore cost planning is still imperfectly understood: Flanagan (1980).

3.1.3 The benefits of cost planning engineering services would include the stimulation of design decision theory, the reduction of abortive work occasioned when tenders differ substantially from the client's budget, a concise plan for the client and as a basis for cost comparison, and a reduction in the volume of post-contract design (Fussell, 1971). The current cost planning approach of analysing elements according to their functional use is an aid to cost control, but is of little benefit in the identification of cost significance and costs-in-use. Currently few cost planning methods make value for money decisions, since they depend upon the accumulation of historical cost analyses which are not readily available for engineering services elements. Difficulties arise in the forecasting of probable design costs from inadequate details, however, at the initial stages of design rules-of-thumb may be used to produce a preliminary cost plan (Edworthy & Chelmick, 1980). Morris (1979) critically examined the accuracy of cost planning techniques. The RICS (1976) gave details of the main weaknesses in the current cost planning practice and highlighted the recurring problem of late application of methods which reduced cost planning to little more than an estimating service.

3.1.4 Cost planning is, therefore, critical to the success of pre-tender cost estimation, the control of costs and for comparative studies into the alternative design solutions. The lack of research into the techniques available to the quantity surveyor, coupled with the absence of an historical cost data base for engineering services and poor technical knowledge (2.3.3) has contributed to the failure of the quantity surveying profession to accurately cost plan M&E services.

3.2 Pre-tender cost estimating

3.2.1 Estimating is fundamental to cost planning, it is the key activity. An estimate provides the basis of the cost plan which is produced principally to establish a realistic forecast of the probable tender price of a project (CIOB, 1979 and RIBA, 1980). The estimation of the cost of engineering services is not an exact science (Russell, 1982), they are guesses of future costs (Fine & Hackemer, 1970), opinions or approximate calculations based on probabilities and are subject to considerable variances. An estimate should be prepared in an explicit and consistent manner which takes account of the methods of construction and all the affecting circumstances. Pre-tender cost estimating is undertaken at the time of greatest potential for value analysis when the project's feasibility, design solutions and probable design related costs are determined. It is probably more vital, and desirable, to the client than any other advice which the quantity surveyor can provide prior to or during the building development (Leeuw, 1977 and Ferry, 1980).

3.2.2 Kemeny & Snell (1972) described the process of estimating as cyclic, through which the quantity surveyor learns from experience. It is a skill which may be structured by a technique or formal method based on historical costs gleaned from projects of a similar nature and adjusted for the current contracting situation. Morrison and Stevens (1980) identified the cost estimating techniques used in current practice. Reference can be made to the many building estimating text books for an explanation of the various techniques (Wood, 1982; Ferry, 1980; Southwell, 1968; Reading University, 1980; Spooner, 1974; Flanagan, 1980; Cartlidge & Mehrtens, 1982; Wood, 1975; Alton, 1982; Barton, 1968; Beeston, 1975; Geddes, 1981; Harlow, 1981; Nisbet, 1961; Stewart, 1982). The following techniques represent the most common methods of estimating documented within the construction industry.

i) Cost limit calculation: A single figure based on the client's cost yardstick.

ii) Lump sum estimate or functional unit: A single price based on the building's function, for example, offices.

iii) 'Floor Area' method: The prediction of total costs based on the relationship between the gross floor area, net floor area or treated area and cost. The estimating method for engineering services has traditionally commenced within an initial estimate based on a square metre price (Clark, 1981).

iv) 'Metre cube' method: The prediction of total costs based on the relationship between volume and cost.

v) Cost per unit or functional place: A single price based on a functional unit (bed, seat, occupant) within a specific building type (hospital, theatre, school).

vi) 'Storey-enclosure' method: Developed by Pritchard in 1954; costs were predicted by the weighting of areas within a building according to their relative position, and multiplied by a price rate. Engineering services were not included within this method (Flanagan, 1980). Although it was an ingenious attempt to express the linear relationship between price, height and shape, no measurable increase in accuracy was achieved. Hence, this method does not appear to have been adopted in practice.

vii) 'Enclosure unit' method: This technique is similar to the storey enclosure method, but it attempts to account for the geometry of the building.

viii) 'Approximate quantities' method: This method is a shortened process based on the take-off procedure used to compile bills of quantities. It is based on the sketch designs, quantities, specifications and unit price rates derived from the analysis of similar bill of quantity items. It is a frequently applied method which relies extensively on the available design information and historical costs which are insubstantial for engineering services.

ix) Elemental target cost estimating or elemental comparative cost planning: Developed by the Ministry of Education and Hertfordshire County Council; elemental categories related to the building function were multiplied by a price per square metre of gross floor area or elemental unit rates.

x) Parametric cost estimating: This method relates each element to a parameter (area of wall, roof etc.) most appropriate to it (Southwell, 1968) but it seems to lack success in practice because of its subjective quality factors.

xi) Cost models: Refer to section 3.3.

Initially, costs at the feasibility design stage for engineering services could be related to the function of the building and the selected services using lump sum estimates or costs per unit. At the later pre-tender estimating stages, costs could be related to quantity and specification using the 'floor area' method and elemental comparative cost planning (Drake, 1984).

Research in the late 1970s undertaken at the University of Strathclyde attempted to develop a cost estimating technique for building conversion based upon the 'space' as a cost prediction unit. Developments were restricted by the quality of information although they indicated that space cost profiles existed, this technique was not suitable for engineering services. Hardcastle (1982) recommended that amendments should be made to the methods of presenting information for pricing to resemble the contractors operational costing approach. This method and Southwell's (1972) parametric approach to estimating both rely on detailed design and cost information, which currently are insubstantial for engineering services, but may be suitable when larger cost data bases are developed. Much research seems to be continuing into the number of estimating elements and components required within an estimate (ABACUS, Reading University and the Property Services Agency) but time and the availability of information seem to be the main restrictions affecting the method of estimating.

3.2.3 Generally the complexity of many construction projects, the interaction between the elements and components, the lack of design details and the instability of the market cause problems for any standardised technique of estimating. Agugua (1979) analysed the merits and limitations of each particular method. There seems to be a great deal of controversy over the 'floor area' method used traditionally to estimate engineering services (The Association of Consulting Engineers; Hardcastle, 1982; Wood, 1975). Cost may not be dependant on areas or volumes since engineering services elements depend on the function of the building, the location and layout of the items, the quality and output required, the fabric of the structure, the ventilation rates and the required room temperatures, all of which directly affect the quantity and type of installations selected. Bauman (1964) discussed these problems but suggested that quick estimates could be produced if all costs were reduced to costs per floor area with associated factors. The 'floor area' method produces deterministic costs which have been accepted within the quantity surveying profession because it is apparently an economic method, produces quick estimates (provided the relevant cost data is available) and allows ease of application.

3.2.4 Estimating techniques should be able to forecast the result of future tendering with a reasonable degree of accuracy, however it is very difficult to determine the accuracy of present estimating techniques (Barton, 1968 and Wood, 1975). Morrison and Stevens (1981) suggested that present methods of estimating were not capable of producing a consistently adequate level of accuracy to support an effective cost planning system. Clark & Lorenzoni (1978), Morris (1979) and Parfitt (1972) examined estimating accuracy, the cost differences between estimates and tenders and the time required to produce an estimate. Accuracy was dependent on the stage of design. At initial feasibility stages an accuracy of 30% could be expected whereas at the pre-tender stage 10% may be achieved. However, very little seems to be known or published about the extent and causes of price variability and accuracy (Flanagan, 1980). Estimators use their knowledge and expertise to draw conclusions on the basis of incomplete facts. Even when the estimator is given all the information possible on the nature of the project and sufficient time in which to undertake a detailed cost estimate, there remains a latitude, a spectrum of prices within which the estimator will select the price. Spooner (1974) recommended that a probabilistic formulation of estimating should be constructed which would account for these cost ranges.

3.2.5 The quantity surveyor relies extensively on the use of adjusted historical unit price rates as the basis for price prediction (Stallworthy, 1980). Surveyors who have had the valuable experience of working in a specialist engineering contractors employment could draw on their experiences of installers' costs and synthesise prices, but these surveyors seem to be in a minority. Unit rate costs can be formulated from first principles to produce resource costings, but detailed information is required. Published information from pricing books (Spons, 1984; Laxtons, 1984; Griffiths, 1984 and Wessex, 1984), cost analyses published by the BCIS (Building Cost Information Service), the Architects Journal and other technical journals can produce an awareness of prices and the context in which they should be used. However, since most analyses are based on priced bills of quantities with little specification, prices for engineering services elements should not be used indiscriminantly. They are all averages which do not allow the user the ability to interpret cost information in its full context. The Department of Construction Management at Reading University (1980) found that the quantity surveying profession had a clear preference for using in-house cost data for estimating purposes, which avoided the pitfalls associated with published data. Other sources of cost information can be obtained from the synthesis of rates from variation settlements, personal contact with M&E specialist contractors, contact with manufacturers particularly with regard to the latest technologies and information published in professional and trade journals. Drake (1984) proposed that cost data used by surveyors was not based on the statistical examination of cost determinants from a variety of sources, but on intuition and opinion. Unfortunately, the experienced estimator is currently unable to pass on this expert judgement to other surveyors (Southwell, 1968).

3.2.6 The quantity surveyor has failed to provide pre-tender cost estimates for engineering services (Berryman, 1980) for a variety of reasons - the lack of: design details and specifications, suitably trained quantity surveyors, a defined cost estimating process and cost data. The penalties to the client of an estimate being over or under the succesful tender sum may include financial embarrassment, project cancellation, delays, redesign, retendering and a general discord. Estimates for engineering services cannot rely solely on published cost data or in-house historical costs obtained from bills of quantities since currently they do not exist in sufficient quantities. The essential information required to determine pre-tender costs would be the function and treated areas of the building, and the design specifications applicable to each service. The research therefore proposes to use in-house cost data based on the traditional 'floor area' method and elemental comparative cost planning techniques. Since there are a lack of estimating methods which recognise cost ranges and levels of accuracy, the research cost data will be used to produce cost models in a probabilistic format.

3.3 Cost Models

3.3.1 A model is a representation of reality which provides a simplified and intelligible understanding to a problem. It imitates and reduces, and may loose some detail, but abstracts and preserves the essentials (Flanagan, 1980). Models invariably incorporate and predict the existence of associations and relationships between variables. They provide a systematic method to present results, summarise data and examine inconsistencies. They may aid in the definition of assumptions and specifications, can be hypothesis formulating, quantitatively predictive and may provide a means of control. Vansteenkiste & Spriet (1982) summarised the role of mathematical models, gave an excellent insight into the modelling process and noted their limitations. Construction cost modelling may be defined as the symbolic representation of a system expressed in terms that influence its cost, notably environmental, design and construction factors. A mathematical expression of the cost of a building element in terms of the factors which incur it (Agugua, 1979). Cochran (1976) stated that the measurement of the factors which effect building costs enables the quantity surveyor to understand the past and provides the basis for confidence in the forecast of future costs. Cost models may be used to optimise the return on investment of the clients resources, cost and time (Maver, 1970; Bennett, 1982 and Gould, 1970). A cost model should, according to Flanagan (1980), supply information for alternative options, counteract preconceived notions and isolate factors pertinent to the problem. Reynolds (1980) further proposed that models should estimate the cost of a change of solution with regard to the target cost. Mathematical modelling offers a means whereby the effect on cost of the many features of engineering services installations can be rationalised and measured.

3.3.2 Cost modelling methods for engineering services have largely remained undocumented and those used for general building construction may not be appropriate. Ferry (1980) and Maver (1970) outlined the categories of theoretical models and discussed their merits and limitations. The degree to which the level of knowledge or expertise is known, permits the formal specification of a model prior to analysis and influences the techniques used. It was important to understand the limitations and requirements of the various modelling techniques before the commencement of the research.

3.3.2.1 Causal or empirical models are generally represented in an algebraic form which expresses a fixed relationship between the design variables and cost. This is a refinement of the traditional estimating techniques where the cost factor applied in the algorithm is constant. A limitation of this method is the over simplification of the design/cost relationship based on broad assumptions. It permits no interrelationships to be measured rendering it inflexible and relies extensively on accurate cost data. Speakers at the CIBSE Conference (1985) commented that this data comes principally from manufacturers, where there exists a derth of reliable information. Morris (1982) showed in his research that algorithms may be used but that their use in cost modelling would be best adapted to research, where purpose generated data was used as there is likely to be insufficient information or control without such data.

3.3.2.2 Regression models fall into three categories: simple or two-variable linear regression, multi-variable linear regression and stepwise regression. The requirement of a deterministic linear model, such as a regression model, is that the relationship should be expressed as an algebraic equation which measures the covariance between two or more quantitative variables and shows the extent of the concomitant variation. Regression analysis may be defined as the statistical technique used for the estimation or prediction of a dependent variable (cost) from the values of other given variables, the independent variables. A regression equation represents the conditional mean of the dependent variable as a function of the explanatory variable(s). Pilliner (1979), Goldberger & Duncan (1973), Draper & Smith (1966) and Wood (1975) explained the concepts of regression analysis. It is a well-defined mathematical procedure which has been used for some time and actively pursued in the field of building construction by Professor E.G. Trimble (1974) at Loughborough University of Technology. A number of MSc research projects have examined various elements of construction using regression analysis: Buchanan (1969), Gould (1970), Morris (1976), Badby (1971), Moyles (1973) and Wood (1975). There are, however, some fundamental inadequacies associated with regression cost modelling. They seem to have acquired an undeserved respectability within the construction industry which distracts from the assumptions upon which the analyses are based (Maver, 1970; Buchanan, 1971; Wood, 1975; Cochran, 1976; Beeston, 1977; O'Muircheartaigh & Payne, 1977; Agugua, 1979; Wilson, 1982; Beeston, 1982; Brandon, 1982 and Bowen, 1982). The regression model depends enormously upon the suitability, quantity and nature of the cost data used. Within the engineering services field, the location and isolation of the variables which affect cost may not be directly measurable or obtainable in quantified terms which limits the accuracy of the resultant models. The weighted averages remove the valuable variations associated with cost data, make little allowance for skewness, may not consider element or component cost interactions and 'scale' effects. This may lead to the oversimplification and trivialisation of cost data, creating insensitive, rigidly defined deterministic models. Errors may occur when inferences are drawn in the presence of multicolliniarity, hetroscedasticity, extrapolations and when there is an assumption of linearity. Difficulties may arise when the resultant costs are adjusted for quality, date, quantity differences and when comparisons are made between alternative design solutions. The partitioning of cost data and the use of transformations can reduce these inadequacies, but it may be difficult to select variables which are well correlated with cost but not with other variables. Previous regression analyses also seems to have specialised research into detailed components or elements, overcoming some of the technique's limitations. Regression analysis is a powerful tool which can, regardless of its limitations and when carefully used, develop new design-cost solutions. However, there seems to be little evidence to support the use of linear models where cost is directly related to size and quality, and to presuppose that cost is deterministic (Mathur, 1982).

3.3.2.3 Heuristic modelling (Maver, 1970) may be used where a 'best' solution is sought from an effectively infinite range of possible solutions. Building or engineering services design problems could be solved by efficient heuristics, but the resultant solutions generated would be dependent on the prior heuristics stated and adopted. In many cases there may be no way of knowing how appropriate these 'heuristic rules' may be. There may also be difficulties in assessing the solution in relation to the optimum.

3.3.2.4 Engineering projects could be viewed as a collection of individual random or stochastic processes where the outcome of each particular component cost may be dependent on some chance event. The statistical analysis of stochastic processes is in its infancy (Digman & Green, 1981). There seems to be a limited amount of published information on the use of probabilistic procedures within the construction industry (Spooner, 1974 and Mathur, 1982). O'Muircheartaigh & Payne (1977) discussed the theory of a stochastic process available to survey practitioners and indicated the growing need for this modelling method. A stochastic model could probe further to where details are insufficient for an algorithm, since probabilities could reveal the nature and distribution of uncertainties associated with cost data. Once the presence of uncertainty is admitted (Ball, 1970 and Wilson, 1984), the uncontrollable variables can be recognised and treated as stochastic variables each with a probability distribution for its possible outcomes. This graphical technique could provide the quantity surveyor with knowledge of the spread and variability of costs, associated statistical parameters, skewness and an assessment of the reliability and risk associated with the estimated costs. Sensitivity tests may be used to highlight components or elements which are cost significant. A probabilistic model has the advantage over regression models since normal distributions need not be used to represent the cost data, enabling more realistic or reliable costs to be selected. Probabilistic models also appear to be more adaptable when updating or when more information becomes available.

In the past, a problem encountered with probabilistic methods was the difficulty of combining many distributions to produce a single total distribution. Monte Carlo simulation can faithfully generate the behaviour of a model (Ferry, 1980 and Maver, 1970). There were various general and sometimes limited definitions proposed for the term 'simulation' (Zeigler, 1976; Meidan, 1980 and

Spriet & Vansteenkiste, 1982) which indicated that the precise meaning was a point of debate. Leimkuhler (1982) discussed the history of simulation models, their limitations and developments since the 1960s. Many authors (Maver, 1970; Goldberger & Duncan, 1973; Jelen, 1970; Fogarty, 1967; PSA, 1973; Flanagan, 1980; Brandon, 1982 and Wilson, 1982) have promoted the use of simulation techniques within the construction industry and discussed the advantages and problems associated with the techniques and continuous frequency distributions. The advantages of Monte Carlo simulation include the speed of operation which is dependent upon the number of iterations or experimental paths undertaken by the model, that it is relatively inexpensive and that general relationships can be inferred from specific results obtained from each iteration which promotes understanding when evaluating alternatives. Input can be non-deterministic and the output unpredictable. The limitations depend upon the assumptions made, whether the model represents an oversimplification of reality and whether the components are mutually independent. Errors may occur when non-representative input from extremes is included within the distributions. The Monte Carlo method has been described as a brute force technique but as yet the method has not been fully exploited.

3.3.3 Previous research into the cost prediction field has mainly been in the development of cost models using regression analysis, which is extensively documented (Appendix 9.1: The development of cost models for construction). The research seems to be confined to areas which have fairly well developed causal theories and where the objective was to confront these theories with data. Various studies have attempted to show the variations in construction costs in terms of the structural design envelope, depth of building, storey height, number of rooms, surface area of the dwelling unit, type of circulation spaces and prices per unit. Apart from simulation cost models, all the models seem to rely extensively on accurate historical cost data (Kemery & Snell, 1972). Generally, the quantity surveyor seems to have placed much emphasis on considering the effect, rather than analysing the factors which cause price differences for construction work (Flanagan, 1980). Goldberger & Duncan (1973) presented examples of regression analysis as an inappropriate estimating procedure due to unobservable variables, simultaneity and omitted variables. He suggested that quantity surveyors should acknowledge the fact that measured variables were commonly contaminated by sources of variation other than those which they were intended to reflect, and proposed the development of a model which would acknowledge this and allow the estimator freedom to select. Yeomans (1968) explained that it would be rare to find two series of figures which were related perfectly by a line. It would be more probable that a general tendency or pattern would be apparent. Mathur (1982) stated:

> "to set a 'single figure' cost limit for the whole building or for its elements, based on the cost analysis of a single previous building, is not only to progressively stifle innovatory solutions, but also to misjudge and misrepresent the true nature of cost which has not only a mean value but also variance."
>
> "Cost is not deterministic."

Little actual research into simulation models has been undertaken in the past, but it was observed (Appendix 9.1) that many of the knowledgeable members of the profession were recommending its use. Flanagan (1980) stated that new approaches, at the early design stages, were required which would be more sensitive to cost significant design items. He advocated that simulation cost models could satisfactorily provide the basis for further research and would provide prediction techniques which would be representative of reality.

3.3.4 To conclude, it was proposed that cost models could provide a systematic approach for the formatting and reduction of the available mechanical and electrical cost data, into patterns that may suggest particular estimating strategies and allow cost comparisons between differing types of installations. The cost models would forecast using the process of drawing inferences about the future from the historical data and expertise available within the ESD. The population of engineering services installations is never static nor are the associated costs. Movements in the market and technologies create changeable situations in an unpredictable way with the progress of time. Design and cost should be considered as time dependent in a probabilistic fashion. Therefore probability distributions could be predetermined from the historical data which would acknowledge the existence of uncertainty, which is a basic ingredient in the estimating process. An alternative modelling approach which better simulates the contractor's method of resource estimating will be considered to take account of the buildability of an M&E project and the variables which influence performance. A simulation technique may offer the chance for greater analysis and experimentation, may provide the estimator with a wealth of design-cost experience in a shorter space of time and may isolate cost significant factors. The models will be no substitute for the quantity surveyor's individual expert estimating judgement but should enhance current cost awareness, with less reliance being placed on comparative assessment and pure judgement when selecting an estimating rate. Accepted heuristic models may be used to test the resultant probabilistic models.

3.4 Computer Applications

> "Computers will not replace quantity surveyors, they will help us to shape the future and enable us to move forward with complete confidence."
>
> Gooch (1985)[2]

3.4.1 The quantity surveying profession is changing, regardless of computer technology, due to the expanding range of cost advice being demanded by clients. The requirement is to analyse, assess and compare not only within projects but between projects, both subjectively and objectively. The quantity surveyor is fast becoming a building economist rather than a measure-and-value technician. A computer can be used to determine correlations or relationships from experimental data. It allows the quantity surveyors, when time is short, to extend their capacity for careful, systematic study. The profession should use these increasingly important tools wisely and for their benefits, not as replacements. Hunt (1985)[2] and Evans (1981) were concerned to safeguard the future of the profession and advised that if the quantity surveyor failed to use computers, then others on the periphery of the profession would take advantage.

3.4.2 As the computer industry has advanced at a far faster rate than the quantity surveyors ability to apply it, the profession has been slow to accommodate the particular processes that the computer can cope with best (Ing, 1985). The penetration of computer applications has been generally restricted to accounting functions, payroll and costing systems (Haghdadi, 1982). They serve to mechanise the existing manual systems such as standard phraseologies, specification clauses, bills of quantities and NEDO calculations (Middleton et al, 1982). It was not until the late 1960s that the first steps were taken to incorporate computers into the estimating functions of construction organisations, although critical path analysis had been used as a planning method from the late 1950s. Cogswell (1967) discussed computerised estimating applications. In 1961 the RICS investigated the possibilities of using computers for working up quantities. By the mid-sixties several large private practices and public authorities, in conjunction with computer companies, had prepared bills of quantities with the aid of computers. The use of computers to simulate the thermodynamics of buildings and energy systems were also developed. CREST, a program developed by Wates Construction, was designed to offer the client the optimum balance between design and cost by generating the total construction estimate. Unfortunately it was based on an American system of pricing and cost control, and was abandoned in the early 1970s. Several of the larger practices, including MDA, became established leaders in bills of quantities production, with most of the programs being largely run on mainframes which proved time consuming and expensive. Many companies became disillusioned with computers because of the large investments required and the restricted outputs obtained. In the late 1970s microcomputers were introduced which could produce bills of quantities for less expense. Simple deterministic estimating computer programs were then developed (Wrobel, 1975). McCaffer and Sher (1981) were members of the Computer Aided Estimating Research and Development Group at Loughborough University which was awarded a contract from the National Research Development Corporation to develop a computer aided estimating system for builders, in 1979. A crude system was developed based on resources, bills of quantity items and deterministic cost rates. The program was named INTEREST BUILD but despite its success, the quantity surveyor seemed unwilling to adopt a resources based estimating technique. Maver (1979) reported on the many computer based models developed by the ABACUS group at the University of Strathclyde, which ranged from detailed design alternatives to energy simulations.

Prior to 1981, the impact of computers was limited to the larger practices (McCaffer, 1981). It was not until the end of 1982 that the range of commercial software was expanded to include different sections of the construction industry (Hunt, 1984). Many teaching organisations and universities became involved in the development of packages for managerial and organisational purposes. The

University of Technology at Loughborough was, in 1981, awarded funds from the Science Research Council to investigate the use of the microcomputer for construction management. They produced MicroPERT which provided project planning and control functions based on the PERT technique of network analysis (see section 3.5). Projects could be analysed at both the tendering and planning stages, and updated during construction. Although this program was developed more for the contractor, it illustrated a flexible and alternative approach to the analysis of project strategies, which may be of benefit to the quantity surveyor.

Computers are now being used to overcome the time consuming and expensive process of data analysis. Davis, Belfield and Everest (Smith, 1985) have developed computerised cost data bases and cost models to aid the quantity surveyor. Brandon (1985)^2 reviewed the results of a collaborative research project undertaken by Portsmouth City Council, Department of Architecture and Design, and the Department of Surveying at Portsmouth Polytechnic. The innovative computer program developed allowed cost analyses,based on the BCIS format, to be stored and updated. Individual and histogram grouped data could be subjectively selected and reviewed, along with the relevant statistical parameters. A single analysis would be chosen which resembled the proposed building to be estimated. Simple two variable linear regression analysis may also be undertaken. It was hoped that the BCIS On-line cost analysis system could be linked to the program to enable a comparison to be made between in-house and published cost data. The National Computer Centre, the British Computer Society, the Computing Services Association and the Construction Industry Computing Association all give advice and information on the various current applications.

3.4.3 Monk Dunstone Associates (MDA) have been involved with computers for some twenty-five years. Initially they invested in fairly inflexible mainframe equipment, but in 1981 they introduced micro computers with a modest central process unit (64 K) and optimal multi-megabyte hard disk storage. They use Intertec's Superbrain computer systems which have proved to be low cost, high performance systems. MDA employ their own programming staff with quantity surveying experience although some programs, for individual building projects, may be produced by the surveyors themselves. Most programs are written in BASIC language. Chelmick (1982) stated that engineering services particularly lend themselves to computerisation but admitted (Chelmick, 1982)[2] that MDA were still in the Stone Age as regards the development of microcomputer usage for building services. Generally programs in regular use at MDA are:

i) Wordstar - a word processing facility;
ii) Supercalc - a simple program used to alter and update financial reports;
iii) N.E.D.O. - a program which permits the calculation of formula adjustment indices;
iv) Cashflow - which enables the quantity surveyor to project theoretical cash flows for the construction and defects liability period;
v) Joblist - a current listing of clients and the progress of each project;
vi) An insurance valuation program;
vii) A bar reinforcement program;
and viii) Bills of quantities programs.

A critical path analysis program is also available, although not generally used, which enables MDA to offer advice on project management and to offer additional services to the architect and contractors. The Engineering Services Division (ESD) has developed further programs:

i) Pipes - a pipework approximate estimating program which uses an updated material cost data base and non-adjustable labour factor data base.

ii) Supaduct - a program which is used to ascertain the weights of rectangular ductwork and associated fittings.

iii) Cosanl and Cosplan - element cost summarising programs with separate labour, material, equipment and sub-contract costs.

iv) PCalc - An approximate estimating package which generates design data from gross floor areas, occupancy levels and areas of glass.

v) Teval - A tender evaluation program.

MDA, like many quantity surveying practices, are keen to implement computers but seem slow on the uptake and very cautious about the investment.

3.4.4 In the past, high installation costs and the common fear that the computer was a threat to livelihoods slowed attitudes towards computer changes in the quantity surveyors work environment. A lack of trust was also sited as a reason for the profession's lack of involvement. In 1984, the RICS made a survey of quantity surveying practice and established that fewer than a third of the sampled companies made regular use of a computer. The explanation (Fennell, 1984) was paradoxically that quantity surveyors had become too enthusiastic too soon about information technology, hence was once bitten, twice shy. In the 1960s computers were eagerly bought and experimented with, but they turned out to be inadequate and inflexible for some practices which caused heavy investment losses. Hunt (1985)[2] stated that 36% of practices used in computers in 1984 and that probably 50% of practices used computers in 1985. This could be as a result of more practices using computers for administrative functions, repetitive technical calculations, computer graphics, specifications, system simulations and bills of quantities production (Crall & Christopher, 1975). Gooch (1985)[2] noted that although over 30% of practices used computers, only about 300 companies were actually using a knowledge based system. As a whole, the profession does not seem to have got very far with computers (Gooch, 1985). With little collaboration within the profession, the following benefits of computers may be slow in arriving:

a. Within an increasing competitive professional environment, the computer may enable the quantity surveyor to offer an improved service to the client, improve office efficiency and improve the presentation of cost information supplied to all members of the construction team.

b. Projects may benefit from a greater degree of accuracy of information within the boundaries of the program and algorithms used (Blow, 1985).

c. An improved success ratio may be achieved, the theory being that the more estimates completed the better the chance of success.

d. Practices may benefit from the computer capacity and flexibility stimulating organisational and technological awareness.

e. The examination of reference or historical data may be more exhaustive than would normally be attempted by hand (Dawson, 1985) and available at a lower cost.

f. A speed of information may be achieved which frees the estimator of the more routine and time consuming tasks (Russell, 1982). Baxter (1985) showed that computers produced a 70% saving in time and cost.

g. The estimator may be able to carry out sensitivity tests on costs and examine the variability of alternative designs.

h. Computers enable the surveyor to check resultant costs and allows freedom from mathematical error.

i. The common format used by the computer produces a defined structure, few ambiguities, discipline and consistency.

j. The generation of a number of quantities and costs may be obtained from a single measurement or statistic.

There are a number of problems associated with computers of which the quantity surveyor should be aware:

a. The need for constant staff training, retraining and encouragement due to staff changes, retirement and the introduction of new programs.

b. Terminal time management.

c. The estimator may lose his 'feel' for a method of calculation if the work is totally undertaken by a computer.

d. Checks on data input and output may take longer than manual methods, especially if the work is not correctly logged.

e. There seem to be no formal evaluation or approval methods for purchased pre-programmed software (Holmes, 1974). The program may not be trusted because the algorithms and system assumptions may not be fully understood.

f. The software may be designed by people who are remote from the end user, and may not appreciate the estimators' requirements (Gibbons, 1983).

g. Small computers may be slow to operate and their development tedious.

The selection of a prospective program requires the user to be aware of the relative advantages and disadvantages for each specific technique. Generally, the quantity surveyor cannot compete with a competent programmer or systems analyst, and should be prepared to communicate his requirements to the computer industry. Sidwell & McIntosh (1982) recommended that the quantity surveyor should find the relevant software initially and then purchase the hardware to suit.

3.4.5 The trend in program development seems to be towards a more integrated application, with an emphasis on reduced data entry (Wix, 1985)[2]. Unilateral computer applications have become increasingly hard to justify (Bunn, 1985). A proliferation of software and hardware can be found on demonstration at exhibitions. A number of authors (Brandon, Moore & Main, 1985; BSRIA, 1984; Hamson, 1982; HMSO, 1969; Howell & Saver, 1980; Hunt, 1985[2]; Hutton & Rostron, 1979, 1984, 1985; Michie & Wix, 1983 and Potter & Scoins, 1982) listed and discussed the available computer program applications suitable for use by the services quantity surveyor and the construction industry. But given the rate of change in the computer industry, such lists may rapidly become out of date. The quantity surveyor should constantly monitor commercially available computer systems.

3.4.5.1 There is a large potential for computer usage in the area of estimating and cost planning, but few computer programs exist for the quantity surveyor (Harris, 1979 and Smith, 1985). The majority of estimating packages are based on resources and are most suitable for the contractor. Deterministic labour, plant, material and sub-contractor costs are calculated and specifications are standardised. Percentage additions for overheads, profits, site factors and builders discount may be altered to account for changes in the market conditions. Elemental cost comparisons may be made and costs linked to design calculations or direct measurement take-offs using digitised sonic or light board systems to directly produce estimates, bills of quantities and schedules of rates (Hunt, 1984). MDA have not explored the use of digitisers because of scepticism about their true value to the surveyor, since the surveyor's skill lies in his ability to estimate the quantities not shown on the drawings. The quantity surveyor may use the BCIS On-line approximate estimating package for cost advice based on elemental budget estimates. Pre-contract estimates may also be produced from bills of quantity software systems, along with tender documentation, detailed estimates, cost analyses, valuations, contract cost monitoring, final accounts, standardised libraries of descriptions and bills of quantities.

3.4.5.2 Critical path logic networks are used predominantly by contractors as project time management estimating techniques. However, they may be used by the quantity surveyor to produce bar charts of time analyses, histograms of resource analyses, network diagrams, time and expense sheet analyses, S-curve graphs and cash flow diagrams (see section 3.6). Network analysis is a widely accepted technique, within the construction industry, for cost planning time and capital cost commitments for proposed building projects.

3.4.5.3 Commercial software is available for the estimation of engineering services design criteria and for the analysis of alternative designs. They cover a wide range of diverse uses including the calculation of heating and cooling loads, condensation levels, U-values, energy losses and consumption, plant and equipment loads and sizes, ventilation rates, air conditioning and heating requirements, ductwork and pipework sizes, lifts and electrical requirements (Dawson, 1985; Bowman, 1985; BSRIA, 1984 and Maver, 1979). The logic, algorithms and approximations contained within many of these proprietory programs are unknown to the user (Bowman & Lomas, 1986) and should be used with care. Wix (1985)[2] warned that the majority of programs were based on CIBS algorithms which are used for quick manual calculations and contain simplified assumptions. Some programs may be used to assess operating costs, alternative fuel costs and energy conservation provisions (Holmes, 1974). D.H. Weight of Thamesdown Borough Council has also developed a design cost planning system which predicts future lift cycle costings. The most sophisticated models require the power of a large mainframe computer, expensive hardware and software, lengthy data input procedures and high training requirements. Others may be operated on mini or micro computers. Unfortunately, much of the design estimating software currently available is not suitable for the quantity surveyor because they require explicitly defined design criteria which may be unobtainable at the early design stages.

Much of the interest in and the application of computers by engineers and architects is concentrated on computer aided design or draughting (CAD) systems. These systems can be used for draughting, co-ordinating, scheduling, interactive calculating, drawing records and two or three dimensional modelling. Chelmick (1982)[2] was enthusiastic about the potential of CAD systems for the quantity surveyor. Fully co-ordinated drawings, incorporating all the design information, could be linked within the system to produce a direct material take-off for the estimator and ultimately direct bills of quantities. Wix (1983), Gathercole & Hutt (1984) and Warman (1986) discussed the benefits associated with CAD systems. Although these systems have been successfully used by the construction industry for some sixteen years, they are presently unsuitable for use by the quantity surveyor since at the feasibility estimating stages of design, engineering services drawings may be unobtainable in sufficient detail.

3.4.5.4 Expert systems are attracting much attention from the computer press. There are many definitions proposed for the term 'expert system' (Bowman & Lomas, 1985; CIBSE, 1985; Goodall, 1985; Newton, 1985 and Shaw, 1985) briefly they can be defined as an application, within a computer, of a knowledge based component formulated from an expert skill, which can offer intelligent advice, make an intelligent decision and justify its logic directly to the user. They have three components, a knowledge base, an inference engine or reasoning section and a user interface. They can handle uncertain data via probabilities and can be modified and enlarged. Expert systems attempt to contain knowledge about a specific area of expertise and the rules for applying such knowledge (Wix, 1985). They may release specialists from the more tractable and routine thinking skills, act as an archive for expertise from previous employees and distribute such knowledge within a company (Pilcher, 1985). They are a tool which can assist in the interpretation and manipulation of operational rules, which can subsequently be applied to new situations. Shaw (1985)^2 and Bowman (1985) discussed the history of knowledge based systems and some of their limitations. England (1985), Turner (1986) and Dunn (CIBSE, 1985) noted that at present expert systems were at a stage of being a solution looking for a problem. There are few in regular commercial use and none operating commercially within the building services industry. Many authors (Gooch, 1985^2; Johnson, 1985; Shafe, 1985 and Shaw,

1985) have discussed the limitations associated with expert systems and many of the exaggerated claims. They have been criticised as expensive algorithmic shells which have just emerged from their academic backgrounds and which require specialist languages to operate. The results are often open to interpretation and may not cover all the possible construction variables. Despite these criticisms, the construction industry is beginning to recognise their potentials. The CCTA (1985) offered guidelines, general descriptions and advice on tackling an expert systems project. BSRIA is evaluating various types of systems for their possible use within building services and a trial system has been installed to advise on the installation of air conditioning systems. The Building Research Establishment (BRE) hopes to identify areas of development for phototype systems in selected domains whilst Oren (1982) considered 'expert systems' for knowledge management. At the beginning of 1986 on RICS/Alvey research project was set up at Salford University, under the direction of Professor P. Brandon, to examine the application of expert systems within the quantity surveying profession. The Polytechnic of the South Bank seems to have undertaken the most research and have produced ACE (Air Conditioning Expert) which selects an appropriate air conditioning system based on the building specification. Research is also being carried out into condensation risks and the selection of heat recovery systems (Wix, 1984). Shaw (1985)[2] highlighted some other systems which are being developed: a knowledge based consultant for structural analysis, building management systems, construction management systems, regulation advice, defect diagnosis and security alarm systems. Dunn (CIBSE, 1985) suggested that they could be used as a teaching aid for designers, as a predictive tool to indicate trends within the industry and to assist in the measurement of the effect of architectural changes on building services provisions. Currently, however, there are no suitable systems available for the estimation of mechanical and electrical costs. Since 'expert' data has not been assimilated and logics have not been researched, the initial systems may rely solely on deterministic results which would question the necessity for an expert system.

3.4.6 Despite the many benefits attributed to computers (3.4.4) there still seems to be a great deal of reluctance on behalf of the construction industry to adopt new methods (Haghdadi, 1982). Programs used for building services have not changed substantially over the past six to seven years. The change that has occurred has mainly been in the use of the computer memory rather than in taking advantage of the power of the processor. Development has occurred in the use of product and component files for such applications as lighting, piping and ductwork design and in the use of data bases for room based design. The calculation algorithms for design estimates and expert systems have remained substantially constant, except where revised calculation methods have been issued by the CIBSE and ASHRAE. Research seems to be ongoing and there appears to be a number of commercially available programs which may enable the quantity surveyor to estimate cost (3.4.5.1), time (3.4.5.2) and design criteria (3.4.5.3) for engineering services installations, however not in a combined probabilistic manner. The utilisation of these new technologies will play a critical path in the future of the quantity surveying profession. In theory the work of the quantity surveyor is an ideal candidate for computerisation as it is based largely on the recording of mathematical information with vast amounts of tedious and repetitive 'number crunching' exercises. The quantity surveyor should be wary of architects and engineers who are obtaining CAD systems with combined estimating packages, and contractors who are already combining the output from estimating packages to produce bills of quantities. The profession should consider carefully whether to develop simplified design cost programs for engineering services, for which they are not qualified, or to use design programs developed by engineers and concentrate on developing alternative costing techniques. The latter is proposed by this research. The research computer program to be developed should enable data to be stored in a flexible and probabilistic format, allow input to be easily retrieved and edited and the computer output to be immediately legible to the quantity surveyor (Holmes & Campbell, 1985 and the 15th Edition of the IEE Regulations, 1981). Cost, time and design criteria should be considered as interactive rather than independent, and should be processed simultaneously within the computer program. Critical path estimation techniques (3.4.5.2) suggest that this approach may be adopted to overcome the limitations inherent in other commercially available programs.

3.5 Review and research proposals

From the prior four literature reviews and the aims and objectives of the research expressed by MDA, a number of guidelines were proposed for the development of the research. Pre-tender cost estimates for engineering services are required by the client, from the quantity surveyor, therefore a systematic procedure should be developed for the collection of mechanical and electrical data, and presented as defined cost analyses. The 'floor area' method of estimating and elemental comparative cost planning techniques have traditionally been used by the estimator and should subsequently be adopted by the research, despite their limitations. Cost models should be designed to reflect the true nature of the historical cost analyses and the expertise of the estimator. The proposed cost models should consider cost, time and design criteria as interdependent and permit alternative installations to be cost compared. There are a lack of estimating methods which recognise cost ranges and uncertainty, therefore it was proposed that the research should examine the production of probabilistic models. A simulation technique may be adopted to combine the probabilistic data and highlight cost significant items. The program selected should be easy to manipulate and update, comprehensive, flexible and relatively inexpensive. Accepted heuristics may be used to test the resultant models. From the literature it appeared that critical path techniques may offer a solution to the research proposals, therefore a second literature review was undertaken to examine these techniques in greater depth.

3.6 VERT: Venture Evaluation and Review Technique

This section reviews the development of the methodology on which this research is based.

3.6.1 The Gantt Chart is a well-known and much used method within the construction industry. It is a graphical approach which displays job operations as a function of time, depicted by horizontal bars representing busy and idle periods on a schedule. It is an excellent display device but provides little assistance with cost control. In 1956, the CEGB (Central Electricity Generating Board) expanded the Gantt Chart and developed a technique named 'The Longest Irreductible Sequence of Events' for the overhaul of power stations. This was later modified into the 'Major Sequence Technique' (Sawyer, 1980) which was concerned with schedules of manpower'. Line of Balance' (LOB) pioneered by Wright, an American, in 1936 was another charting technique which related time and progress. It was basically a means of integrating and monitoring the flow of materials, components and sub-components into manufacturing in accordance with phased delivery requirements. Currently, this type of analysis can be undertaken by Materials Requirements Planning (MRP) systems.

The limitations of these charting techniques led to the development of network analysis methods. Peterman (1983) and Sawyer (1980) showed that three main groups of techniques were recognised by the construction industry:

i) Activity-on-arrow networks, of which Critical Path Methods (CPM) was most widely used;

ii) Activity-on-node networks;

and iii) Modified networks: Programs Evaluation and Review Technique (PERT), the Precedence Diagram Method (PDM) and the Graphical Evaluation and Review Technique (GERT).

3.6.2 The Critical Path Method (CPM) was developed by E.I. duPont de Nemours in 1957 and was first applied to the construction and maintenance of chemical plants. It is a deterministic, activity oriented approach for which there are numerous articles, methodological developments, applications and computer programs (Kelley, 1961; Moder & Phillips, 1964; Beattie & Reader, 1971; Roderick, 1977 and Meidan, 1981). It is a basic planning technique of the work involved in a project (Levy, Thompson & Wiest, 1963). The advantages of the critical path method can be the discipline of thought required to produce a logical sequence of events, the control of a project within strictly defined limits, the preparation of long-term planning, the focusing of attention on the most effective activities and the harnessing of the speed and accuracy of computers. The critical path method or technique does not, however, make decisions, it requires a trained person to operate it and interpret the results in conjunction with personal judgement.

Activity-on-node systems were claimed by Sawyer (1980) to be easier to use than the now conventional critical path techniques and are achieving greater acceptance in some large European computer companies.

3.6.3 The Program Evaluation and Review Task (PERT) method was developed by the United States Navy to measure and control the progress of a Polaris Fleet Ballistic Missile Program (Malcolm, Roseboom, Clark & Fazar, 1959). PERT is a probabilistic, event oriented approach concerned with the occurrence of events rather than the planning of events. It is an activity-on-arrow network technique which implements node definition with activity duration times. PERT emphasises the uncertainty of the duration of network components, introduces probabilities, monitors and co-ordinates components, and summarises progress reports. It was considered revolutionary in its approach because of the three-way probable time estimates used, an optimistic, most likely and pessimistic event schedule. It is closely related to the critical path method and is probably the most widely used, accredited and available network technique. The second generation of PERT was PERT/COST (DOD/NASA, 1962) which was developed for the specific purpose of expanding the PERT-time methods to include the associated financial data. It was developed by the United States Government for weapon-system projects. Since 1970 other adaptations of the PERT system have been developed: PERT II, PERT III, PEP, PEPCO, Super-PERT, PERT/CPM, PERT/Reliability (Lee, Moeller & Digman, 1982) and PERT/LOB (Schoderbek & Digman, 1967).

Probability theory was used in PERT to calculate the measure of uncertainty in meeting scheduled dates. This practice was designed to help dissassociate the engineer from his built-in knowledge of the existing schedule and to provide more information concerning the inherent difficulties and variability in an activity being estimated. It was postulated that a three-point distribution would be representative of an estimate range, with low probabilities associated with optimistic (a) or pessimistic (b) estimates, and a most likely value (m) which could take any position between the two extremes. It was assumed that the probable duration of an activity was beta distributed (DOD/NASA, 1962 and

Beattie & Reader, 1971) although its applicability had not been rigorously proved. A formula was used:

$$t_e = \frac{a + 4m + b}{6}$$

where t_e = expected time
a = optimistic time
m = most likely time
b = pessimistic time

This was a simplified approximation for the mean of the beta probability function, which did not take advantage of the flexibility contained within the beta distribution family. Other assumptions were made (Malcolm et al, 1959; Fulkerson, 1962; Grubbs, 1962; Murray, 1963; MacCrimmon & Ryavec, 1964; Welsh, 1965; Hartley & Wortham, 1966 and Johnson & Montgomery, 1974):

i) PERT made the simplified assumption that the mean and variance of a project's time were the sums of the means and durations of the activities on the critical path.

ii) The activity durations on the critical path were assumed to be independent variables.

iii) It appealled to the Central Limit Theorem and assumed the normal distribution as the probability model for the project duration time.

iv) It was assumed that the standard deviation of the distribution was one-sixth of the range (b-a). This may cause absolute errors in the mean and standard deviation of 30% and 15% of the range respectively, although some degree of cancellation was expected by positive and negative values in the network similation.

These assumptions caused the mean and often the variance of the project's duration to be underestimated and biased. There was also the possibility that some other path may be the critical path because of errors in the series and parallel combinations of events. MacCrimmon & Ryavec (1964) stated that the most probable critical path may occur only rarely and an activity that had a high probability of being on a longest path may not be on the most probable critical path. It was suggested that a critical activity concept may be more valid in a stochastic model rather than a critical path concept. Healy (1961) investigated the effect of sub-dividing activities in PERT flow diagrams on computed probabilities for meeting scheduled dates. He showed that greater planning and scheduling detail could be rather significant, as resources may be overallocated or scheduled dates unrealistically slipped. Grubbs (1962) discussed the subjectivity of the estimates and stated that they may not bear a close relation to sampling the actual or true beta distribution of times in an ordinary statistical or random sampling sense. The validity and seriousness of the assumptions made in PERT should not be overlooked, however, considering the nature of the input data, the utility of the other outputs possible from the data and the need for speed and economical implementation, PERT may be used to produce satisfactory results. Management personnel who use PERT probabilities to aid their judgement should, however, be aware of the potential limitations and bias inherent in the computation of probabilities. PERT-type systems possess the advantages of serving as integrated planning and control systems, but their limitations seem to reduce their applicability to one-time deterministic activities, largely in the design and development phase. Unlike CPM, PERT takes explicit account of the uncertainty in the activity duration estimates, although its network construction is identical to that of CPM. They are both useful for the basic managerial functions of planning, scheduling and controlling, provide a good basis for sophisticated resource planning (Kidd, 1985) and have developed exceptionally broad applications in industry and military environments.

Suggestions have been made by many authors on the extension of PERT. Malcolm et al (1959) stated that ideally they would have liked to evaluate a given schedule in terms of resources, technical performance and time, commenting that it would then be possible to arrive at an 'optimum' schedule. Freeman (1960) continued the Malcolm et al discussion and suggested that PERT could have been greatly improved if cost and performance were considered in the same way as time. As, he stated, all time and cost estimates are based upon a specified technical objective or level of technical performance. Eisner (1962) made the first significant attempts to develop network models with stochastic flexibility. He suggested the inclusion of logical elements and described a configurational and mathematical tool termed a 'decision box'. Hartley and Wortham (1966) presented a modified PERT network which used random selection techniques to counteract the limitations of optimistic project completion times and misidentifications of critical paths. Elmaghraby (1964) developed a notation and algebra for a multi-parameter branch and logical elements for nodes which were named 'generalised activity networks' (Whitehouse, 1966 and Pritsker & Happ, 1966). Kapur (1978) indicated some of the drawbacks of the conventional PERT/CPM techniques and developed an alternative method called 'Multi-Level Network Analysis' (MLNA). This facilitated organisational communication but according to Barrett (1982) it could give a false impression of the overall timing of a project.

3.6.4 The Graphical Evaluation and Review Technique (GERT) was developed by Pritsker and Happ (1966), it adds to PERT the ability to explicitly deal with uncertainties in flow through the network. It combines flowgraph theory,moment generating functions and PERT, and was the first computer oriented networking methodology. GERT was used to solve networks which contained multi-parameter stochastic branches, where activities were not undertaken unless certain conditions or probabilities existed. It has a relatively sophisticated looping process and overcomes many of the PERT deficiencies. Individual activities were assigned 'a probability of occurrence', a 'parameter set for time' and a 'distribution type'. Constant, normal, uniform, Erlang, lognormal, Poisson, beta and gamma distributions were used which overcame the forced usage of the beta approximation in PERT. GERT incorporated cost figures directly into its format and output. For each activity, the user may specify a fixed cost, a cost which varied with time, or both. Output in the form of nodes realised, the mean time of realisation, the standard deviation of time realised, minimum and maximum realisation times and a frequency distribution of time, could be obtained. GERT is substantially more sophisticated than PERT (Samli & Bellas, 1971) but its probabilistic branching attribute can make it cumbersome to use as a control technique. Peterman (1983) advised that it would be best used at the preliminary design stages for the analysis of alternative methods of construction.

GERT has been used to analyse such diverse applications as space vehicle countdown, the zone refining of semi conductor materials, Markov processes, queueing and inventory theory, reliability engineering, management science, review processes, market research, scheduling and transportation system modelling (Pritsker & Happ, 1966; Whitehouse, 1966; Moore, Taylor & Cattanach, 1980; Elayat, Elsayed & Ragab, 1981 and Morris, 1982^{2}). There is a large capacity for growth within GERT, which has produced many other satellite members of the GERT family. Q-GERT, an acronym for Queueing-Graphical Evaluation and Review Technique, determines the reliability and mean-time-to-failure (MTBF) of complex systems without resorting to complicated mathematics therefore providing a comprehensive tool for estimating the availability of analysing the impact of fluctuating logistics support levels, reliabilities and variations in maintenance times. The concepts behind this program were used to model a number of USAF (United States Air Force) weapon systems with minor modifications. A great deal of research seems to have been undertaken using the Q-GERT system over the past few years for the analysis of adjustment stations for television set manufacturers, the simulation of robotics, squadron training levels, the comparison of circuit and packet switching techniques, the productivity rates in civil engineering, tactical missile operation scenarios, aircraft repair cycles, job flow times, planning and administrative problems, the analysis of the judiciary system in America and machine breakdowns (Pritsker, 1978; Medeiros et al, 1980; Taylor & Moore, 1982; Taylor, Keown & Barrett, 1982 and Taylor, Clayton & Grasso, 1982). Huang, Philipoon and Rees (1983) compared Q-GERT with one of the most widely used and popular of all simulation languages, GPSS (General Purpose Simulation System). They proposed that Q-GERT was both easier to use and explain. Another network modelling approach, SLAM simulation (Park, 1980) combined Q-GERT and GASPIV for risk analysis of investment evaluations. GERT appears to be an excellent tool for the simulation of varying project policies with respect to production loads, material availability and work scheduling. However, it should be noted that cost is treated as a secondary variable, a dependent variable which precludes the manipulation of cost to determine the impact on time schedules.

3.6.5 One main advantage of probabilistic networking techniques, in addition to their added realism, was their ability to simulate project outcomes. The networks could incorporate both favourable and unfavourable occurrences, so that it was possible to develop a distribution of likely outcomes through repeated runs of the network. This gave the user a valuable picture of the probabilities of success and the risks of failure, as well as an indication of which activities were critical to these outcomes. This technique known as risk analysis may be used to improve decision making in a risk environment. The analysis uses the estimated probability distributions for each factor affecting a decision to simulate the possible combinations of the values for each outcome, to determine the range of possible outcomes and the probabilities associated with each possible outcome. If an analytical apporoach were used to combine the different distributions the task would be tedious and it may be difficult to manage the probabilistic information in a simple and meaningful manner. Hertz (1964) suggested that Monte Carlo Simulation (see section 3.3.2.4) could be used as a relatively easier method for combining probabilistic distributions. The quantity surveyor could use risk analysis to assess the degree of financial risk associated with projects, store and rationalise the judgement of experienced surveyors, assess the combined effect of design variations on cost and for sensitivity analyses to determine the influence of each factor on resultant costs and to identify the factors most critical because of their high cost, high uncertainty or both. Conventional risk analysis fails, according to Hespos and Strassman (1965), to take account of skewed distributions, so they introduced stochastic decision tree methods which permitted the use of subjective probability estimates or empirical frequency distributions for some or all factors which affect the decision. They applied Monte Carlo techniques and GPSS simulation to analyse the risks involved in investment decisions. GERT could also be used as a stochastic decision tree method for time schedule risk analysis, but it lacks the ability to handle cost as the predominant variable. There is also an inability to link cost with performance or technical design factors.

3.6.6 A mathematical network analyser, MATHNET (1970), was developed from GERT by Mathematica of Princeton, New Jersey. It enabled events, activities, activity times and cost to be modelled probabilistically by the combination of the AND and OR logic with the ALL input logic and probability output logic. This program was subsequently corrected, modified and expanded by the United States Army Logistics Management Centre and renamed the Risk Information System and Cost Analysis (RISCA) program. SOLVNET (1972) and STATNET (1971) were also developed from MATHNET. RISCA (1970), RISCA II (1971) and RISCA III (1973) allowed for the analysis of event uncertainty but could not evaluate the risk of failing to attain the performance objectives. There was a need to include the performance variables in the total risk analysis methodology. TRACENET (1977) was formulated from RISCA III and aided in the development of the Venture Evaluation and Review Technique (VERT) which was capable of accounting for performance variables (Mann, 1979 and Lee, Park & Economides, 1978).

The Venture Evaluation and Review Technique (VERT) is a stochastic networking technique similar to GERT in basic concept, but it specifically deals with time, cost and performance parameters for nodes and activities. The significant feature of VERT is that it considers cost and performance as equally important as time. VERT was developed and applied by Moeller in 1972, who assessed the risks involved in the development of military systems. VERT-2 was completed in 1979 and added many new features and refinements to the basic VERT. VERT-3 was a completely new program development with more advanced features and improvements in coding, it also corrected the malfunctions and defects that remained in VERT-2. Lee, Moeller and Digman (1982) stated that VERT-3 added more detail and illustrative documentation to VERT-2. VERT-4 (1983) has extended VERT-3 and is the program used throughout this research. When reference is made to VERT, version 4 will be implied. The main advantage of VERT is that it can be applied to any decision involving risk in the concept, design and development stages of a project. It seems to successfully strike a balance between having enough features to effectively model a decision situation without over-burdening the user. It also seems to be a helpful tool in cases where there is a requirement to make decisions with incomplete information. VERT allows for a number of competing installations to be networked individually, each method with differing costs, time factors, technological dependencies and performance criteria. The technique can handle large amounts of highly interrelated stochastic data via its comprehensive array of logical, statistical and mathematical operands. VERT relays its results through simulation. The user can explore conditional non-linear multi-variate situations which defy ready mathematical analysis and determine the risks involved. Like GERT, VERT uses probability distributions to realise nodes, although there is a greater choice of distributions available to the user. The selection of the correct distribution to model the raw data is of the utmost importance (MacCrimmon & Ryavec, 1964). The technique has procedures available for modifying the network, changing the transaction flow, collecting statistics, reproducing sub networks and augmenting the file structure. Learning curve effects, historical data and engineering performance changes can be fed back into the model. VERT optionally prints out the terminal node index and the critical path index in the form of bar graphs. The critical path is the path through the network with the longest completion time, highest cost and lowest performance, or the least desirable weighted combination of these factors based on user-developed weights. Time, cost and performance correlations and plots can be printed upon request for internal and terminal nodes, which enables the possible determination of relationships between these variables.

Digman and Green (1981) showed that VERT was a useful tool in the general areas of strategic design analysis and project management. They successfully utilised the program to assess the risks involved in new ventures and projects, in the estimation of future capital requirements, in control monitoring and in the overall evaluation of on-going projects. Since 1973 VERT has been used almost extensively by United States Army program managers, who have apparently accepted it as a flexible and valuable technique. One of the most noteworthy applications occurred during the 1975 demonstrations and validation phase of the US Army's XM-1 Tank development program. Other projects included the Cannon-Launched Guided Projectile program, the Army's Platoon Early Warning system, the M110E 1 self-propelled howitzer and the Advanced Attack Helicopter. These analyses enabled the army to identify early the possible impact of activities with high probabilities of not occurring as planned; the benefits were enormous. To explore the capabilities of VERT further, the US Navy ran a test application on the radar system for the F-18 aircraft. The risks were related to new performance requirements and the simulation examined the amount of testing to be conducted in the laboratory versus aboard a flight-test aircraft. The program successfully provided the program managers with valuable information. Fighter planes, artillery, electronic sensors and air defence systems were all areas of development. Moeller (1972) illustrated VERT with a hypothetical abbreviated example of a decision-risk problem, by supposing a large helicopter consumer was considering funding one of two possible helicopter development programs. He stated that VERT had contributed to the development of a more formalised decision-risk analysis method, for government and business ventures. Applications have recently broadened to include other types of planning, for example, flood control programs, pollution abatement methods, earthquake analysis, production line balancing and war gaming (Mann, 1979).

In 1979, Moeller (and later Moeller & Digman, 1981) claimed that VERT was more powerful than techniques such as GERT which were basically time and cost oriented, because it had been more helpful to management in cases where there was a requirement to make decisions with incomplete or inadequate information about the alternatives. Mann (1979) commented that VERT appeared quite promisisng and devoid of major problems, but had not enjoyed wide use because of the inadequate understanding of risk analysis concepts in general. Many program managers seemed to be handicapped by the lack of familiarity with quantitiative risk assessment techniques and few people in the military services were experienced enough to perform the analyses. Similarly, it appeared that few managers were accustomed to using the outputs of risk analysis. Moeller & Digman (1981) gave a simplified application of an operational planning problem which illustrated the basic features of the VERT program. They concluded that the technique had proved successful in a variety of project and strategic areas, but no detailed explanations or ciriticisms were given. Digman & Green (1981) and Barrett (1982) suggested that the optimal approach would be to use VERT as a stochastic type network at the planning and evaluation stages, when activity uncertainty exists. They produced a 'roadmap' through the morass of information, decision needs, parameters, phases, techniques and processing requirements for the relatively inexperienced management team. Mattheiss, Moeller and Kilar (1982) showed that large project savings could be made using VERT.

3.6.7 The VERT program is a relatively new risk analysis approach which will take time and empirical research before its usefulness can be validated. It may not necessarily be better than other stochastic networking techniques but it does offer the project manager the ability to combine deterministic and probabilistic cost, time and performance data with equal ease in a stochastic manner, which may reflect a closer picture of reality. Digman and Green (1981) critically compared network based management techniques (PERT/CPM, PERT/Cost, LOB, GERT and VERT-3) and indicated that despite the relatively high operating costs of VERT and the time-consuming preparation of the input data, its flexibility, applicability, reporting and comprehensiveness were all bonuses for the management team. Network analyses appear to be playing an increasingly important role in the description and improvement of operational systems, primarily because of the ease with which systems can be modelled in a network form (Pritsker and Happ, 1966). It was therefore proposed that VERT should be researched as a modelling technique for the development of probabilistic cost models for mechanical and electrical services installations.

4.0 RESEARCH DESIGN

4.4 Cost data variability

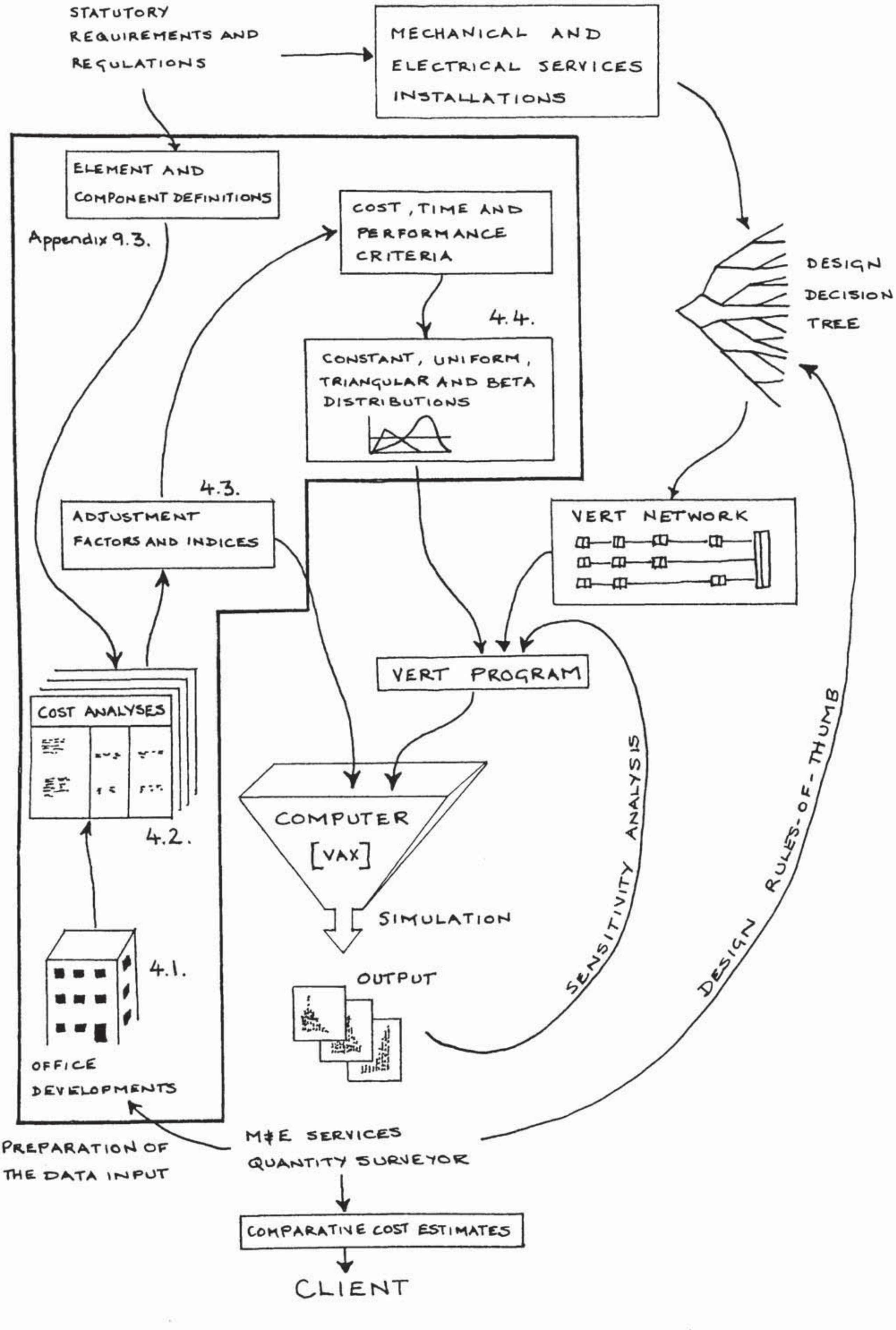


Figure 1.0 Research operation - data preparation

4.0 Research design

The research design was based on the seven process steps recommended by the VERT user/analyst manual (Moeller and Atzinger, 1983^2). This chapter refers to the preparation of the sample input data associated with step 1: the definition of the decision situation, and step 3: the collection of the raw data (refer to section 5.0). Thirty-five office developments were collected, defined, analysed, formatted, adjusted, indexed and characterised in the form of probabilistic distributions. An historical cost data base was developed for the analysis and manipulation of cost-design data for engineering services installations, required by the quantity surveyor at the inception, feasibility and outline proposal stages of construction. Figure 1.0: Research operation/data preparation illustrates the research processes and highlights the sections researched in this chapter.

Although the methodology was designed specifically to suit the requirements of the Engineering Services Division (ESD) within Monk Dunstone Associates (MDA), the underlying theory could be used to construct cost models for the estimation of builders work as well as alternative mechanical and electrical engineering services within differing buildings.

4.1 Raw data

Much of the hard work involved in this research lay in the collection, verification and the presentation of the raw data in an acceptable format for further analysis and the VERT program. This effort was required to ensure that the subsequent results were capable of mathematical interpretation and could be shown to be reliable and significant (Wood, 1975). The major problem was the lack of accurate services cost data inth a readily available consistent form. From the literature review (3.3) it was apparent that very little analytical work had been devoted to establishing the cost determinants of services installations, therefore few guidelines were available.

4.1.1 Data on building costs is produced in many forms and is available from numerous published sources. Unfortunately, such data for engineering services is far less comprehensive that for building work and tends to be so generalised as to be of little value (Chelmick, 1982). Cost limits and yardsticks are published by government departments which can be used for preliminary budgets and cost limit estimates for particular building types, but little is specified for mechanical and electrical services. Cost information published in the specialist sections of builders price books (Spons Architects' and Builders' Price Book, Laxton's Building Price Book, Wessex New Comprehensive Building Price Book and Griffiths Building Price Book) and in mechanical and electrical services price books may be used for preliminary estimates. However, much of this published data is represented by undefined 'unit' prices and averages with little or no factual description on the sources of information, the construction details and the variability of the source data (Hughes, 1978). Some of the cost analyses published in the many professional and trade technical journals may be used for estimates after careful study and comparison with in-house information. Some of these sources (Architects' Journal and The Building Cost Information Service (BCIS)) are more reliable than others but in many cases there is insufficient information for the quantity surveyor. Trade catalogues and manufacturer price lists can provide a source of resources cost information but, as with direct contact with specialist contractors, a detailed knowledge of the services components required is necessary which may not be possible at the pre-tender stages. University and polytechnic research should also be consulted but as research data for quantity surveying is relatively sparce and in terms of engineering services, relatively non-existent, little cost information can be gained here. Published cost information appears to be simply not available for mechanical and electrical services and it would appear that the situation has been worsened because when this data has not existed it has been replaced by apocryphal information and opinion (Chelmick, 1982)[3].

4.1.2 Since the research could not use the published cost data, an examination of the Engineering Services Divisions' in-house data was made. Information was available in three broad categories: bills of quantities, final accounts and pre-tender cost analyses or estimates. Originally it was proposed that the research should be based on adjusted and indexed cost information obtained from M&E bills of quantities. A number of authors (Flanagan, 1980 and Kelly, 1982) have recognised the weaknesses associated with existing price prediction systems based on bills of quantities; because of the competitive nature of the contracts they are low bids which may not be representative of the true cost and because of the distortions made by the contractor when structuring the tender documents. However, regardless of these problems, it was not possible to use bills of quantities as a data source because there were insufficient numbers available within MDA. This situation appears to be not uncommon within the quantity surveying profession (Ryding & Chelmick, 1982) as M&E bills of quantities are a relatively new innovation and, in many cases, they did not fit in with the varied established tendering systems used in the building services industry. Many projects were tendered for on the basis of specifications and drawings produced by the quantity surveyor, architect, consulting engineer and/or specialist engineering services contractor. Final accounts were available for M&E projects but, like bills of quantities, there were insufficient numbers of comparable examples. Pre-tender estimates and cost analyses were the only sector which could provide a wide variety of installation types located within a number of buildings serving a variety of functions. Also they did not possess the inherent weaknesses associated with bills of quantities.

4.1.3 In order to carry out this research it was necessary to obtain all the cost and technical data concerned with services installations available within MDA. This was no easy task because most of the historical data was not collected systematically or catalogued. Data had to be painstakingly collected throughout the ESD and all the MDA offices throughout the country; as the ESD handled many services projects which were elements of total building constructions, the services information had to be bundled and returned to the appropriate surveyor dealing with the construction project. Data was therefore dispersed throughout the whole company. Stratification of the data collected made it apparent that there were a wide variety of project types and levels of information presented in a variety of formats (drawings, lump sum estimates, detailed cost analyses, computerised estimates, specifications, alternative design estimates and manufacturer quotations). Each of which tended to be of a different structure, highlighting different components with a variety of levels of detail and specification. All were collected, analysed, disentangled and filed. An historical data base was created.

For the research purposes, it was thought more beneficial to concentrate on examples about which the quantity surveyors knew as much as possible about the circumstances surrounding the pricing of the project, rather than to rely on data gleaned from many sources about whose background little or nothing was known or could be remembered. The type of data most useful seemed to be in the form of historical cost estimates together with quantified variables and a description of the costs, along with additional drawings and sketches. The criterion for proceeding with data extraction on any project was that it should be possible to obtain, from the estimates and drawings, a price for each element and for a number of components including gross floor areas and criterion on the contract. In the case of some projects it was impossible to accurately segregate the cost of elements or components from lump sum estimates, or specify the component content since no technical information was supplied. For several of the more recent projects it was possible to gain further information by referring to the sketches or drawings, or by direct contact with the quantity surveyor responsible for the estimate. Indeed, this was often necessary because of the lack of description. Surveyors were also questioned to determine the exact meaning of estimate specifications to avoid the later comparison of non-comparative items, as some minor components may be categorised under a variety of headings. No matter to what extent descriptions were narrowed and defined however, a disappointing amount of unexplained variability remained.

4.1.4 Models derived from a range of building projects have not proved successful in the past, because they were difficult to manipulate and their accuracy was difficult to determine (Morris, 1976 and Ashworth, 1981). It was therefore proposed that a single type of building project should be selected. A minimum of thirty examples were also necessary to ensure that the model was statistically reliable (Ashworth, 1981). The more examples that could be procured, the more satisfactory the final models would be in terms of accuracy and reliability. There were a wide variety of building types within the historical data base, but only office developments represented a sizeable sample of more than thirty projects, with a wide variety of mechanical and electrical installations specified with detailed cost data. It was proposed therefore, that office developments would form the basis of the models. They offered a wide range of levels of prestige, were based mainly in London and most previous cost studies undertaken within the ESD were based on alternative office mechanical services designs. In order to obtain as many office projects as possible, however, some comparability was sacrificed on the evidence produced by Beeston (1975).

From the initial collection of forty-eight MDA cost analyses for office developments, a potentially useful sample of forty-four projects were selected. Close scrutiny of the services elements, their contents or lack of it, pruned the sample down to thirty-five projects which contained a sufficient amount of cost and technical data. The office developments selected were dated from the beginning of 1978 to the end of 1983, a six year span. They were of a medium size, an average of five storeys in height and 4600m^2 in gross floor area. They were judged by the Engineering Services Division to be representative of office development mechanical and electrical services installations. Offices which contained integral basements, shops or car parks were excluded from the data base. All costs obtained from the estimates were included, therefore eradicating the criticisms of subjectivity (Beeston, 1983).

4.1.5 No estimate could be expected to be more precise than the information upon which it was dependent. Cost data is inherently inaccurate (Newton, 1982). O'Muircheartaigh and Payne (1977), Flanagan (1980), Morrison and Stevens (1981), Harper (1982) and Mansfield (1984) examined the sources of these errors. It may not be possible to eliminate errors, but it was possible to reduce their impact by recognising their existence and estimating their effects. Errors may be due to the incorrect copying of figures from the estimate to the cost analysis form, and was usually spotted by careful checking. Extreme values within estimates were examined carefully. Ambiguous specifications could have produced errors due to misinterpretation or misclassification, but every effort was made to combat these errors by the direct contact of the researcher with the quantity surveyors who prepared the estimate. At times this proved extremely difficult as the information was no longer available or the quantity surveyor had forgotten the original context in which the project was costed. Technical terms and jargon may also have produced errors due to ill-definition. It was observed that two quantity surveyors used the same terminology to define different specifications. In fact, getting the members of the ESD to agree on element, component and especially composite-component definitions was very difficult, but once definitions were formulated, errors should have been minimised. Approximation and the averaging of lump sum estimates may have produced errors due to a loss of detail, but discussions with the quantity surveyors concerned as to their build-up of lump sum estimates, generally isolated any obvious errors. It was the practice within MDA to round-up values to the nearest hundredth place i.e. 76.882 would be rounded down to 76.88 and 76.885 would have been rounded up to 76.89. This practice may have produced cumulative rounding errors when large numbers of components were involved and could account for an error of over one percent within the models. However, it was anticipated that these errors will have been minimised by the use of the continuous distributions used in VERT, which may take account of these marginal errors, as they are concerned with the grouping of data rather than precisely accurate figures which are meaningless when transferred to other projects.

Systematic errors were, therefore recognised but human bias, accidental and random errors may also be present in the historical cost data base. Flanagan (1980) concluded that the quantity surveyor did not exhibit consistent high degrees of inaccuracy within the profession but showed that there did appear to be consistent inaccuracy within a particular organisation, probably due to the bias and expertise of particular senior personnel. A typical standard deviation of percentage errors made by estimators was found by Morrison and Stevens (1981) to be 12%. Flanagan (1980) produced an error range of ±20% for mechanical and electrical services estimates. Since this research specialised in a particular type of work for a specific type of building, a reduction in the dispersion of data errors may have been achieved although it was not known to what extent. Values could not be changed, only recognised, for fear of introducing further subjectivity into the models. It was hoped that once the modelling format was operational, defined procedures and computerised estimates would reduce the inherent errors to a minimum.

4.2 Cost analyses

Cost analyses provide a standardised format for the systematic breakdown and presentation of cost and design data from historical projects. They reveal the distribution of the costs of engineering services among its elements and components. Cost comparisons can be made by the surveyor between various design alternatives and estimates of equivalent elements in future projects from cost analyses (BCIS, 1969 and Sidwell, 1980). Nisbet (1986) stated that their primary purpose was to compare costs, provide justifiable explanations of why costs differ between buildings and to identify the unexpected. A reliable historical cost analysis library can give a computer estimating system its validity.

4.2.1 "Cost is the principal dimension in value analysis. Without cost for comparsion, the analysis of value must necessarily be subjective."
O'Brien (1976)

Cost is the amount paid by the client or purchaser for the construction of the engineering services installations. It is seldom related directly to a simple parameter but is based on a number of factors (Southwell, 1968), for example:

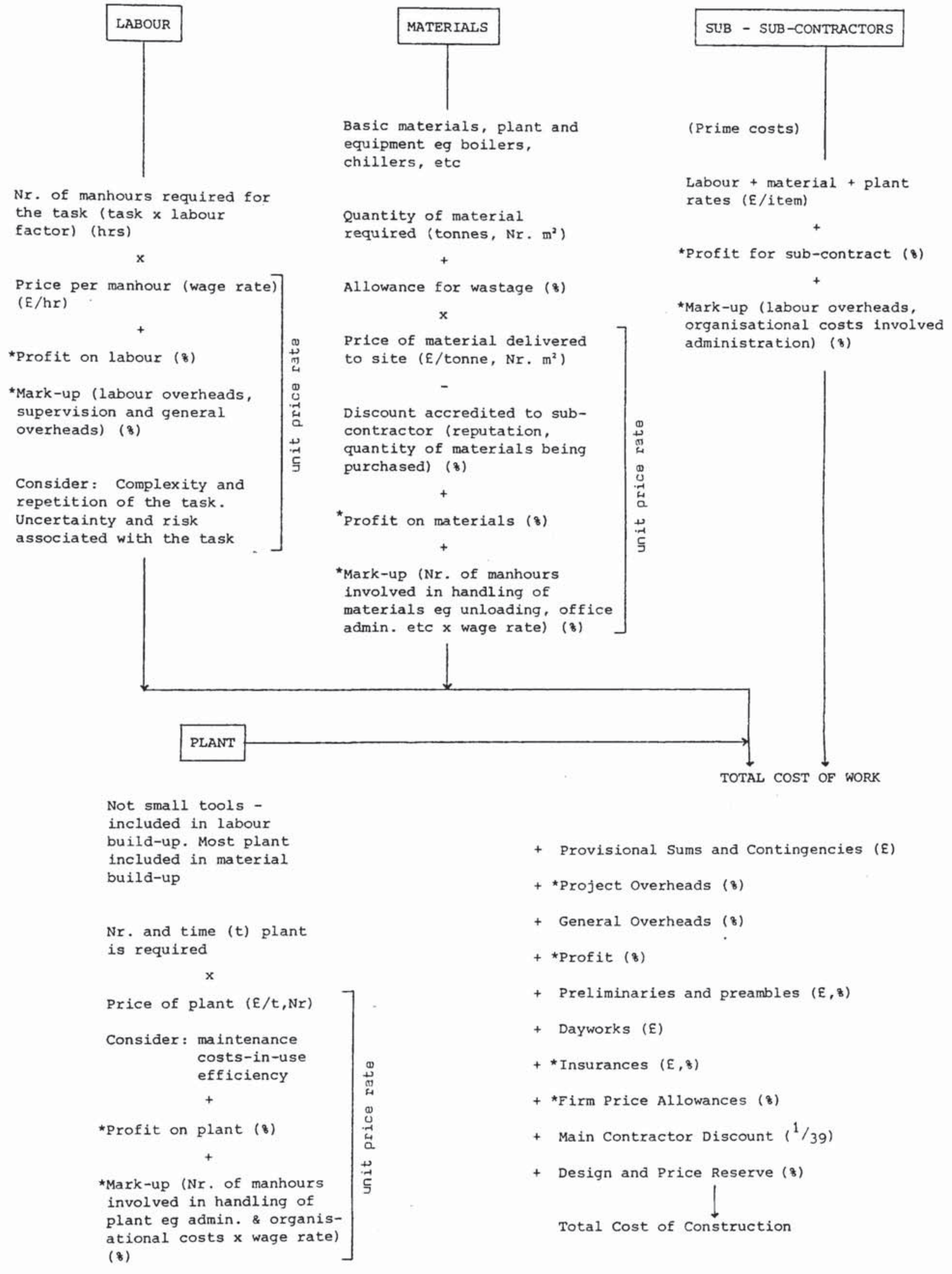
i. Material and labour costs
ii. The climate of tendering
iii. The degree of competition
iv. Acceptable profit margins
v. Percentage additions for overheads and preliminaries
vi. Site factors such as location, ground conditions and accessibility
vii. Prestige
viii. The building type, size, content and shape.

Some of the factors that affect the variations in cost may be identified (planned factors) but it may be difficult to identify all of them (chance and trend factors) and establish relationships for the accurate prediction of costs for a new project. Chance factors such as inclement weather or strikes on the construction site, cannot be directly planned, but it is possible to accommodate such changes. Trend changes in technology and fashion should be monitored and identified where possible, so that resources can be reallocated and alternative design solutions considered. Cost is a factor which influences design solutions in just the same way as does the site orientation or location. It is necessary to control the cost as the design develops to ensure that initially each component and element has a reasonable sum of money devoted to it. Geddes (1981) itemised the individual elements of cost which contribute to the total cost of construction work.

4.2.2 There have been a number of standardised cost analysis formats produced over the years, which have attempted to collate cost information for engineering services. In 1969 the first Standard Form of Cost Analysis was published by the BCIS (Building Cost Information Service) of The Royal Institution of Chartered Surveyors (RICS). Concise, detailed and amplified forms allowed progressively more detailed analyses to be submitted but according to Edworthy and Chelmick

(1980) these were woefully inadequate for the examination of engineering services. The ESD produced their own services cost analysis sheets (see Appendix 9.2) based upon the 'principles of analysis' proposed by the BCIS (1969). Edworthy and Chelmick (1980) explained where these analyses departed from the BCIS standard forms and explained why MDA thought these departures were necessary.

The building services cost analysis form prepared and used within MDA is the basis of their library of cost information. (Two examples of actual M&E cost analyses are given in Appendix 9.2.) The forms deal with information which directly affects the services installations, the basis of the tender and the elemental cost data for public health, fire protection, mechanical, special and electrical installation groups. Data from cost studies, quotations or detailed measurements from tenders may be used to provide different levels of cost advice using the same format. However, this research was concerned only with pre-tender estimating cost analyses. Costs were expressed using the yardsticks of 'cost per square metre of gross internal floor area' or 'cost per square metre of treated floor area' to two decimal places (BCIS, 1969). The former method of measurement is the most common, widely accepted and convenient measure of costs (refer to 3.2) although the limitations of this method should be acknowledged. Building costs may not vary proportionally with changes in area and no account may be taken of possible expensive vertical items, the height and shape of the building (RICS, 1976). However, as no other more suitable basis for expressing costs currently exists which is common to all elements and which allows comparsions to be undertaken between components, the limitations of the method were accepted in order to provide a practical tool for cost examination. An alternative measure of cost, a performance variable, was also expressed in terms of an appropriate functional unit per component, for example, £/KW per boiler or £/point for cold water. This was used to establish other possible cost-design relationships.



* optional

Figure 2.0 M&E Sub-contractor pricing structure

At the estimating stages, information on the costs of all the resources required for a project were not always easy to find (Ferry, 1980). Since the majority of main contractors required a main mechanical and electrical sub-contractor, who in turn employed specialist sub-contractors to undertake the construction of the services elements, the pricing structure was highly complex. Figure 2.0 illustrates the most M&E sub-contractor pricing structure and the factors considered when evaluating the total cost of the engineering services construction. Unit rates are based on the labour, plant, material and sub-sub-contractor costs per component per square metre.

4.2.3 The cost of the labour element was estimated in terms of an operative's all-in rate, made up of wages and the costs incurred in labour employment, and the operative's production output or labour factor (CIOB, 1979). To avoid the necessity for negotiating terms of employment for each project, the National Agreement for the Heating and Ventilating, Air Conditioning, Piping and Domestic Engineering Industry Working Rule Agreement (HVCA, 1982) was used as a basis for the labour rate (see Footnote 1). The quantity surveyor should keep an up-to-date check on current wage settlements and changes in the Working Rules and Conditions. Barton (1968), Page (1980) and Bishop (1982) gave some guidance on the assessment of man-hour rates required for different operations, and an insight into the factors which influence the estimation of labour factors. A labour factor details the installation time for the construction of individual components, it is affected by the human variances of skill, familiarity of operation, equipment used, motivation, requirements, security, job satisfaction and physiology; and the external conditions of the overall mechanisation, site layout and organisation, the complexity of the design, supervision and the climate. Labour factors can be adjusted to take account of different conditions prior to tender. In the case of non-standard items a best estimate of fixing times would have to be made. The labour factors depend heavily on the operative's individual skills, their ability to carry out the work and the grouping of the individuals within a 'gang' (the ratio of fitters, assistants and mates within a working team). Footnote 2 indicates the basic assumptions, scope and limitations of 'standard' fixing time factors. The quality of the workmanship should be consistent with the best accepted current practice and safe methods of working.

There are a variety of methods which can be adopted to establish labour factors ('Unit Labour rate' method, the 'Counted Fitting' method and the 'Foot Run' method - Webster, 1976). The ESD uses a composite labour factor for a hybrid fitting. This is an imaginary composition of fittings (tees, elbows, unions, bends, connectors, pairs of flanges and reducers) which limits the time-consuming and laborious effort required when detailing lists of all the types and sizes of fittings involved in pipework installations. The number of hybrid fittings may vary considerably between pipe sizes, types or sections of an installation for example: steel welded fittings are approximately 50% elbows (70% at 90^0 and 30% at 45^0), 25% tees, 15% branches or bends and 10% flanges whereas cast iron fittings are approximately 30% bends, 50% branches, 10% access doors and 10% bosses. Hybrid fittings were costed using an 'average' cost per three to four metres of pipe, but this was dependent on the complexity of the installation.

4.2.4 An estimate should include sufficient allowances to cover the cost of mechanical and non-mechanical plant. The mechanical and electrical sub-contractors generally supplied their own non-mechanical plant and small tools, the costs of which were covered by a mark-up percentage addition on labour or material rates or included in the preliminaries (see Footnote 3). The method used to include the plant in the estimate was dependent on the type of plant required, the purchase price, the maintenance and repair costs, and all the incidental running expenses over that part of the item's life when it was in use. This was 'judged' by what it could produce at that time. Depreciation, interest on capital and sinking funds were also considered by the estimating quantity surveyor. Because of the difficulties of precise allocation of costs, general site items such as tower cranes or hoists, and non-mechanical plant such as scaffolding, were often included in the project overheads. The Standard Method of Measurement (SMM6) requires that the plant costs be priced against the appropriate elements and separated into value related costs (transport, erection and dismantling) and time related costs (the hire of the plant) for bills of quantities. Since the estimator rarely prices the plant items separately, the plant costs were assumed to have been included within the project overheads, preliminaries or unit rates for labour and materials. It was therefore extremely difficult to isolate the plant costs in the cost analyses and estimates used, so the estimator should be aware of their possible inclusion within the resultant models under a number of headings, which increases the uncertainty associated with deterministic costs.

4.2.5 The cost of the materials element was estimated in terms of an all-in rate for the material or component and the quantity which had to be purchased. The all-in rate included for the cost of the materials to be delivered to site, wastage, shrinkage and consolidation (average 10%), finishes (for example, screwed or bevelled ends) and quantity discounts (economies of scale). The unloading, storing, removing into position, hoisting and lowering, mixing and the assembly of the components were not included in the material rate but included for in the labour and plant charges. There were also occasions where extra costs were incurred due to double handling because of restricted work spaces or access and the need to pay premiums to secure deliveries. In some cases the delivery distances were responsible for substantial cost factors. Discounts were carefully considered but it was almost impossible to obtain material costs with all preferential discounts as quoted to the contractor. Anticipated discounts were therefore included within the estimates to produce competitive and comparable costings.

Materials can be divided into three categories:

i) Basic materials - pipework, fittings, pumps, valves and ancillaries for example;
ii) Equipment - boilers, chillers and air-handling units for example;
and iii) Sub-sub-contractor materials - such as ductwork specialist materials, insulation, water tanks and controls.

The quantity surveyor may have obtained quotations for specific nominated or specialist materials from builders merchants, manufacturers or contractors. Generally, basic trade or list prices for materials were taken from Luckins Standard Pricing Manual, inclusive of any inflationary allowances shown. It seemed to be the policy of almost all of the mechanical and electrical contractors to mark-up material prices to cover, for example, office administration or building departments. Basic materials acquired a high mark-up (generally $12\frac{1}{2}$%) whereas equipment acquired a lower mark-up (generally 4%), this was probably due to the lower overheads incurred through the purchase of one-off components. Some sub-sub-contractor materials had acquired low mark-ups because the work was undertaken by a specialist sub-contractor of good reputation, whilst others acquired high mark-ups due to possible management problems. The ESD considered $7\frac{1}{2}$% percent as a representative mark-up. It was not clear whether profit had been added to the material prices, from the available data. Pricing manuals indicated that it was, but the practical examination of the estimates did not substantiate this view.

The main source of information about the selection of type and quality of the materials used in the office developments was the project specification or description. In the early cost analyses this information was virtually non-existent therefore references had to be made to the drawings, original client requirements and the manufacturer quotations. This inability to compare specifications easily for similar components was a grave defect in the cost analysis system used within the ESD (Southwell, 1968). A 'performance' measure or an appropriate functional unit per component was required from the estimates to provide some quality indication, to enable components to be categorised according to their 'quality' or a characteristic related to their specification. These performance evaluations were approximate assessments since they were functions of various properties, partly qualitative and partly quantitative; there was no way of measuring the performance factor directly (Reynolds, 1980). There were also difficulties when combinations of components, with varying performance specifications, needed to be evaluated because no common denominator could be found.

4.2.6 Since cost analyses were primarily founded to compare alternative cost-design solutions, the cost of overheads, profit and mark-ups were excluded as they were not considered functions related to the general design of the mechanical and electrical installations (Hardcastle, 1982 and Wilson, 1982). It was proposed that if it were possible to isolate the direct labour and material costs and indirect production costs from the other cost factors of overheads and profit, it may be possible to establish the cost of production and design decisions. The profit and overheads were uncertain variables, specific to the project undertaken, which were to be assessed separately as percentage additions to the overall cost model once the components and design alternatives had been assessed. The project overheads were the costs of administering the project and providing the general plant, facilities and site based services. They consisted of items which could not be satisfactorily allocated to individual unit rates and were generally removed as lump sums against items in the preliminaries. The general overheads were the costs covering the administration of sub-sub-contractors and for the provision of off-site services. They varied with different project cost analyses and may have included rent, rates, fees, salaries and wages for off-site staff, head office equipment, stationery, postage, telephones, cars, head office heating, lighting, insurances and the interest on capital borrowed by the M&E sub-contractor. Preliminaries were used to include the descriptions of the works, any special requirements for construction, site conditions, site access, the cost of drawing and maintenance manuals, setting out of the work, the protection of unfixed materials and equipment, design fees, contingency sums, the costs of retention and the defects liability period. They are a relatively new inclusion within the services estimate, and may be kept separate from the labour, material and plant unit rates or applied as a percentage addition over the contract sum (Southwell, 1968; Flanagan, 1980 and BCIS, 1982). Individual preliminary percentages varied widely within the sample data depending on the contract size and the tendering climate. They were removed from the unit rates along with the overheads and profit additions by the removal of the sub-contractor, material and equipment mark-ups or percentage additions and lump sums. The 'mark-up' was the term used within the construction industry to cover the value of overheads, on-costs, head office charges and net profit. Mark-ups on estimated costs seemed to depend on the time of year, the type of construction, the type of tender, the client and design team, the capital requirements, the current and anticipated work load of the company, the location of the project, the prestige of the project and the competition. From the raw data the mark-ups on sub-contractor rates varied between 5% and 20%, 7½% being the most usual addition (50% of the projects), the mark-ups on materials varied between 5% and 20%, 20% being the most usual addition (66% of the projects) and the mark-ups on equipment varied between 5%

and 20% with 5% being the most usual addition (75% of projects) although not all projects included mark-ups on equipment. Preliminary percentage additions varied between 3% and 15% with 3% plus a lump sum being the most usual allowance.

Other percentage additions to the raw data consisted of allowances for the design and price reserve (or risk), the cash discount and builders work in connection (BWIC) with the mechanical and electrical services installations. All were removed from the project costs. The design and price reserve (D & PR) was used to cover for unforeseens during the construction of the project, as a contingency sum, and to cover likely increases in the costs between the estimate data and tender date. It depended on the complexity of the design and price movements in the market. From the raw data the percentage additions ranged from 5% to 15% with $7\frac{1}{2}$% as the average and most likely addition. The cash discount, an addition of one-thirty-ninth or $2\frac{1}{2}$% on the total cost of the works, was applied to cover administration costs when the main M&E sub-contractor was instructed to enter into a sub-contract with a nominated specialist firm. This was considered a monetary reward for the risk in co-ordinating a nominated sub-contractor into the main contractor programme. Builders work in connection was usually not included in the services estimates, but when applied it referred to the construction work undertaken by a builder. It seemed to be directly related to the building structure, its complexity of design and fabric. Provisional sums, contingencies, dayworks and insurances were also all removed from the raw data cost analyses.

4.2.7 Once the thirty-five office project cost analyses had been carefully checked and reduced to labour and material costs, by the removal of all the percentage additions and lump sums, the raw data was re-entered onto the ESD cost analysis forms for direct comparison, under the appropriate element headings. An element was defined (BCIS, 1969) as a major installation that fulfilled a specific function or functions irrespective of its design, specification or construction. Within elements there existed components which were broadly defined as distinct composite units of work, based on an installation type, which formed cost significant features within elements. For example under the Fire Protection Element sprinklers, hosereels, wet and dry risers were defined as the main components (see Appendix 9.2). All the components specified by the ESD cost analysis format were broad and ill-defined, making direct comparisons extremely difficult. It was perceived that a major problem that had to be tackled by the research was the identification and development of component definitions for mechanical and electrical installation, as the basis for comparative cost analysis.

After the careful examination of the raw data collected and the estimating system used within the ESD, a new cost analysis format was designed which categorised the data under eight element headings (Figure 3.0 illustrates the cost analysis breakdown of elements into levels 1, 2 and 3). It was then essential to develop component definitions to provide an understanding of the variations associated with each composite component and element, and to provide a common base from which the research could develop. The installations selected were specific to the raw data, so although alternative heating methods, specialist installations such as catering equipment, rainwater installations, external drainage and disposal services were omitted, these could be included within the models at a later date when further information became available. The composite component definitions were listed under the appropriate element titles and defined under general specifications which gave details of the installation types available, the sub-components and material variations. Current statutory requirements and

LEVEL 1 : ELEMENTS	LEVEL 2 : COMPONENT INSTALLATIONS	LEVEL 3 : COST SIGNIFICANT SUB-COMPONENTS
1.0 SANITARY FITTINGS	1.1 Water Closets (WCs)	
	1.2 Wash Hand Basins (WHBs)	
	1.3 Urinals	
	1.4 Cleaners Sinks	
	1.5 Macerators	
	1.6 Overflows	
	1.7 Sanitary Points	
2.0 COLD WATER	2.1 Mains	
	2.2 Cold Water Points	
	2.3 Cold Water Storage	
	2.4 Insulation to Pipework	
3.0 HOT WATER INSTALLATIONS	3.1 Hot Water Points	
	3.2 Hot Water Storage	
	3.3 Insulation to Pipework	
	3.4 Pumps	
	3.5 Heat Source	
	3.6 Electrical Work in Connection (EWIC)	
4.0 HEATING	PIPED HEATING SYSTEMS	
	4.1 Radiators	4.1.1 Distribution
		4.1.2 Heat Source
		4.1.3 EWIC
	4.2 Perimeter Convectors	4.2.1 Distribution
		4.2.2 Heat Source
		4.2.3 EWIC
	4.3 Fan Convectors	4.3.1 Distribution
		4.3.2 Heat Source
		4.3.3 EWIC
	DUAL PIPED HEATING SYSTEM	
	4.4 Fan Convectors	4.4.1 Distribution
		4.4.2 Perimeter Convectors
		4.4.3 Distribution
		4.4.4 Heat Source
		4.4.5 EWIC

Figure 3.0 The cost analysis breakdown of elements (1)

AIR CONDITIONING SYSTEMS

- 4.5 Versatemp Units
  - 4.5.1 Central Air Handling Plant
  - 4.5.2 Ductwork
  - 4.5.3 Grilles and Terminals
  - 4.5.4 Pipework
  - 4.5.5 Heat Source
  - 4.5.6 EWIC
- 4.6 Variable Air Volume Units
  - 4.6.1 Central Air Handling Plant
  - 4.6.2 Ductwork
  - 4.6.3 Grilles and Terminals
  - 4.6.4 Pipework
  - 4.6.5 Heat Source
  - 4.6.6 EWIC
- 4.7 Central Air Handling Plant
  - 4.7.1 Ductwork
  - 4.7.2 Grilles and Terminals
  - 4.7.3 Pipework
  - 4.7.4 Heat Source
  - 4.7.5 EWIC

DUAL AIR CONDITIONING AND PIPED HEATING SYSTEMS

- 4.8 Perimeter Convectors
  - 4.8.1 Distribution
  - 4.8.2 Variable Air Volume Units
  - 4.8.3 Central Air Handling Plant
  - 4.8.4 Ductwork
  - 4.8.5 Grilles and Terminals
  - 4.8.6 Pipework
  - 4.8.7 Heat Source
  - 4.8.8 EWIC
- 4.9 Perimeter Convectors
  - 4.9.1 Distribution
  - 4.9.2 Versatemp Units
  - 4.9.3 Central Air Handling Plant
  - 4.9.4 Ductwork
  - 4.9.5 Grilles and Terminals
  - 4.9.6 Pipework
  - 4.9.7 Heat Source
  - 4.9.8 EWIC

Figure 3.0 The cost analysis breakdown of elements (2)

5.0	UNTREATED VENTILATION	5.1	Extract Plant	5.1.1	Ductwork
				5.1.2	Terminals
				5.1.3	EWIC
		5.2	Supply Plant	5.2.1	Ductwork
				5.2.2	Terminals
				5.2.3	EWIC
		5.3	Supply and Extract Plant	5.3.1	Ductwork
				5.3.2	Terminals
				5.3.3	EWIC
6.0	FIRE PROTECTION	6.1	Sprinklers		
		6.2	Hosereels		
		6.3	Loose Equipment		
		6.4	Dry Risers		
		6.5	EWIC with Fire Alarms		
7.0	LIFTS	7.1	Electric Lifts	7.1.1	EWIC
		7.2	Hydraulic Lifts	7.2.1	EWIC
8.0	ELECTRICAL	8.1	Mains and Switchgear		
		8.2	Earthing and Cable Distribution		
		8.3	Trunking Conduits		
		8.4	Lighting Fittings	8.4.1	600 Lux
				8.4.2	500 Lux
				8.4.3	300 Lux
		8.5	Emergency Lighting		
		8.6	Small Power and Trunking		
		8.7	GPO Telephones		
		8.8	Lightning Protection		
		8.9	Computer Trunking		

Figure 3.0 The cost analysis breakdown of elements (3)

regulations were referenced along with guidance notes to give the quantity surveyor a greater insight into the cost-design determining factors. Arc code names were included on the component definition format for cross-referencing and data transfer into the VERT program. Figure 4.0 illustrates the standard component definition format devised for the ESD. Appendix 9.3 contains the full set of component definitions and background details of the raw data collected and used within the research. The definitions concentrated mainly on the cost significant items as suggested by Berryman (1980) and Morrison (1981) who stated that approximately 90% of project costs were contained in 10% of the measurable items. Unfortunately, as with most research, what was desirable in terms of component or element breakdown and analysis gave way to what was available.

From the elemental and component definitions a new set of M&E Standard Cost Analysis Forms were derived (Appendix 9.4) for the examination of services costs (material costs + labour factors x labour rates), time (labour factors) and performance or design criteria (unit quantities per square metre). The historical cost analyses therefore formed a comparable basis for this design-cost research into engineering services.

ELEMENT

COMPONENT	ARC	GENERAL SPECIFICATIONS	REGULATIONS	GUIDANCE NOTES

Figure 4.0 Standard component definition form.

FOOTNOTES:

1. Whilst the estimator is not expected to have a detailed knowledge of the Working Rule Agreement (HVCA, 1982), an appreciation of the financial implications of the rules is desirable:

   Craftsmen, labourers and labourers with extra skills or responsibilities are paid on an hourly basis in accordance with the rates of wages agreed by the Heating and Ventilating Contractors Association and the National Union of Sheet Metal Workers, Coppersmiths, Heating and Domestic Engineers. The calculation of an 'all-in' hourly rate for services installation estimates should be calculated on the total hours worked plus overtime, minus public and annual holidays, and sick days. Allowances should be made for:

   i) Inclement weather
   ii) Non-productive overtime
   iii) Different worker categories (calculated on a percentage of the fitters' hourly rate)
   iv) Welding supplements
   v) Holiday credit welfare stamps
   vi) Daily travelling allowances and fares
   vii) Swings, cradles and ladders
   viii) National insurance contributions
   ix) C.I.T.B. Levy
   x) Public holidays with pay
   xi) Severance pay
   xii) Employer's liability and third party insurance
   xiii) Bonus incentives.

   Government departments give guidance on statutory on-costs, training levies and grants.

   The Meteorological Office may be contacted for weather data used to assess allowances for inclement weather.

2. Standard labour fixing time factors were based on the following assumptions:

   i) The work was carried out at floor level in an easily accessible, unoccupied building.

   ii) Productivity achieved when working a maximum of a five day, forty hour week, with labour forces up to 25 in number.

   iii) No excess waiting time.

   iv) Normal working conditions using conventional materials and tools.

v) Of the standard eight 'worked' hours each day, the labour fixing times assume six hours being spent fabricating, assembling or installing materials; the remaining two hours being spent in welfare needs and concentrating materials and effort at work points such as briefings, drawing material and plant from site stores, walking between the site compound and the work point, washing hands, morning and afternoon paid breaks, toilets and general duties in the site compounds.

vi) No allowances have been made for builders' or other trades work such as cutting away and making good walls or floors, painting or fixing other than rawlbolts or similar items.

The labour factors do include where appropriate:

i) Erecting and dismantling once only, stores, workshops and compounds.

ii) Preparation - planning, layout, obtaining measurements, reading drawings, marking out and checking builders' work.

iii) Handling - taking delivery, unloading, uncrating, sorting, storing, stacking, distributing, returning, emptying crates etc.

iv) Fabrication - positioning, setting up equipment, marking, clamping, cutting, reaming, screwing, tacking, welding, brazing, shearing, notching, seaming and bending.

v) Location - positioning, aligning, levelling and hanging.

vi) Installation - setting up equipment, assembling, removing, and replacing, jointing, connecting, clamping, inserting, cutting-in, securing, screwing, tacking, welding, brazing, nailing, riveting, locking, tape jointing and bolting.

vii) Testing of the mechanical and plumbing installations - filling up systems, checking equipment for operation sequence, checking for leakage and starting up.

viii) Testing of the electrical installations.

ix) Heavy handling - cranes and lifting equipment operator time factors.

The labour factors do not include:

i) Clearing - descaling, degreasing, painting and touching up.

ii) Transporting - work undertaken off the site.

iii) Builders' work in connection, of any description, except drilling and plugging where appropriate.

iv) The removal, cutting up and handling of existing equipment.

v) Commissioning as defined in the IHVE codes or other specialist requirements.

vi) The supervision provided by non-working foreman or engineers.

3. The sub-contractor costed plant items may include for tools, the re-sharpening of tools, rules, baskets and slings, dust sheets, tarpaulins, templates, staging, jenny wheels, pulleys, ropes and tackle, vices, screens, bending and screwing machines (and the like), trestles, hose piping, ladders, cranes, hoists and electric drills. Estimated plant rates may include for the cost of the fuel, lubricating oils, grease, maintenance, replacement of spare parts, licences and insurances applicable to the items of plant.

4.3 Adjustment factors and indices

4.3.1 An estimate is dependent on a wide variety of macro and micro conditions which effect the supply and demand of labour and materials, and the overall design. Macro factors such as the current market conditions, the tendering climate and inflation rate affect all project costings and can be statistically measured and accounted for by cost or price indices. The contract conditions, physical characteristics of the particular project site, size, accessibility, location, technical complexity, shape height, quality and function combine to produce a unique cost. In order to compare cost analyses from a variety of locations, with differing requirements, quality, prestige and because the superficial method fails to take account of any variations in the building shape or height, adjustment factors were required to bring all the projects to a common base. The following factors were investigated:

1. Location
2. Selection of contractor
3. Contract sum
4. Building function
5. Measurement of structural steelwork
6. Building height
7. Form of contract
8. Site conditions
9. Refurbishment.

All adjustment factors were based on research undertaken by the BCIS (1983) into 'the effect of location and other measurable parameters on tender levels', as no specific factors for engineering services could be found. Some factors were altered because the ESD was not convinced of their validity for services installations. Further research into the area of factor adjustments is required in order to produce non-subjective alternatives. It was felt that making an assumption about some of the factors would provide a starting block for further research, and was better than assuming the effects were zero (Beeston, 1983). The quantity surveyor subjectively includes adjustment factors on costs when preparing an estimate (Drake, 1984), therefore they should be removed to improve the homogeneity of the raw data. Insufficient data on the effects of the building shape and size, internal arrangements and many other factors meant that not all adjustments could be considered, but it was proposed that by the removal of some of the variables the quantity surveyor could concentrate on a narrower range of costs when examining historic cost analyses.

4.3.2 Certain areas of the country tend to have different tender levels than others. Location indices are generally compiled from the tender price index and attempt to make some allowance for variations due to location. Avery (1982) attempted to identify the main causes of differences in construction costs which were attributable to locality: remoteness from the source of material supply, local labour costs and productivity, water, power and sewage connections, access, security costs, climate, weather and hours of daylight, local market conditions or climate of tendering, local planning and building regulations, local building design practice and vandalism risks. Morris (1979) stated that location had a marked effect on the price of buildings both overall and elementally, and that large errors in price prediction could be caused by ignorance of the proposed buildings' locational pecularities. He also felt that the adjustment of estimates to take account of all the factors affected by location would be impossible, and requested further research into location regions. Flanagan (1980) studied the impact of geographical location upon labour, material and transport prices, and showed that variability of cost did exist with the main influence being on the labour cost. The BCIS (1983) attempt to identify some of these general locational differences using information derived from the BCIS Tender Price Index. They selected regions of administrative value and not as significant cost boundaries. Areas were grouped into regions by the Department of the Environment Standard Statistical Regions (except for the South-East for which smaller groups were used) and split into Districts where several projects were available from the same district. These location cost indices were used to convert the capital cost of projects used within the research, to those expected in the London Postal District, as 55% of projects were originally based in London. As a region, London was significantly more expensive (Wood, 1975) than the rest of the country because of the premiums paid for labour and the difficulties of access to the site for personnel and deliveries, the limited supply of land and the extra transport costs. The estimator should be aware that the indexed total costs include for the higher London rates for office developments. The estimator should also be aware that there was seldom enough data in many of the factor groups to provide reliable averages (Beeston, 1983) and that the BCIS stress that even within counties or large conurbations great variations in tender levels were evident, which may outweigh the effect of the general regional factor.

4.3.3 Each project was then adjusted for the selection of contractor (BCIS, 1983) on the basis of a competitive, negotiated, extension or serial contract. Since 72% of projects were based on a competitive tender, all projects were adjusted to comply with this basis. An adjustment to the total costs was also made for economies of scale or the influence of the contract sum on tender prices. Contract sums for mechanical and electrical services were adjusted to the 1st quarter 1974 prices and entered into the formula:

$F = 1.533 \times C^{-0.03515}$ (BCIS, 1983)

where F = the adjustment factor

C = contract sum at 1974 prices.

Since the average contract sum at 1974 prices was approximately £200,000, contracts below this value were consequently made cheaper in value, and contracts above this value made more expensive to counteract the economics of scale experienced on larger projects. The BCIS (1983) stated that it was difficult to isolate the effect of the size of the contract sum from the building function as the effects were not independent. Since all the projects were office developments, no adjustment factor was required for the building function.

4.3.4 The cost analyses for M&E services contained no details on the measurement of steelwork for projects. The factors derived for this purpose were omitted from the research, although a factor of 1.00 could be applied which indicates that some measured steelwork was included, but which results in a non-adjustment.

4.3.5 The impact of height on construction prices is not precisely known but generally the fewer the number of storeys, the more economical the scheme, as there exists a higher proportion of net lettable floor area to gross floor area. Flanagan & Norman (1977) stated that there seemed to be no good reason for assuming that the cost per square metre for developments would increase linearly with height. They tested this relationship using a number of office developments and proposed that the relationship should be U-shaped with an initial decrease in costs per square metre from one to five storeys, before a sharp rise after six storeys. Newton (1982) and Wiles (1976) agreed with this proposal and stated that optimum economics could be achieved with a building of four to five storeys high. The reasons for the initial fall in costs could be due to learning curve effects, repetition and the reduced proportion of foundation and roof costs per floor. But as buildings are built taller, vertical ducts tend to increase in size, intermediate service zones may be required and vertical circulation cores, lift costs increase, construction costs increase because of the difficulty of working and time lost on operatives moving up and down the building. Services increasingly form a higher percentage of reduced plan floor areas. The National Working Rule Agreement allows extra payments to be made to operatives when they are working at heights, therefore an adjustment was made to the labour factors contained in the research. The building height factors proposed by the BCIS (1983) were not designed specifically for engineering services applications and did not seem to reflect the results from previous research. New factor adjustments were defined in consultation with the ESD (Figure 5.0). Since the average height of all the office developments was five storeys and the optimum storey height lies between four and five storeys, it was proposed to adjust labour factors to reflect a height factor of five storeys. Basement car parks were not included within the raw data.

Number of storeys	FACTOR
Not Known	0.98
1	0.97
2	0.98
3	0.99
4	1.00
5	0.98
6	0.99
7	0.99
8	1.00
9	1.01
10	1.02

Figure 5.0 Building Height adjustment factors

4.3.6 Pre-tender estimates are prepared when limited knowledge is known about the site conditions. London sites are predominantly restricted in working space, but the ground conditions vary widely. The BCIS (1983) used these two aspects of the construction site to determine the influence of site conditions. The raw data projects were adjusted to reflect a restricted working space and moderate ground conditions. No adjustment was made for the form of contracts used within the research because all estimates were based on the JCT 1963 Forms of Contract. It was, however, necessary to adjust the price of services installations in refurbishment projects to those installations undertaken in new developments. Refurbishment installations usually acquire a 5% mark-up on labour factors because of the difficulties involved in working around existing structures and accommodating the original building. Refurbishment projects were therefore reduced in cost by 5%. Both the site condition factor and refurbishment factor were applied to the labour factors, since increases were incurred because of labour difficulties not increases in the material content of the projects. Composite labour and total cost adjustment factors were produced and applied to the raw data. Overall the estimates were adjusted for new competitive office developments, located on restricted London sites with an average height of 5 storeys and 5000m^2 in gross floor area.

4.3.7 Tender price indices can be used to compare estimates which were compiled at different dates, to adjust estimates and cost analyses to different dates and update them to the present. Tender price indices reflect the relative changes in the prices paid for construction work by the client over periods of time. Future price trends can be forecasted by the projection of trend graphs. Flanagan (1980) recommended the use of tender price based indices for cost planning because they consider the costs the client may pay for the building, combine market conditions and inflation factors, reflect price changes resulting from variations in labour and material prices, and productivity. The BCIS and DOE published tender price indices are accepted throughout the construction industry, they take account of the contractors method of work, technological changes and incorporate economies of bulk purchase schemes. Many authors, Jupp (1971), Flanagan (1980), Ferry (1980), Tysoe (1981), Cartlidge & Mehrtens (1982) and Beeston (1983) have considered the characteristics and types of indices available, and examined their background, history, formation and use. Tender price indices are generally compiled by comparing the prices of specific quantity weighted items within a number of accepted tenders for a specified period (usually three months) with the same specific quantity weighted items from another prior specified period. The geometric or arithmetic mean of the sample price changes becomes the index for the period. Three possible formulae can be used depending on whether base year, given year or typical year quantities, denoted by q_o, q_n or q_t respectively, are used: (Spiegel, 1976)

1. Laspeyre's index or base year quantity weighted index:

Weighted aggregate price index with
base year quantity weights $= \dfrac{\Sigma\, p_n q_o}{\Sigma\, p_o q_o}$

where $\Sigma\, p_o$ = sum of all item prices in the base year
$\Sigma\, p_n$ = sum of corresponding item prices in the given year.

2. Paasche's index or current-year quantity weighted index:

Weighted aggregate price index with
given year quantity weights $= \dfrac{\Sigma\, p_n q_n}{\Sigma\, p_o q_n}$

3. Typical year method index:

Weighted aggregate price index with typical year quantity weights $= \dfrac{\Sigma\, p_n q_t}{\Sigma\, p_o q_t}$

For $t = 0$ and $t = n$ this formula reduces to Laspeyre's and Paasche's index respectively

Laspeyre indices are much more common than Paasche indices because they do not require actual quantities to be ascertained for each year of the series, the denominator does not need recomputing each year, and different years in a Laspeyre index can be directly compared with each other, whereas for the Paasche series different years can only be compared with the base year. With regards to the final index figure, there is probably very little difference between the index formulae, unless there has been a substantial change in the purchasing patterns, user trends, technologies or relative item importance. Tysoe (1981) stated that nationally there was a range of approximately thirty percent about the index figure. The price indices may be presented as a table of figures, generally with a certain year as a base of 100. The base year should be a recent year of economic stability. Any change in cost is calculated as a percentage of the base year and the figure added to or deducted from 100. The principles of adjusting by indices may be illustrated by an example:

original tender value : £500,000

date of tender index : 194

current index : 240

adjustment in tender price : £500,000 × $\frac{240}{194}$

updated price : £618,557.

It should be remembered that tender price indices only give an indication of general trends and attempt to summarise a whole mass of data into one figure (Harper, 1982). The types of average index produced will always depend upon the number of individual indices collected. They are a compromise between opposing price movements. The effect on costs due to technological improvements are rarely built into indices (Miller, 1978) and there is usually no indication of how important each item is in the index, nor what weightings were applied to produce the index. There is still too little data, despite their major importance, about the reliability of published indices (Flanagan, 1980; Eldworthy & Chelmick, 1980). Indices are subject to many limitations and it is the responsibility of the estimator to balance all factors and judge which index to use and the real significance of any single index number in the series. The RICS (1976) recommended that indices should not be taken too seriously, to the exclusion of common sense.

There are a number of indices produced in the technical press, from government departments and in builders price books. The quantity surveyor places a great deal of reliance on price indices as the basis for adjusting historical prices but their derivation is not always known and little is published about their accuracy. The following three tender price indices are accepted within the quantity surveying profession:

1. The DOE DQSS public sector building tender price index

This is compiled quarterly by the Director of Quantity Surveying Services and published in the Chartered Quantity Surveyor journal. It measures the changes in unit rates in accepted tenders for new public sector building works undertaken by the PSA (Property Services Agency) excluding those for housing, civil engineering, mechanical and electrical engineering, alterations and extensions. It is restricted to government projects and makes no allowance for changes in price additions (Tysoe, 1981).

2. The Davis, Belfield and Everest Tender Price Index

This is compiled by the Davis, Belfield and Everest Cost Information and Research Department and is published in the Architects' Journal and Spons Architects and Builders Price Book. It measures the level of pricing for the lowest public and private competitive tender based new projects undertaken in the London area. It includes new housing projects but not mechanical and electrical work.

3. The BCIS Tender Price Index

This is the copyright of the RICS, and is published by the Building Cost Information Service. It comprises a combination of public and private sector projects and measures the trend of tender prices for new building work. It does not however cover mechanical and electrical installations. It includes both firm price and fluctuating price contracts. The BCIS (1983) claimed that the methodology for their Tender Price Index Series has provided an accurate and effective measure of the variations in contractors' prices over time and the influences of economic conditions operating at the time in the competitive market. Morris (1979) claimed that the BCIS indices were the only ones to take account of market conditions, variations in different building types and alternative contract types. The BCIS does make a clear statement about the assumptions and methodology used.

The raw data cost analyses were updated to the 1st quarter 1984 using the BCIS (1983) fluctuating price adjusted project indices, because of the factor adjustments provided and their acceptability within the ESD. They were considered the most suitable tender price indices although M&E services were not included, the ESD felt that because no M&E tender price indices were available, the BCIS Tender Price Indices provided a best alternative option. The adjustment factors on labour and total costs were compounded with the tender price indices to provide current index figures for application to the labour factors and total costs.

4.4 Cost data variability

"There is no one price for a given building, but rather several prices according to a range of circumstances."

Flanagan (1980)

4.4.1 Large modern office developments are rarely repeated in their design and construction. Mechanical and electrical installations are invariably unique. Each installation is individually tailored to the requirements of the building, its shape, height, size, location, the design specification and the client's special requirements. It could be argued (Flanagan, 1980) that even if there were complete certainty with respect to unit rates and the factors which affect them, errors in cost prediction would be unavoidable because of the lack of essential design information at the early pre-tender estimating stages. Variations in costs are structured by the context in which each estimate was prepared. Numerous authors have attempted to identify the causes of cost variability and their associated uncertainties: Gates (1967), Fine & Hackemer (1970), Spooner (1974), Ashworth (1981), Skitmore (1981), Wilson (1982), Fine (1982) and Gibbons (1983). The quantity surveyor cannot, at present when analysing historical cost data, make quantitative adjustments for unpredictable factors such as sub-contractor disputes, defaults, contract litigations and the prior estimator's intuition and expertise. The task is made worse because estimators often identify different components as being cost significant (Wilson, 1982). Cost estimating is shrouded in the mystique of intuitive and expert judgement (Newton, 1982). Morrison and Stevens (1980) identified categories of data which were unpredictable and studied their behaviour. Beattie and Reader (1971) showed a number of methods by which uncertainty could be quantified within a project. Ashworth (1981) noted that a considerable variation in prices between apparently identical bill items, and Beeston (1975) produced a coefficient of variation of just under 4% for estimators tendering for the same project. Indeed, Wood (1975) showed that the variation of contract bids was in excess of 12% which, he suggested, meant that an accuracy of 10% was not obtainable from historical data.

In the real world costs tend not to be deterministic but should take account of the non-deterministic, unpredictable or random factors (O'Muircheartaigh & Payne, 1977). Price prediction, according to Morris (1979), is not a science and hence should not claim to be exact. At present, the RIBA Plan of Work (1980) requires feasibility statements in terms of cost ranges with quality indications and confirmation of the client's cost limit. Southwell (1968) stated that there was a latitude, a spectrum of prices, within which the estimator pitched his price. Beeston (1975) described a price for a component as existing within a large imaginary family of prices, and Smith (1985) indicated that ranges of costs were associated with elements and components, even within defined specifications. Morrison (1981) established a range of acceptable costs associated with design proposals. The problem for the estimator lies in the definition and combining of these cost ranges, to discover the reasons and quantitative values for the differences in cost. Since the raw data, within this research, contained few technical details other than the type of building, gross and net floor areas, height, location and types of installations, it was extremely difficult to isolate and determine all the variables affecting the costs. It was therefore decided that the M&E cost models should indicate the cost ranges rather than to produce linear algorithms and averages which disguise the true dispersions of the data. The shape of the dispersions needed investigating since within the profession there was some disagreement as to whether the data should be skewed. Smith (1985) and

Southwell (1968) suggested that ranges would be normally distributed, therefore the mean value would be representative of a cost estimate. Flanagan (1980), Beeston (1982) and Harmer (1983) predicted that the usual shape of a dispersion would probably be slightly skewed. The BCIS have shown in many of their studies, of average building prices, that peaked distributions occur with long 'tails' to the right of the peak. This, they implied, showed that the majority of building prices occur around the peak values but there was a possibility of some other factor affecting the cost. This shape of histogram emphasises that there is a natural lower limit on the costs, but the upper limits can be extended almost indefinitely by increased standards.

4.4.2 After collecting, formatting, defining, indexing and tabulating the raw data it was presented in the form of frequency diagrams or histograms. This gave a visual summary of the component data, its cost, labour and performance factors, revealing facts about the data that would require careful study to detect in the tabulated format. The shape of the histogram was characteristic of the variable measured. The frequency of any values of a variable was the number of times that value occurred in the data. Because of the wide ranges and lack of data for some components, it was useful to distribute data into classes or categories, to determine the frequency or class frequency. Although such grouping does result in the loss of detail, an advantage was gained from the clearer 'overall' picture which was obtained. The frequency distributions highlighted relationships. Harper (1982) stated that although grouping was well worth while, it may mean that calculations made from a grouped frequency distribution cannot be exact, but cost data is never exact, and consequently excessive accuracy can only result in spurious accuracy.

A procedure was adopted (Spiegel, 1976) to produce frequency distributions from the raw data.

1. The range was determined from the difference between the highest and lowest reported figures. This was an obvious method of measuring variability but it had the disadvantage of being sensitive to 'wild data' extremes.

2. The range was divided into a convenient number of class intervals having the same size. To avoid ambiguity class boundaries did not coincide with actual observations. For the purposes of analysis, all observations belonging to a given class interval were assumed to coincide with the class mark or class mid-point. Classes were usually dependant on the number of significant figures, decimal places and the number of observations. Great care was taken to lessen grouping error, however, when data was sparse or wide ranges were observed, detail was sacrificed to enable skewness of distributions to be observed.

3. The number of observations falling into each class interval was then recorded and plotted manually. Approximately 200 graphs were drawn and plotted manually to represent the cost, time and performance factors associated with each component.

4. Frequency polygons were then plotted to represent the frequency distributions. A frequency polygon is a line graph of the class frequency plotted against the class mark. The raw data within the research was considered to be continuous data, where all values were possible within the range. The area of the frequency polygon was equal to the area of the

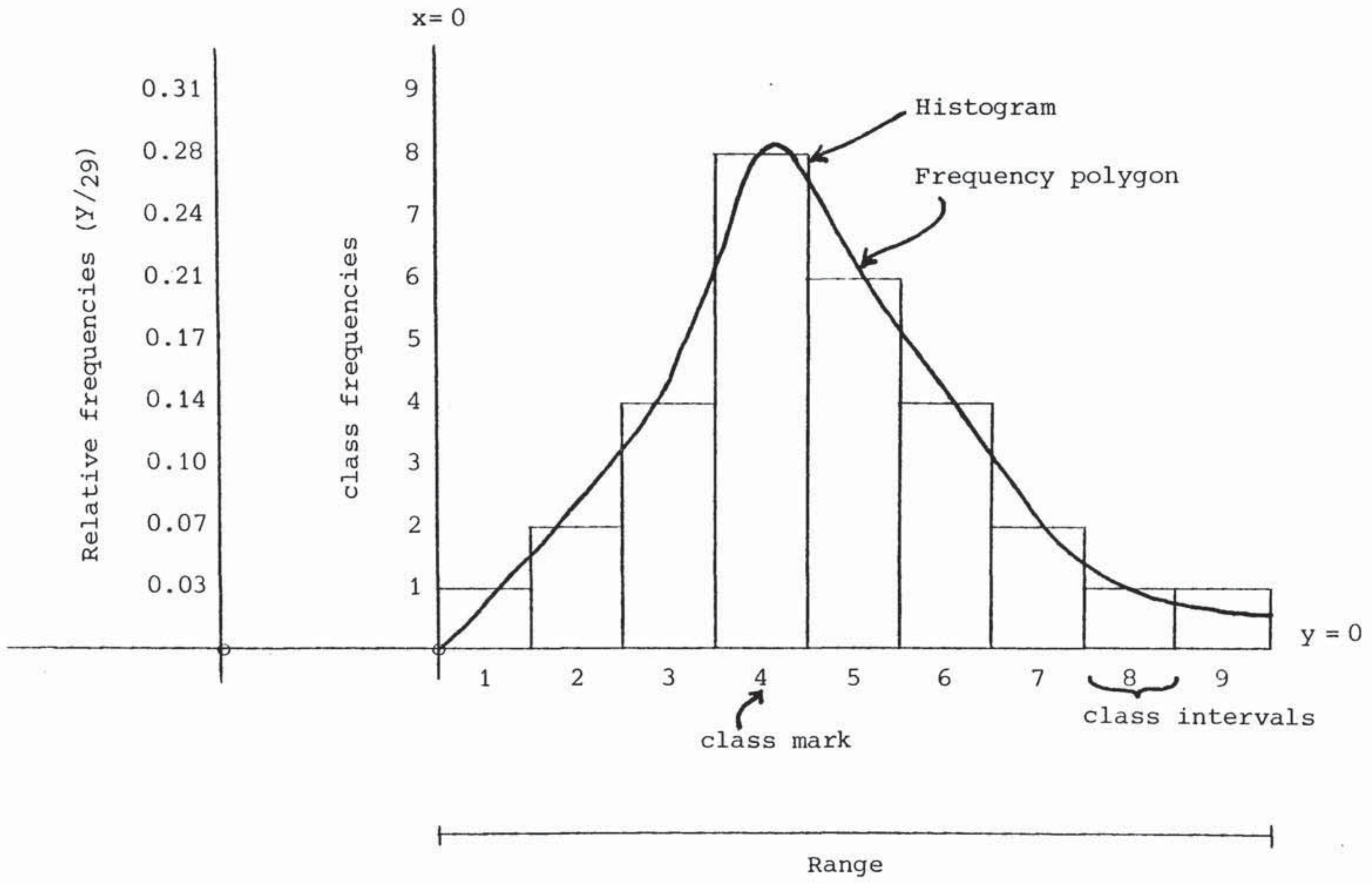
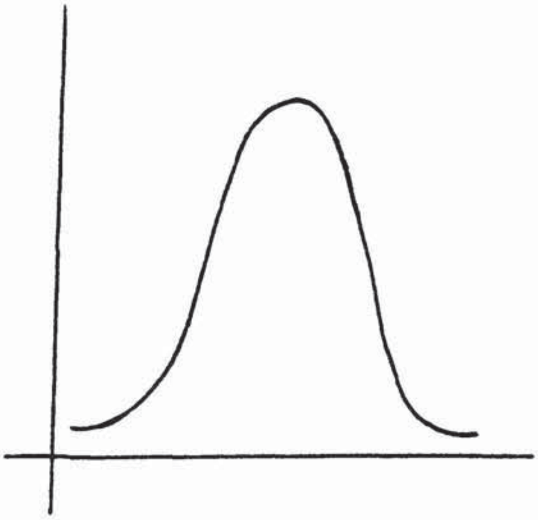


Figure 6.0 Frequency diagram

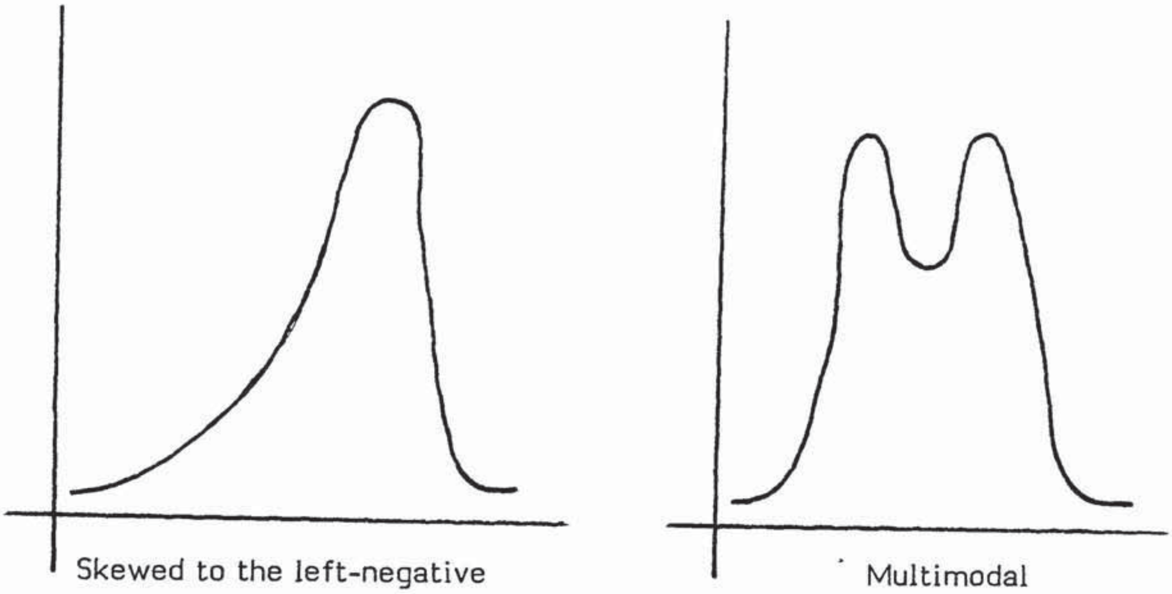
histogram, which was proportional to the frequency. Appendix 9.5 illustrates examples of the frequency polygons obtained from the historical raw data.

To avoid the difficulties associated with the comparison of two data sets of different sizes (the original data polygons and the VERT simulated polygons) due to the change of frequency height with size, these distortions were avoided by drawing relative frequency polygons. (The relative frequency of a class is the class frequency divided by the total frequency of all classes and is generally expressed as a percentage.) Graphical representation of the relative frequency distributions (RFD) was obtained from the frequency polygons by simply changing the vertical y-axis scale from frequency to relative frequency (see Figure 6.0 Frequency diagram). The total frequency of all values less than the upper class boundary of a given class interval is called the cumulative frequency up to and including the class interval. Cumulative frequency polygons can be smoothed to give cumulative frequency curves or ogives. The relative cumulative frequency or cumulative frequency density (CFD) is the cumulative frequency divided by the total frequency. The raw data frequency curves took on certain characteristic shapes:



Symmetrical or bell-shaped

Skewed to the right-positive



Skewed to the left-negative

Multimodal

Figure 7.0 Frequency curve shapes

4.4.3 Curves, where possible, were drawn to represent the sample data. Relative frequency curves can also be described through probability theory. The traditional definition of probability was defined by Phillips (1973) as 'the relative frequency of occurrence of an event after an infinite number of similar trials has occurred'. The use of probability distributions allowed the estimator to express uncertainty and quantify opinion. They provided more information on the associated risks involved with alternative courses of action (Beattie & Reader, 1971). Probability theory was used to express a degree of belief held by a person about some hypothesis, event or uncertain quantity. Within the research, they were used to express the estimator's opinion, in the light of the raw data frequency distributions, about uncertain component costs, labour factors and performance criteria. Phillips (1973) stated that statisticians of all persuasions agreed that human judgement was a necessary ingredient of statistical practice. The relationship between the probability distributions and the frequency distributions, which were used to describe the data, was that the estimated probability or empirical probability of an event was taken as the relative frequency of occurrence of the event. Probability distributions attempted to represent the overall distributions of all the M&E installations, if they were available, whereas relative frequency distributions were representations of the actual sample installations.

4.4.4 The relative frequency distributions were modified using opinion analysis to represent probability distributions. Interesting research (SERC, 1985) undertaken by a team of psychologists, surveyors, statisticians and programmers at Salford University, sponsored jointly by the SERC (Science and Engineering Research Council) and the university's Venture and Enterprise Fund, examined the influence of expertise in the early stages of cost estimating. They showed that the variability of estimates was based on expert opinion, and related the results to the estimating experience, recall abilities and confidence associated with each surveyor. Ferry (1980) suggested that the subjective building of distributions could be allowed provided that they could be justified by reason and sound professional judgement. Hawkins and Martin (1964) also examined subjective probability estimates. Spooner (1974) stated that although a lack of data appeared to prevent the handling of historical data in a quantitative fashion, it was possible to describe the qualities that could be expected in the form of probability density functions. Yeomans (1968) proposed that a combination of objective analysis and subjective commercial knowledge were more likely to produce estimates with acceptable margins of error than either approach used in isolation. Since the gathering of sufficient quantities of data for analysis was an obstacle within the research, a 'more realistic' assessment of the relative frequency distributions or probability distributions was achieved through the judgement, knowledge and experience of the senior surveyors within the ESD. The surveyors were presented with the original frequency distributions and were asked to amend the shapes of graphs to reflect their opinion about the raw data. Many distributions were not altered, curves were smoothed and most extreme values questioned and checked against the original project details. Through discussion, some were revised to reflect the ESD's considered opinion, although surveyors were reluctant to alter the raw data, they readily commented on the position of the peaks with relation to the range. In time, the probability distributions specified were considered to adequately reflect the ESD's subjective uncertainty about the values that may occur for the parameter being estimated. This modelling of judgement was a good way of transferring the senior estimators expertise and gave an insight into the factors involved in judgement. It was important that the full degree of uncertainty was shown, that the curves were based on the raw data provided and 'wild data' which were possible solution values, were not omitted. The distributions did not reduce uncertainty, which was already present in the raw data, but gave a full appreciation of its existence.

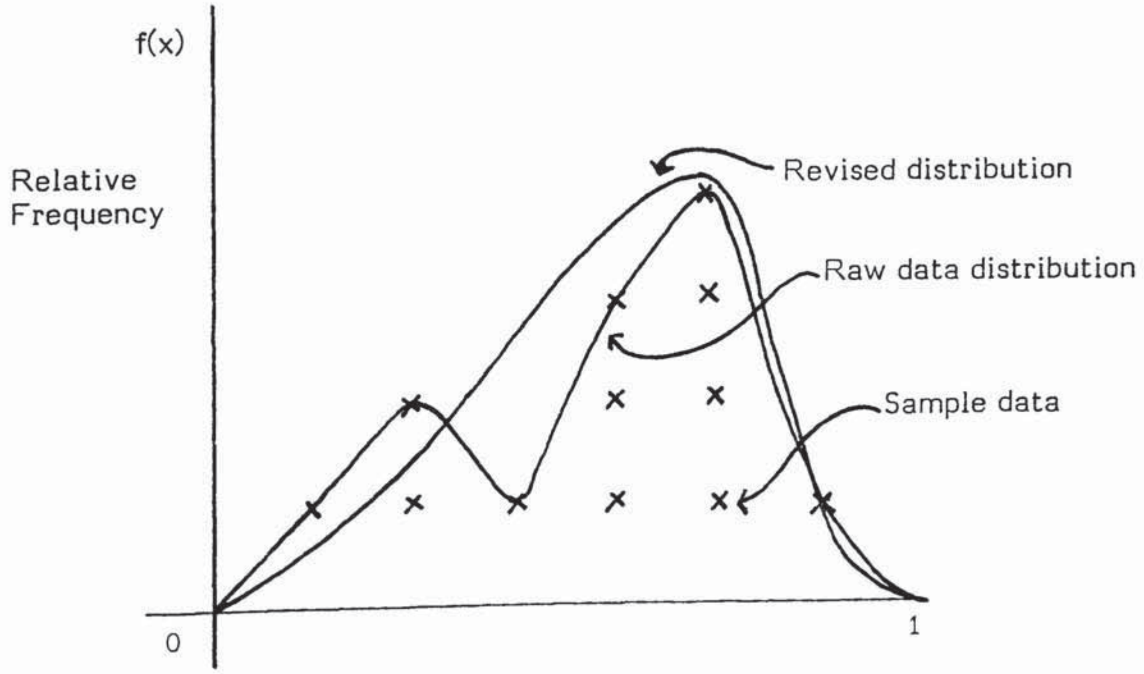


Figure 8.0 Revised frequency distribution

4.4.5 Three types of distributions were identified from the research data. Uniform distributions, which had the advantage of finite ranges and the disadvantage of assigning equal probabilities to all the variables in the ranges. These were used where data was evenly spread throughout the range and when the values contained a high degree of risk. Triangular distributions were selected to describe data which was spread over the full range but where some clustering occurred around a particular value. These again were used where the data was scarce, opinions low and risk was high. Thirdly, Beta distributions, where the probability of an occurrence of an event decreased non linearly. Significant attention was paid to the selection of the correct Beta probability function, to describe the variability of cost, time and performance variables. Many authors (Gates, 1967; Johnson & Kotz, 1970; Spooner, 1974; Johnson & Montgomery, 1974 and Flanagan, 1980) have recommended the use of Beta distributions.

4.4.6 The Beta distribution is closely related to the binomial; it results when the binomial parameter is turned into the beta variable, and the binomial variable becomes one of the two parameters (p,q) of the beta distribution. These parameters (p,q) need not be integers but when they are, cumulative beta probabilities may be obtained directly from the tables of the cumulative binomial distribution using the relationship:

$$F_\beta\ (x/p,q) \ = \ R_B\,(X/n - 1\ ,\ p) \quad \text{for } x \leqslant 0.5$$

$$F_\beta\ (x/p,q) \ = \ 1 - R_B\,(n - X/n - 1\ ,\ 1 - p) \quad \text{for } x \geqslant 0.5$$

Ullman (1976)

When p and q are not integers, cumulative beta distribution tables can be used (Pearson, 1968). Appendix 9.6 i) illustrates the formulation of the Beta distribution from the Bernoulli or binomial distribution.

VERT defined the Beta distribution as:

$$F(x) = \frac{G(A + B)x^{A-1} (1 - x)^{B-1}}{G(A)\, G(B)}$$

where $A = p > 0$

$B = q < 0$

G = gamma function Γ

X = the range where $0 < x < 1$

therefore:

$$F(x) = \frac{(q + p - 1)!}{(p-1)!\,(q-1)!} \quad X^{P-1} (1 - x)^{q-1}$$

The Beta distribution can also be related to the chi-square and gamma distributions (Lloyd, 1980) and the rectangular, Pascal, Poisson and Normal distributions (Ullman, 1976). Appendix 9.6 ii) shows the statistics of the Beta distribution.

The use of the Beta distribution allows for non-symmetrical probabilities to be examined as distributions can be U-shaped, uniform, bell-shaped or asymmetrical bell-shaped. Figure 9.0 illustrates examples from the Beta family distributions. The bell-shaped and asymmetrical bell-shaped distributions were used predominantly in the research. Phillips (1973) supplied a pictorial appendix on Beta density functions (see Figure 10) for modes 0.5 - 0.9. These were used to identify suitable prior distributions in this research. Curves of modes less than 0.5 were mirror images of those supplied, for example, mode 0.3 was the mirror image of mode 0.7 about 0.5 on the x-axis. It was noted that as p and q became larger, the distributions became more peaked. When p and q were unequal in value, the distribution was skewed to the left or to the right. The relative frequency

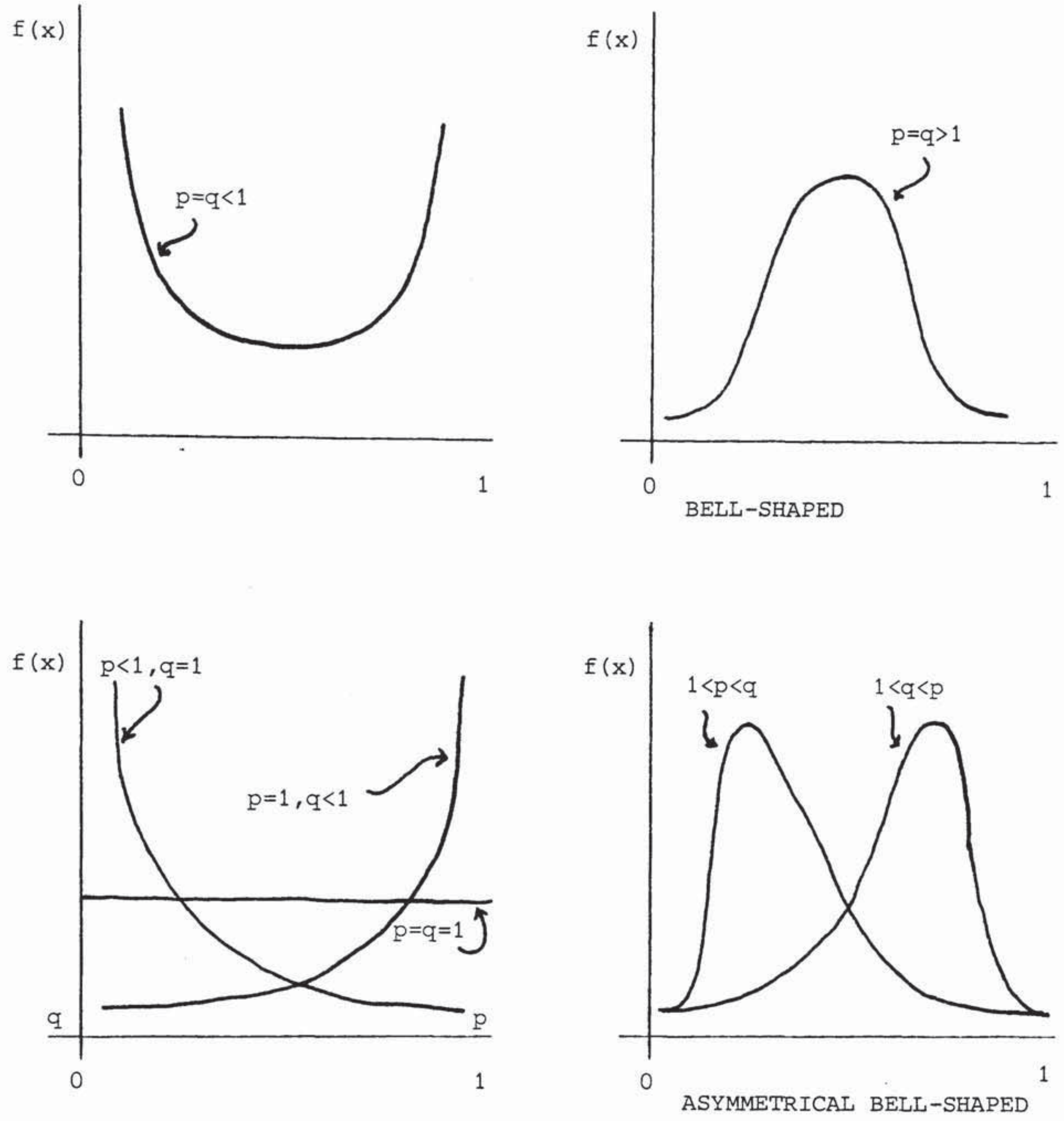


Figure 9.0 Beta family distributions. Larson (1982)

distributions were normalised for comparison with the beta density functions, by adjusting the x-axis, so that the area under the curve was equal to one unit (Ullman, 1976). The degree of certainty could then be measured by the area under the curve rather than the height of the curve. The lines at the bottom of the graphs indicate intervals of equal area, for example, for mode 0.5 p = 1 q = 1 a third of the data lies between 0 and 0.33 on the x-axis, a third between 0.33 and

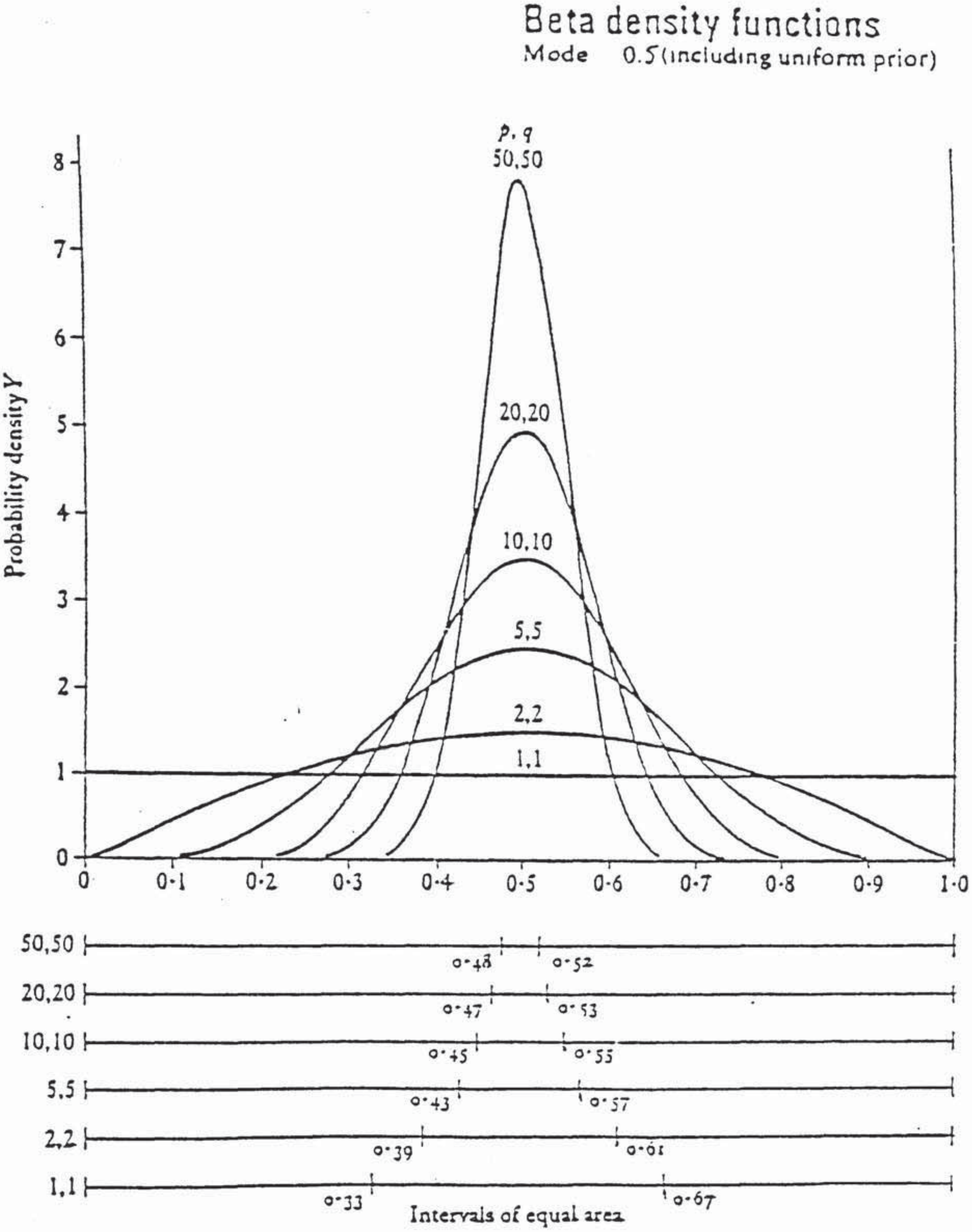
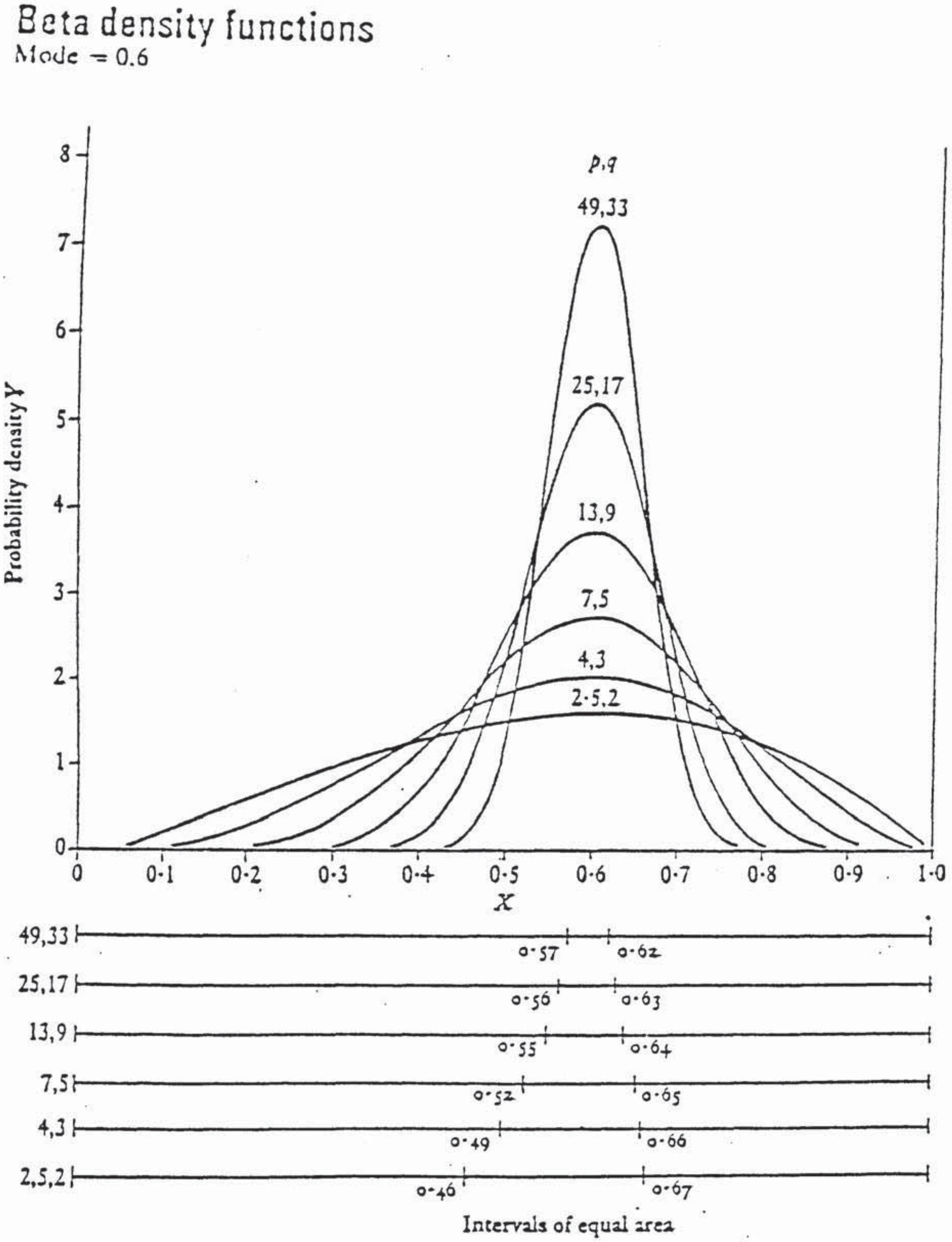


Figure 10 Beta density functions (1)
(Phillips, 1973)



Beta density functions
Mode = 0.6

Figure 10 Beta density functions (2)

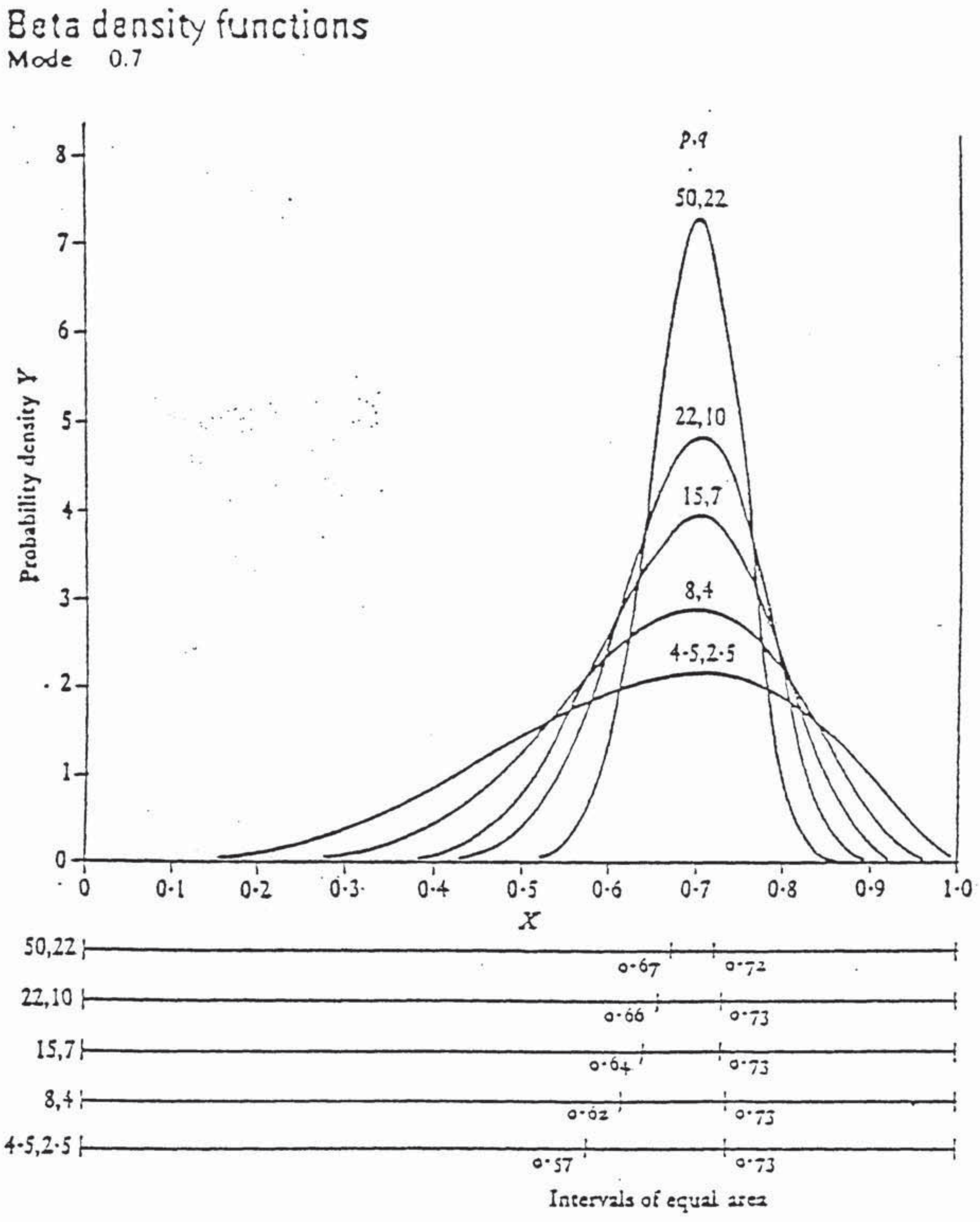


Figure 10 Beta density functions (3)

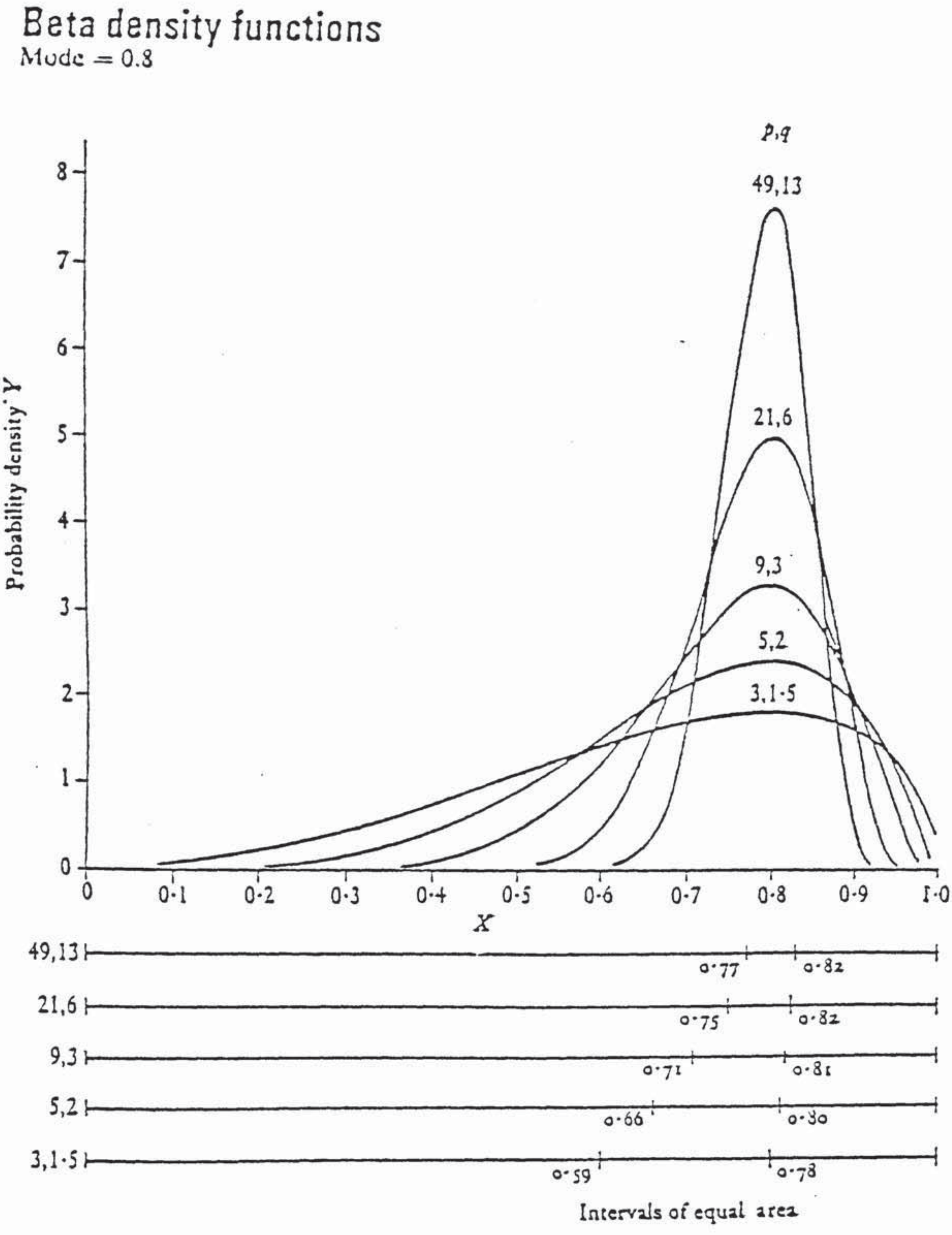


Figure 10 Beta density functions (4)

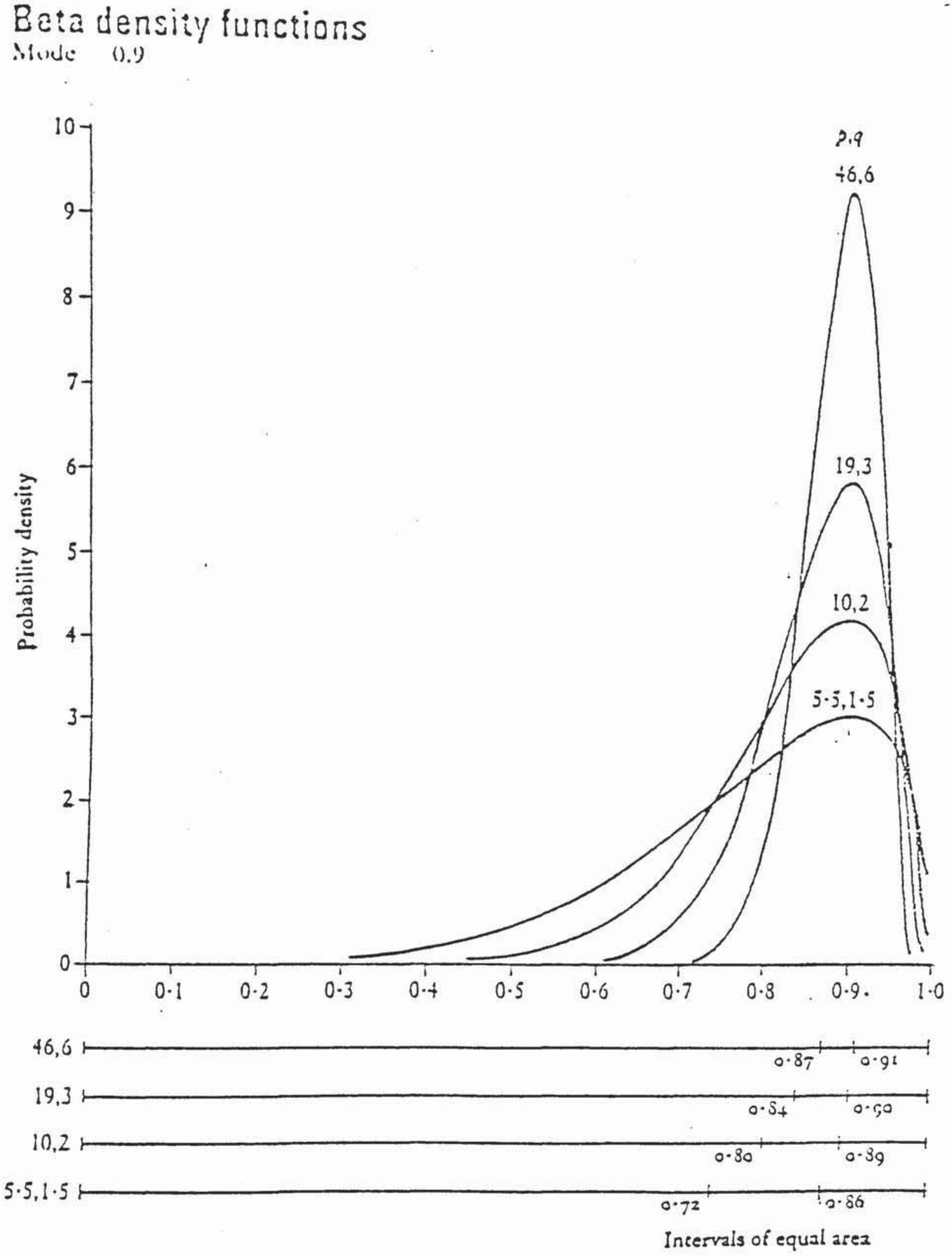


Figure 10 <u>Beta density functions</u> (5)

0.67, and the remaining third between 0.67 and 1.00. They are intervals of equal credibility. The relative frequency distributions were used to select the appropriate beta density function by the assessment of the mode and the equal credibility intervals. An alternative method was used to check that an appropriate distribution had been selected from the statistics of the beta distribution since:

$$\overline{X}_\beta = \frac{P}{p + q} = \text{mean}$$

$$\sigma 2_\beta = \frac{p\,q}{(p + q)^2\,(p + q + 1)} = \text{variance}$$

Derman (1978) showed that:

$$p = \overline{X}_\beta \left[\frac{(\overline{X}_\beta)\,(1 - \overline{X}_\beta)}{\sigma^2{}_\beta} \quad -1 \right]$$

and

$$q = (1 - \overline{X}_\beta) \left[\frac{(\overline{X}_\beta)\,(1 - \overline{X}_\beta)}{\sigma^2{}_\beta} \quad -1 \right]$$

where $0 \leqslant x \leqslant 1$.

As an example the beta approximation to the normal density function, mode 0.5, was selected to test this approach, where $p = 5$ and $q = 5$. For the normal distribution 34.135% of the data lies in one standard deviation from the mean. This is approximately equal to a third, the credibility interval is approximately equal to $0.1508 \hat{=} s$

since $\sigma^2 = s^2$ where σ^2 = variance

$= 0.0227$

$\overline{X} = 0.5$ where $\overline{X}$ = mean.

$$p = 0.5 \left[\frac{(0.5)(1 - 0.5)}{0.0227} - 1 \right] = 5.0$$

since $\overline{X} = 1 - \overline{X} = 0.5$ $p = q = 5.0$.

Therefore the alternative method could be used to check that the appropriate beta distributions had been selected to represent the frequency distributions.

Revision of these prior distributions can be made through the application of Bayes Theorem, which proposes that the probability of a certain event may change and may need to be revised as further information is obtained (Vazsonyi, 1977). An argument against Bayesian ideas is that prior opinion is vague and incapable of being quantified. I recognise this but felt that this merely reflected the problems associated with the cost analysis of mechanical and electrical services, and without prior statements on which to build, no posterior opinion could be formulated, systems could not be developed. The only difference between prior and posterior probabilities is the amount of data on which they are based. If the posterior or future cost frequency distributions belong to the beta family, which I suggest, then the prior parameter can be simply changed to the posterior parameters where:

$p'' = p' + \bar{s}$

$q'' = q' + \bar{f}$ Phillips (1973)

$N = \bar{s} + \bar{f}$ = the number of observations

$\bar{s}$ = the number of successes

$\bar{f}$ = the number of failures.

The posterior will probably be more peaked and less broad than the prior distributions, as it is possible to reduce the spread of costs when homogenity is improved (Flanagan, 1980). However, because the Beta family of distributions is so flexible, if a radical change occurred, p and q could be altered accordingly. Bayesian concepts provide the means for building in subsequent information to modify estimates of probabilities (Magee, 1964 and O'Muircheartaigh & Payne, 1977).

5.0 EXPERIMENTAL RESEARCH

5.0 Experimental research

This chapter examines the programming procedures required by the Venture Evaluation and Review Technique (VERT) for the production of the resultant output. A decision tree diagram was produced, from the cost analyses and component definitions, to structure the possible mechanical and electrical design alternatives and then coded using the VERT logic operands. The simulation process is outlined and the resultant output formats available to the VERT user. The VERT-4 program has a comprehensive array of logical, statistical and mathematical features which made it possible to stochastically model and analyse the M&E estimating process. The user/analyst manual, Moeller and Atzinger (1983)[2], developed by Venture Analytical Associates, Incorporated, provided sufficient description and instruction to successfully complete the modelling. As VERT-4 was written initially for the IBM 360/65 computer in Fortran level five, it is essentially a batch-oriented system. It was adapted for use on the VAX/VMS operating system at Aston University's computer centre (refer to 6.0) and communicated using the Digital Command Language (DCL).

The VERT-4 user/analyst manual recommended seven process steps to succeed in the production of an analytical model:

(1)	Step 1	Definition of the decision situation: The components, installations and element inter-relationships were defined.
(2)	Step 2	The development of a generalised network flow diagram: A decision tree was used to represent the alternative design installations available for both mechanical and electrical services.

(3)	Step 3	The collection of the raw data: Thirty-five office developments were collected, defined, analysed, formatted, adjusted, indexed and characterised in the form of probabilistic distributions.
(4)	Step 4	The development of the VERT-4 network: This chapter outlines the networking procedure, the programming operands available to the user, the process of Monte Carlo simulation and the possible outputs.
(5)	Step 5	Exercise the simulation: A 500 iteration simulation was completed and the resultant output formats examined.
(6)	Step 6	The analysis of the results: Chapter 6 undertakes model verification, validation and parameter tests. Heuristics were used to test the applicability of the results.
(7)	Step 7	Documentation of the findings and recycling of the processes: Further research is discussed in Chapter 7.

Figure 11.0; The research operation diagram, illustrates these process steps with regard to this research. Steps 1 and 3 have been completed in Chapter 4.0. This chapter undertakes steps 2, 4 and 5.

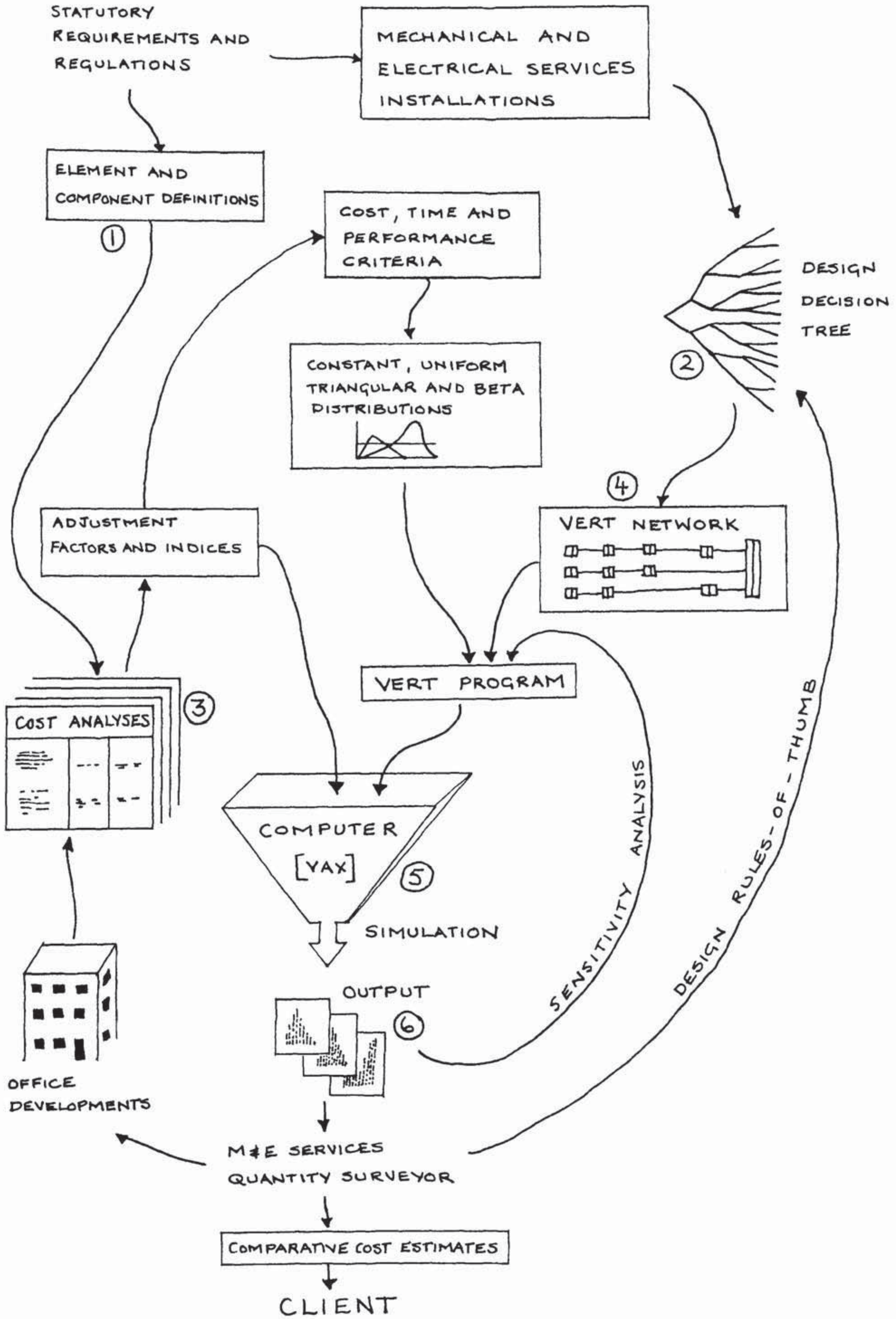


Figure 11.0 Research operation

5.1 Network design

5.1.1 VERT was used to symbolically model the 'real-world' pre-tender mechanical and electrical estimating procedure. A decision tree diagram (Meidan, 1981) was employed to evaluate the alternative design solutions available to the quantity surveyor and to reflect the probabilities of each type of installation for selection. The component definitions (Appendix 9.3) were used to determine the element-component interrelationships. The formulation of the pictorial diagram required considerable knowledge of the installation types and their components, and was based on the probabilities contained in the historical data. The VERT operands were then used to convert the decision tree diagram into a generalised flow network.

The generalised flow network employed two basic symbols to structure the estimating model, nodes or decision points (rectangles or squares) and arcs (lines). The arcs represented the coded components and contained, within VERT, two sets of information: the primary and cumulative data. The primary information set contained the component cost data, labour factor and performance distributions. The cumulative information set contained all the accumulated raw data information processed by the VERT program, prior to the particular arc being examined. The nodes regulated the flow of the information into the arcs and carried the cost, time and performance data from the input to the output nodes. They represented decision points within the network, where input arcs were processed by the node logic and output arcs were generated according to the node logic. The research employed nodes that expressed a split input/output logic. Several authors (Lee, Moeller & Digman, 1982; Barrett, 1982 and Moeller & Atzinger, 1983[2]) have explained the input and output logics required to produce the generalised flow network.

5.1.2 The following section details the input and output logics used in the research so that the reader can interpret the final mechanical and electrical services network (5.1.4). Prior to the selection of the final network, a successful pilot study was undertaken, using a single element (Public Health) to assess the VERT mechanism.

Input logics:

INITIAL - This acted as the starting point for all the element sub-networks, with the time, cost and performance information valued at zero.

AND - This logic required the successful completion of all incoming arcs to be processed and recorded before distributing the information to the output logic.

PAND - Partial AND acted similarly to the AND logic except that only one successful incoming arc was required, although all incoming arcs must have reached the node, for the process to continue.

OR - This logic required only one successful incoming arc to be processed before immediately transferring the information to the output logic.

Output logics:

ALL - This simultaneously initiated all the output arcs.

MC - Monte Carlo logic, where arcs were initiated randomly according to their probability of success. An arc would be completely processed if selected, and the unsuccessful alternatives were ignored. For example, Element 4: Heating, radiators (RADS) may have been the only successful installation, all others would not have been initiated.

TERMINAL - The final logic where there were no output arcs and all the processed information was collected.

FILTERS 1, 2 and 3, and the four unit logics COMPARE, PREFERRED, QUEUE and SORT were not used within the research (refer to section 7.0).

5.1.3 Component definitions (Appendix 9.3) were coded for arc referencing, for example RADS: radiators, LEQUIP: loose fire fighting equipment and HLIFT: hydraulic lifts. Node codes were used for programming and to indicate choice decision points within the network, for example, DRK/CLN: where having already selected whether drinking fountains were to be included in the estimate, a choice was to be made as to whether to have cleaners sinks, and ELEMENT 7: where there was a choice between having an electric or hydraulic lift or no lift at all.

5.1.4 Figure 12.0 illustrates the mechanical services network and Figure 13.0 the electrical services network. They were combined to form the whole VERT network, which considered all the possible M&E installations possible from the historical office developments. The arcs were determined as follows:

i) The nodes ELEMENT 1 (sanitary fittings), ELEMENT 2 (cold water installations), ELEMENT 3 (hot water installations), ELEMENT 4 (heating including air-conditioning), ELEMENT 5 (ventilation), ELEMENT 6 (fire fighting

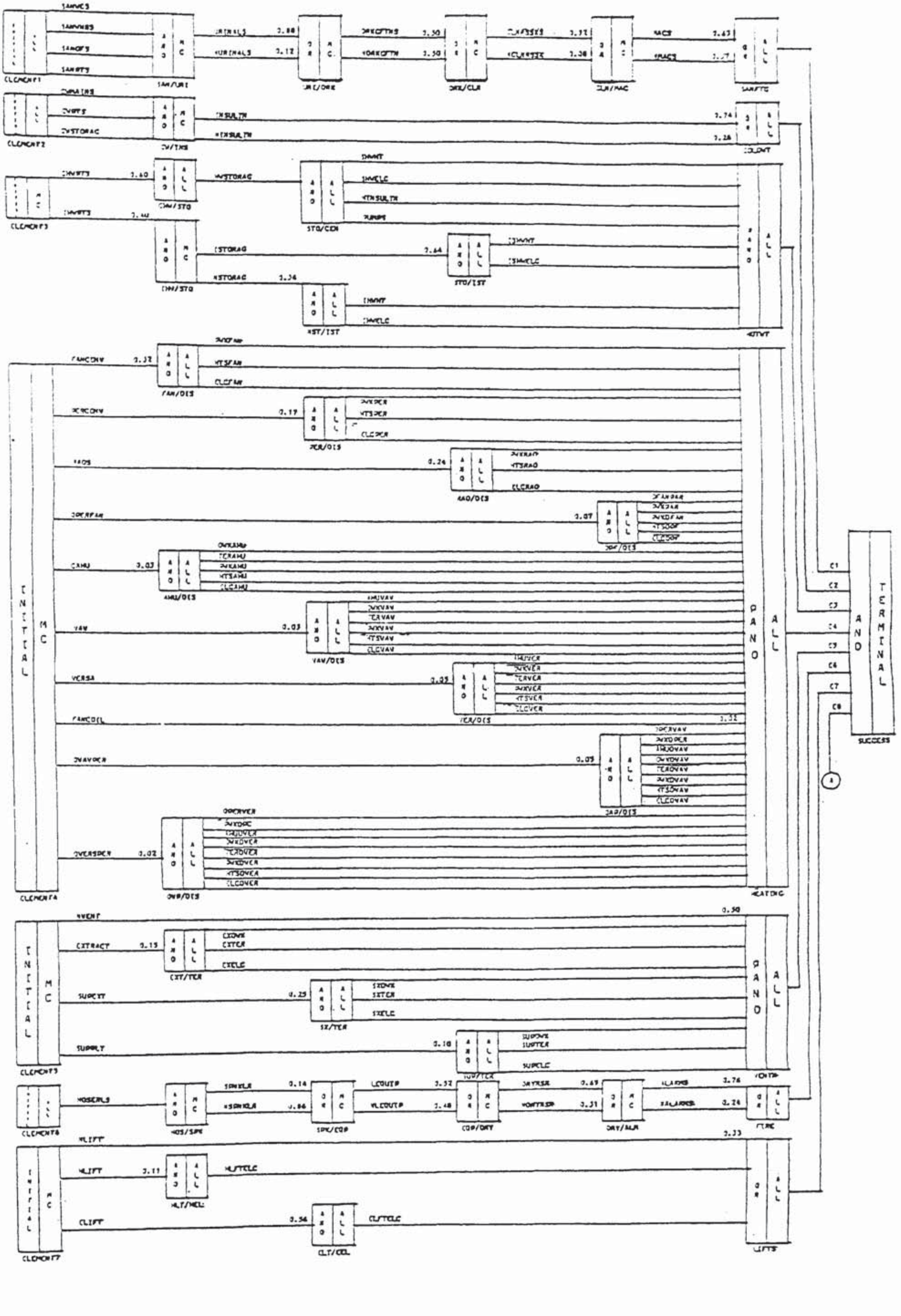


Figure 12.0 Mechanical services network

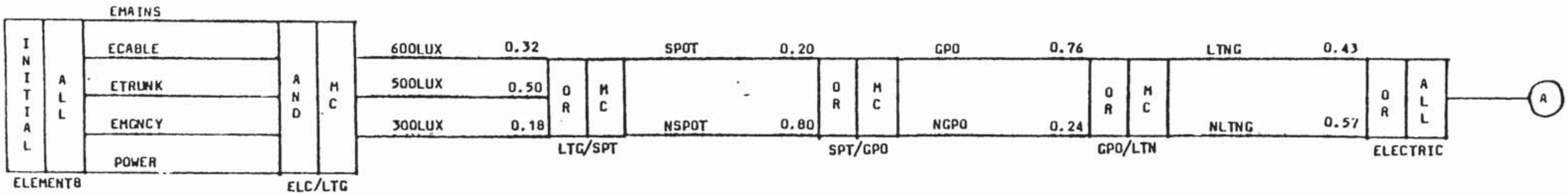


Figure 13.0 Electrical services network

protection), ELEMENT 7 (lifts) and ELEMENT 8 (electrical installations) were all initiated with zero values in all the time, cost and performance information sets.

ii) In ELEMENT 1, water closets (SANWCS), wash hand basins (SANWHBS), overflows (SANOFS) and sanitary points (SANPTS) were all compulsory processed arcs. The cumulative data was collected at the node SAN/URI, where there was then a successive choice of sanitary fittings: urinals (URINALS), drinking fountains (DRKGFTNS), cleaners sinks (CLNRSSKS) and macerators (MACS) which were dependent on the Monte Carlo probabilities assigned to each arc. The total cost, time and performance data relating to element 1, sanitary fittings was collected at node SANFTG.

iii) In ELEMENT 2, cold water mains (CWMAINS), cold water points (CWPTS) and cold water storage (CWSTORAG) were all compulsory processed arcs. The cumulative data was collected at the node CW/INS where there was then a choice of including cold water insulation (INSULTN) within the estimate. Not all projects allowed for cold water insulation, which should be kept separate within the estimate because it may well be undertaken by a specialist sub-contractor and would incur different mark-up percentages. The total cost, time and performance data relating to element 2, cold water installations was collected at node COLDWT.

iv) In ELEMENT 3, there was an immediate choice between centralised hot water points (CHWPTS) and instantaneous hot water points (IHWPTS) depending on the Monte Carlo assigned probabilities. If the centralised hot water installation was selected nodes CHW/STO and STO/CEN initiated the compulsory components: hot water storage (HWSTORAG), hot water insulation (HINSULTN) again kept separate because the work may be undertaken by a specialist sub-contractor, hot water pumps (PUMPS), a centralised hot water heat source (SHWHT) and electrical work in connection (SHWELC). If the decentralised or instantaneous hot water installations were selected the node IHW/STO then gave the choice between storage instantaneous hot water (ISTORAG) and non-storage hot water (NSTORAG) depending on the Monte Carlo assigned probabilities. Nodes STO/IST and NST/IST initiated the compulsory associated heat sources (ISHWHT and IHWHT) and electrical work in connection (ISHWELC and IHWELC) with the appropriate installation type. The total cost, time and performance data relating to element 3, hot water installations was collected at node HOTWT.

v) In ELEMENT 4, there was an immediate choice between fan convectors (FANCONV), perimeter convectors (PERFONV), radiators (RADS), dual perimeter and fan convector systems (DPERFAN), centralised air handling unit air-conditioning (CAHU), variable air volume (VAV), Versatemp (VERSA), fancoil (FANCOIL), dual variable air volume and perimeter convector systems (DVAVPER) and dual Versatemp and perimeter convector systems (DVERSPER) depending on the Monte Carlo assigned probabilities. Whichever installation was selected the appropriate nodes FAN/DIS, PER/DIS, RAD/DIS, DPF/DIS, AHU/DIS, VAV/DIS, VER/DIS, DAP/DIS and DVP/DIS were used to combine the compulsory distribution information associated with each installation type. Fan convectors required a pipework component (PWKFAN), a heat source component (HTSFAN) and an electrical work in connection component (ELCFAN). Perimeter convectors required a pipework component (PWKPER), a heat source component (HTSPER) and an electrical work in connection component (ELCPER). Radiators required a pipework component (PWKRAD), a heat source component (HTSRAD) and an electrical work in connection component (ELCRAD). The arc DPERFAN measured the perimeter convectors and arc DFANPAR measured the fan convectors for the dual system, which also required pipework in connection with the perimeter convectors (PWKPAR), pipework in connection with the fan convectors (PWKDFAN), a heat source component (HTSDPF) and an electrical work in connection component (ELCDPF). The centralised air handling unit air-conditioning installation required a ductwork component (DWKAHU), a terminals component (TERAHU), a pipework component (PWKAHU), a heat source component (HTSAHU) and an electrical work in connection component (ELCAHU). The variable air volume installation required a centralised air handling unit (AHUVAV), a ductwork component (DWKVAV), a terminals component (TERVAV), a pipework component (PWKVAV), a heat source component (HTSVAV) and an electrical work in connection component (ELCVAV). The Versatemp system required a centralised air handling unit (AHUVER), a ductwork component (DWKVER), a terminals component (TERVER), a pipework component (PWKVER), a heat source component (HTSVER) and an electrical work in connection component (ELCVER). The fancoil system (FANCOIL) was considered a complete installation as no further detailed information was available within the raw data. The DVAVPER arc measured the variable air volume units and the arc DPERVAV measured the perimeter convectors for the dual system, which also required pipework in connection with the perimeter convectors (PWKDPER), an air handling unit (AHUDVAV), a ductwork component (DWKDVAV), a terminals component (TERDVAV), a pipework in connection with the variable air volume units component (PWKDVAV), a heat source component (HTSDVAV) and an electrical work in connection component (ELCDVAV). The DVERSPER arc measured the Versatemp units and the arc DPERVER measured the perimeter convectors for the dual system, which also required pipework in connection with the perimeter convectors (PWKDPC), an air handling unit (AHUDVER), terminals (TERDVER), a ductwork component (DWKDVER), pipework in connection with the Versatemp units (PWKDVER), a heat source component (HTSDVER) and an electrical work in connection component (ELCDVER). The total cost, time and performance data relating to element 4, heating installations, was collected at node HEATING.

vi) In ELEMENT 5, there was an immediate choice between extract (EXTRACT), supply (SUPPLY) supply and extract (SUPEXT) and no ventilation (NVENT) at all, depending on the Monte Carlo assigned probabilities. Attached to the three ventilation installations there were compulsory arcs signified at nodes EXT/TER, SX/TER and SUP/TER: ductwork components (EXDWK, SXDWK and SUPDWK), terminal components (EXTER, SXTER and SUPTER) and the electrical work in connection components (EXELC, SXELC and SUPELC). The total cost, time and performance data relating to element 5, ventilation installations was collected at node VENTN.

vii) In ELEMENT 6, hosereels (HOSERLS) was a compulsory processed arc. After node HOS/SPK there was a successive choice of fire protection installations: sprinklers (SPNKLER), loose equipment (LEQUIP), dry risers (DRYRSR) and fire alarms (ALARMS) which were dependent on the Monte Carlo probabilities assigned to each arc. The total cost, time and performance data relating to element 6, fire protection installations was collected at node FIRE.

viii) In ELEMENT 7, there was an immediate choice between hydraulic lifts (HLIFT), electric lifts (ELIFT) and no lifts (NLIFT) at all, depending on the Monte Carlo assigned probabilities. Attached to the two lift installations there was a compulsory arc signified at nodes HLT/HEL and ELT/EEL for the electrical work in connection with the installation (HLFTELC and ELFTELC). The total time, cost and performance data relating to element 7, lift installations was collected at node LIFTS.

ix) In ELEMENT 8, electrical mains (EMAINS), electrical cables (ECABLE), electrical trunking (ETRUNK), emergency lighting and power supplies (EMGNCY) and small power supplies (POWER) were all compulsory processed arcs. The cumulative data was collected at node ELC/LTG, where there was then a choice of light fittings for 600 Lux, 500 Lux and 300 Lux illumination after which there was a successive choice of electrical installations: spot lighting (SPOT), telephone installations (GPO) and lightning protection (LTNG) which were dependant on the Monte Carlo probabilities assigned to each arc. The total cost, time and performance data relating to element 8, electrical installations, was collected at node ELECTRIC.

x) The SUCCESS node was used to collect all the element total costs, times and performance data for an overall estimated cost for mechanical and electrical installations.

NOTE: Reference should be made to the component definitions (Appendix 9.3) for a full understanding of the composition of the coded arcs.

5.2 VERT programming

To load the network into the VERT-4 program required the use of three data modules - the control and problem options module, the arcs module and the nodes module. These were used to describe the network, the options required, how the data was to be processed, all the component distributions and the inter-relationships between the arcs and nodes.

5.2.1 The control and problem options module specified the installations and the various options available. To provide assistance in structuirng the input data an

80 column Fortran coding form was used for the spacing of each input record. When a line of data was recorded this was then loaded into the program. The control and problem options module required the following input data:

Column : 1 The problem identification option. The value 1 was entered into the first column so that the title 'Mechanical and Electrical Services' could be inserted after the control record.

2 The type of input option. The network was a complete stand-alone problem and was placed on the master file as a new master problem, requiring a zero or blank to be placed in the second column.

3 The type of output option. The output options were grouped together under three major running modes which were debug, the high information and the fast computation modes. A value of zero or blank entered into this field allowed the initial checks on the running of the program. Option 3, the high information output option was selected as the most useful output for the quantity surveyor. This output was in the form of a one line listing of the winning terminal node's time, cost and performance values observed during each simulation iteration, a listing of the winning terminal node index plus an arc and node critical path index, a one page listing of the a) relative frequency distribution, b) cumulative frequency distribution (ogive), c) mean observation, d) standard error or sample standard

deviation, e) the coefficient of variation, f) the mode, g) the beta 2 measure of kurtosis, h) the Pearsonian measure of skewness and also the inclusion of the median for the internal nodes, intervals between internal nodes, node and arc slack times and cost-performance time intervals.

4 The available cost and performance computational variations. VERT-4 was structured to value fully or partially the cost and performance generated on the arcs that were partially completed. Options 2, 3 and 5 were selected for the network, requiring a 2 to be entered in this field. This option requested that partially completed activities should be partially valued, the cost and performance values of unprocessed arcs should be pruned and common activities should be singularly counted.

5 The full print trip option. A value of 1 was entered into this column requiring a record to be entered, following the problem identification record, which carried the name of the print triggering arcs. When these arcs were active the program listed all the arcs and nodes that were active during the given iteration. The heating components were chosen to examine the relationship between the total cost and heating installations selected.

6 Correlation computation and plot option. To obtain the terminal node correlation and plot combination of the overall cost against performance, a 1 was placed in this field.

7 Cost-performance time interval option. A zero was placed in this field as this option aids management in the budgeting process where critical periods of time are assigned to the project. This was considered unnecessary at the present. When a zero was entered the program used the observed minimum and maximum distribution values to construct the histograms.

8 Composite terminal node minimum and maximums option. Again this record, which provides a scale for structuring the composite terminal node histograms was considered unnecessary. Observed values during the simulation were sufficient, so a zero was entered in this column.

9-10 Composite terminal node output option. Two zeros were entered in these fields to indicate that time, path cost, overall cost and performance values were all desired for the composite terminal node.

11 80/80 listing of input records. An entry of 1 in this field suppressed the listing of all the input records following the control record.

12 Listing the nodes by their mean time value. A list of nodes in an ascending mean completion time order was considered important when analysing the network internal node print-outs; a 1 was therefore inserted in this column.

13-22	Seed. This field was used to select the seed of the two uniform random number generators structured within VERT. A number of 765432 was entered into this field so that different simulations could be compared.
23-27	Number of iterations. When the debug mode was run, 15 was entered into this field which were required to identify in sufficient detail any flow and parameter errors. When the programming was complete 500 iterations were recommended by the program so 500 was inserted in this field.
28-31	Inflation rate. At the time none of the data input required inflating so the field was zeroed. The model represented costs for the 1st quarter 1984, however if a suitable index percentage were used the historical data could be updated as required.
32-35	Discount rate. This field could be used to enter a yearly interest rate used to discount the data input. None of the research data required discounting, so this field was zeroed.
36-38	Time converter to a yearly base. A time factor could be entered in this field to convert the program time factors to a yearly basis to aid in budgeting, interest calculations and inflation. This function was not required, therefore a zero was entered.

39-41	Time weight for winning terminal node selection. Since there was only one terminal node, a zero was entered into this field.
42-44	Cost weight for winning terminal node selection. Since there was only one terminal node, a zero was entered into this field.
45-47	Performance weight for winning terminal node selection. Since there was only one terminal node, a zero was entered into this field.

NOTE: The following three fields had positive values assigned to them which resulted in the selection of the critical path as the path with the longest time, largest cost and the lowest performance values.

48-50	Time weight for critical path selection. A zero was entered into this field.
51-53	Cost weight for critical path selection. A 1 was entered in this field as the cost was the main criteria for the quantity surveyor. The critical path was therefore the highest cost route.
54-56	Performance weight for critical path selection. A zero was entered into this field.

57-64 Network start-up time. Zero was entered into this field to indicate that the model was for a new development. Zero was therefore assigned to all initial nodes for time.

65-72 Costs incurred prior to network start up time. No costs were incurred therefore zero was entered.

73-80 Performance generated prior to network start-up time. No performance criteria were assigned to all the initial nodes therefore zero was entered.

The problem identification option:

Columns 1-80 The title of the program output was recorded 'Mechanical and Electrical Services'.

The full print trip option:

Columns 1-8 Node and arc requested print. The names of all the heating arc options were printed resulting in a full printout of all the active arcs and nodes observed during each iteration. This resultant printout determined under what set of circumstances, or what components caused the resultant total costs within the model. The maximum of ten arcs were listed in fields of eight columns.

Correlation computation and plot option record:

Columns 1-2 Codes were provided within the VERT manual to request a two dimensional plot for the terminal node SUCCESS. The code numbers for overall cost (3) and performance (4) were entered to see if there was a geometric pattern or relationship between these two variables. Also time (1) and overall cost (3) were requested to see if a generalised labour : material ratio could be adopted for services installations.

Cost-performance time intervals option: This was not required at present due to the discontinuity of the labour factors.

Composite terminal node minimums and maximums option:
These fields were zeroed allowing the program to select the minimum and maximum values observed during the simulation to model the histograms.

5.2.2 The master arcs module was used to enter the distribution data, processing instructions and to specify the outputs desired for the arcs. Coded arcs were defined between two nodes, some were given probabilities of successful completion and all were described fully. The distribution data input was coded and assigned to the appropriate arcs. <u>The master arcs module</u> required the following input data:

Columns	1-8	The name of the arc being modelled was entered, for example SANWCS. This was repeated as required until all the arcs had been entered. The last record of this module had ENDARC punched into columns 1-6 while the remaining 74 columns were left blank. This indicated that all the arcs had been entered.
	9-16	The arcs' input node names were entered, for example, ELEMENT 1.

17-24 The arcs' output node names were entered, for example, SAN/URI.

NOTE: All the arcs had input and output node code names which had to be specified accurately to guarantee the correct network paths. Arc and node code names had to be unique to the particular network, as confusion was caused within the simulation if there was any repetition of codes.

25-28 The probability of the successful completion of an arc was entered. Once selected all arcs had a 100% chance of being successfully completed. There were no partially completed arcs.

29 The letter S could be inserted in this column to request histograms of slack arc times, but since the critical path was calculated primarily for cost, this column was left blank.

30-80 The description of the arc represented by the code was entered, for example, DATA INPUT TOILETS for SANWCS.

Time statistical distribution satellite arc record: This record carried the data input parameters needed to define the time distributions associated with each arc.

Columns 1-8 The name of the arc was entered under the master arc record, for example SANWCS.

9-13	The satellite type identifier was entered - DTIME.
14-15	A 1 was placed in column 15 as a record sequence number, as only one record was required to carry all the distribution data needed to define time.
16-25	The distribution type was entered, for example, 3 represented a triangular distribution and 10 a beta distribution.
26-35	The minimum distribution value was entered or the constant.
36-45	The maximum distribution value was entered.
46-55	The most likely value was entered for a triangular distribution and the p parameter for the beta distributions.
56-65	The q parameter was entered for the beta distribution.
66-75	Field six data was left blank.

Cost statistical distribution satellite arc record and the performance statistical distribution satellite are record: These records carried the data input parameters needed to define the cost and performance distributions associated with each arc. They were similar to the time statistical distribution satellite arc record except DCOST and DPERF were entered in columns 9-13.

Time, cost and performance histogram satellite arc records: These records were not required as the data had been defined by the distributions. The actual raw data histogram information could have been recorded but because of the limitations associated with the observed data and the limitations on the storage capacity available (99 records) this process would have been lengthy and deterministic.

Time, cost and performance math-related satellite are records: These records carry the mathematical relationships used to create in part or in total the time, cost, performance values for the arcs under consideration. Although this facility was considered extremely valuable, at present the research could not define the relationships between the time, cost and performance variables. This facility could be used once rules-of-thumb or definite relationships were defined.

Filter 1, 2 and 3 satellite arc records: These records assist an arc's input node logic function, but since no filter 1, 2 or 3 options were used in the network, these records have not been used.

Monte Carlo Satellite arc record: This record assists an arc's input node logic function. The Monte Carlo technique was used extensively throughout the model network therefore a record was inserted where required, after the statistical distribution satellite arc records.

Columns	1-8	The name of the arc for which the satellite record was carrying information was entered, for example, URINALS.
	9-13	The satellite type identifier Mbbbb (four blanks) was then entered.

14-14 Only one record sequence number was required to carry all the information needed for the Monte Carlo technique, so a 1 was entered in column 15.

16-25 The arc's probability of being Monte Carlo initiated was then entered. These probability figures were obtained from the historical data and allowed the model to cover combinations of components in a fairly realistic manner.

Monte Carlo time, cost and performance conditioned satellite arc records: These records are a modification of the previous satellite arc record and enable the user to construct conditional probability situations: where the probability of an arc initiation is a function of either the time, cost or performance accumulated on an arc's input node. At present there seemed to be insufficient evidence within the data to execute these records, but it was hoped that further research would enable the quantity surveyor to limit the selection of components through performance, cost and time criteria.

Slack histogram satellite arc record: Slack time calculations were not required from the model, therefore this record was omitted.

5.2.3 The master nodes module was used to enter the description of the nodes within the network, the logics used, the desired outputs and weights. The module was the main entry point for the information regarding the network's flow devices and channelling points. The master nodes module required the following input data:

Columns 1-8 The names of the nodes were entered, for example, SAN/URI. This was repeated as required until all the nodes had been entered. The last record of this module was ENDNODE, this indicated the completion of all the node inputs.

9 The input logic code number was entered using the following code numbers:

Input logic code number	Type of input logic
1	INITIAL
2	AND
3	PAND
4	OR

10 The output logic code number was entered using the following code numbers:

Output logic code number	Type of output logic
1	TERMINAL
2	ALL
3	MC

13-14 The numeric code zero was entered for the type of output desired as the time, path cost, overall cost and performance variables were all desired outputs. Other combinations were available within VERT.

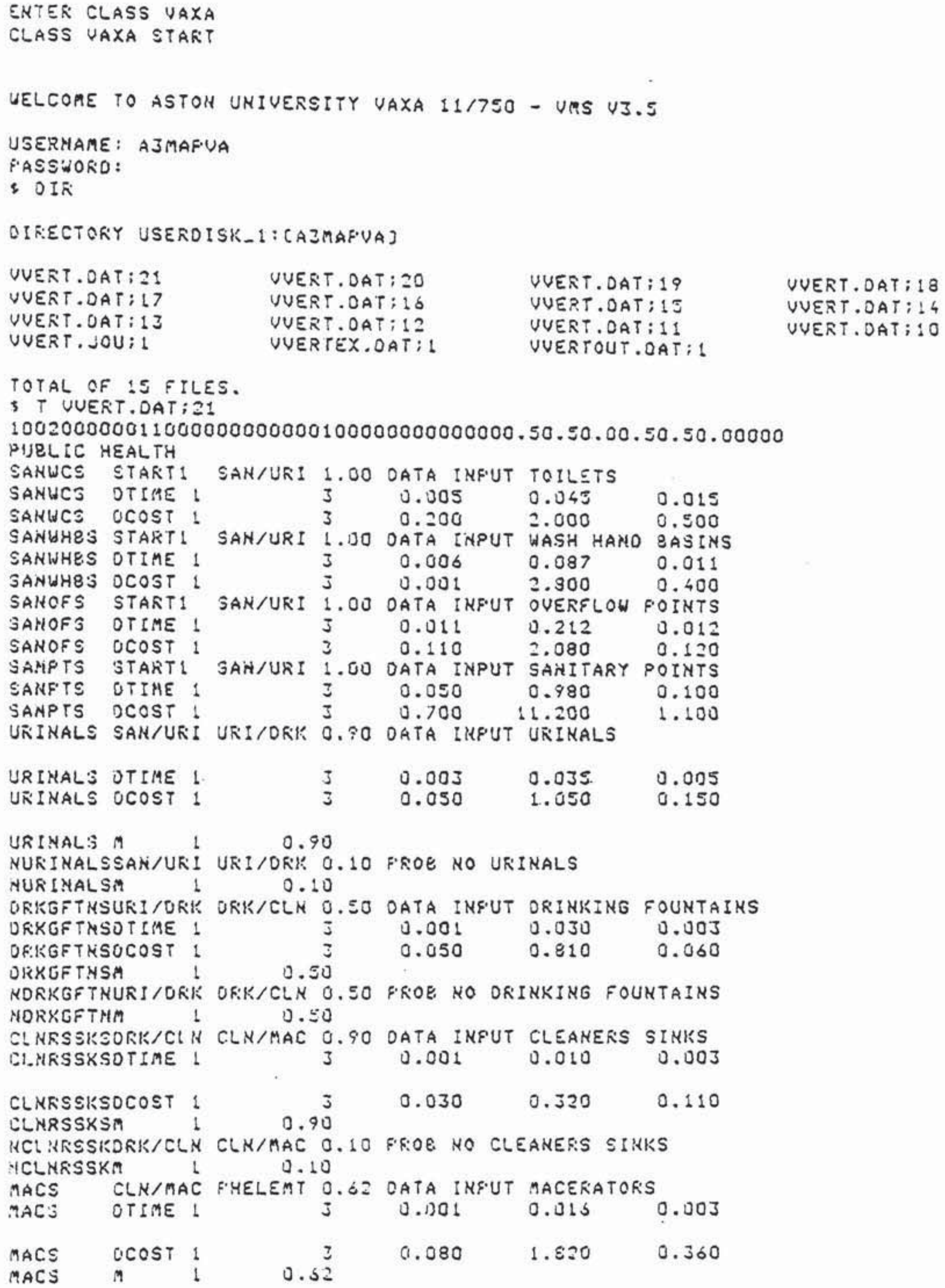
15-16 The program has the capability to print time, cost and performance histograms for a limited number of internal nodes. The limit was set by VERT's check variable MHIST. Internal nodes were designated as candidates for histogram printouts by assigning the node a number which corresponded to the requested position in the internal node histogram storage arrays. All the element collection nodes were entered, for example, FIRE, HEATING and ELECTRIC. Time, cost and performance histograms could be constructed for intervals between two nodes by entering the same designation number in this field for the two nodes bridging the interval. This was not considered useful at present, but could be used to examine specific areas of the network in detail at a later date.

Time, cost and performance histograms record: This record can be used to enter the minimum and maximum values for time, path cost, overall cost and performance histograms for either terminal or internal nodes. This record was not entered as VERT used the minimum and maximum values observed during the simulation for the construction of the histograms. This facility may be used in the future when a specific client budget for M&E services is given and the quantity surveyor wishes to find out the system alternatives available to the client.

Subtract satellite record: This record should be used in conjunction with the FILTER 1 output logic. As this was not used in the network, this field record was omitted.

Slack histogram satellite record: No slack time histograms were required for the nodes.

This completed the programming of VERT and represented the network for mechanical and electrical services installations. Figure 14: VERT data input records, gives an example of the data input layout. Figure 15 gives an example of the summary output provided for the VERT user-selected options.



```
ENTER CLASS VAXA
CLASS VAXA START


WELCOME TO ASTON UNIVERSITY VAXA 11/750 - VMS V3.5

USERNAME: A3MAPVA
PASSWORD:
$ DIR

DIRECTORY USERDISK_1:[A3MAPVA]

VVERT.DAT;21        VVERT.DAT;20        VVERT.DAT;19        VVERT.DAT;18
VVERT.DAT;17        VVERT.DAT;16        VVERT.DAT;15        VVERT.DAT;14
VVERT.DAT;13        VVERT.DAT;12        VVERT.DAT;11        VVERT.DAT;10
VVERT.JOU;1         VVERTEX.DAT;1       VVERTOUT.DAT;1

TOTAL OF 15 FILES.
$ T VVERT.DAT;21
100200000011000000000000010000000000000.50.50.00.50.50.00000
PUBLIC HEALTH
SANWCS  START1  SAN/URI 1.00 DATA INPUT TOILETS
SANWCS  DTIME 1           3     0.005     0.043     0.015
SANWCS  DCOST 1           3     0.200     2.000     0.500
SANWHBS START1  SAN/URI 1.00 DATA INPUT WASH HAND BASINS
SANWHBS DTIME 1           3     0.006     0.087     0.011
SANWHBS DCOST 1           3     0.001     2.900     0.400
SANOFS  START1  SAN/URI 1.00 DATA INPUT OVERFLOW POINTS
SANOFS  DTIME 1           3     0.011     0.212     0.012
SANOFS  DCOST 1           3     0.110     2.080     0.120
SANPTS  START1  SAN/URI 1.00 DATA INPUT SANITARY POINTS
SANPTS  DTIME 1           3     0.050     0.980     0.100
SANPTS  DCOST 1           3     0.700    11.200     1.100
URINALS SAN/URI URI/DRK 0.90 DATA INPUT URINALS

URINALS DTIME 1           3     0.003     0.035     0.005
URINALS DCOST 1           3     0.050     1.050     0.150

URINALS M     1       0.90
NURINALSSAN/URI URI/DRK 0.10 PROB NO URINALS
NURINALSM     1       0.10
DRKGFTNSURI/DRK DRK/CLN 0.50 DATA INPUT DRINKING FOUNTAINS
DRKGFTNSDTIME 1           3     0.001     0.030     0.003
DRKGFTNSDCOST 1           3     0.050     0.810     0.060
DRKGFTNSM     1       0.50
NDRKGFTNURI/DRK DRK/CLN 0.50 PROB NO DRINKING FOUNTAINS
NDRKGFTNM     1       0.50
CLNRSSKSDRK/CLN CLN/MAC 0.90 DATA INPUT CLEANERS SINKS
CLNRSSKSDTIME 1           3     0.001     0.010     0.003

CLNRSSKSDCOST 1           3     0.030     0.320     0.110
CLNRSSKSM     1       0.90
NCLNRSSKDRK/CLN CLN/MAC 0.10 PROB NO CLEANERS SINKS
NCLNRSSKM     1       0.10
MACS    CLN/MAC PHELEMT 0.62 DATA INPUT MACERATORS
MACS    DTIME 1           3     0.001     0.016     0.003

MACS    DCOST 1           3     0.080     1.820     0.360
MACS    M     1       0.62
```

Figure 14.0   VERT data input records

```
PUBLIC HEALTH

PROBLEM IDENTIFICATION OPTION------------------------------          1

TYPE OF INPUT OPTION---------------------------------------          0

TYPE OF OUTPUT OPTION--------------------------------------          1

COSTING AND PRUNING OPTION---------------------------------          1

FULL PRINT TRIP OPTION-------------------------------------          0

CORRELATION COMPUTATION AND PLOT OPTION--------------------          0

COST-PERFORMANCE TIME INTERVAL OPTION----------------------          0

COMPOSITE TERMINAL NODE MINIMUMS AND MAXIMUMS OPTION-------          0

TERMINAL NODE LISTING OPTION-------------------------------          0

80-80 LISTING OF INPUT RECORDS-----------------------------          1

MEAN VALUE COMPLETION TIME LISTING OF THE NODES------------          1

INITIAL SEED-----------------------------------------------          0

NUMBER OF ITERATIONS---------------------------------------        500

YEARLY INTEREST RATE USED FOR INFLATION ADJUSTMENTS--------       0.00

YEARLY INTEREST RATE USED FOR PRESENT VALUE DISCOUNTING----       0.00

TIME FACTOR WHICH CONVERTS PROGRAM TIME TO A YEARLY BASE---       0.00

                                     TIME      COST      PERF

TERMINAL NODE SELECTION WEIGHTS      0.50      0.50      0.00

CRITICAL PATH WEIGHTS                0.50      0.50      0.00

INITIAL VALUES                       0.00      0.00      0.00


            W A R N I N G  NO.  3811

            W A R N I N G  NO.  3822
```

Figure 15.0   Summary of VERT user-selected options

5.3 Simulation

Once the programming of VERT was completed, the computerised technique constructed its results via simulation.

5.3.1 Simulation may be said to be a computational technique which studies the behaviour of sample data in order to re-generate the entire population model, from which the sample was drawn (Spriet & Vansteenkiste, 1982 and Vazsonyi, 1977). It can be used most effectively when: a) not all the values of the variables are known in advance, b) there is no simple means of finding them, c) no ready-made formulae are known and d) the only property known is the relationship which indicates that a solution to a future project could be found from the analysis of previous projects. Simulation provides a means for finding successive states of a situation or system by the repeated application of the rules and associations by which the system is operated, until the nth term or overall population can be depicted (Springer, Herliky & Beggs, 1965). VERT was used to derive procedures for using sample information, to simulate the possible values of the population of mechanical and electrical services installations and to learn what the values of the population parameters may be. Simulation was utilised to generate random labour factors, costs and performance units for each component in the network, by the random selection of feasible values from the probabilistic distributions which were used to represent possible outcomes for the components. The complex stochastic probabilistic raw data was combined in a realistic manner. No assumptions were made as the the shapes of the element and SUCCESS completed distributions, so technically the results provided were unbiased and reliable (Crandell, 1976).

5.3.2 The Monte-Carlo method is a particular simulation process available within VERT. The term 'Monte Carlo' was derived from the fact that roulette, or an analogue of it, played a fundamental role in the generation of random events. It was utilised, within the research, to stochastically model the possible choices of installations or components available to the estimator, depending on the user assigned probabilities for 'Monte Carlo' initiated arcs. Mathur (1982) demonstrated the use of Monte Carlo simulation and described its use to discover the total cost of elements within his research. Virtually every stochastic problem which defies analysis by analytical means can be studied by the Monte Carlo method and simulation (Smith, 1973 and Kohlas, 1982).

Risk analysis by means of Monte Carlo simulation has been suggested as an alternative cost estimating method. Van Slyke (1963) used the technique in association with PERT, and Hartley and Wortham (1966) in a network time reduction process. They showed that Monte Carlo experiments could:

i) Represent the procedures for using statistical inference to evaluate the methods used in estimation and testing;

ii) Obtain a sample from an estimator's underlying probability distribution of estimates and then seek to learn about the process which provided the sample;

iii) Be used to provide reproducible knowledge concerning the accuracy of parameter estimates;

iv) Aid in the construction of confidence intervals in causal prediction.

v) Be useful as a teaching or learning device;

and vi) Provide the means for assessing the sensitivity of particular model results, especially stochastic events, to the assumptions underlying their construction.

5.3.3 Simulation and Monte Carlo methods have been criticised over the years (Cellier, 1982; Beeston, 1983 and Ince, 1985) primarily because the models may rely on untrustworthy data, there may be an assumption of independence between components and because the simulation process may be time-consuming and costly due to the large quantity of iterations required to satisfactorily reproduce a model. The arguments against random testing have been powerful in the past, but researchers from the University of Texas and the Open University (Ince, 1985) have suggested that only a few test executions need to be examined by a programmer during random testing. VERT successfully overcomes the past criticisms. The structures of the mechanical and electrical services networks were checked by the services quantity surveyors at MDA and because of the probabilistic nature of the component distributions, the variables were identified before simulation. The user is able to analyse the network logic, both before and after simulation, with the aid of VERT's iteration print-outs, to ensure that the results are representative of the actual problem under study. The assumption of component independence was upheld by the M&E services networks, but VERT will enable the modelling of relationships via algorithms which may produce interrelationships between components. The Manpower Services Commission (Palframan, 1985) stressed the affordability of simulation techniques to the industry and predicted an ever-growing demand for simulation. The VERT software was inexpensive in relation to its size and capabilities. The costs of operating the technique were dependent on the size of the program, the output required and the frequency at which updated historical data was required. The maximum operating time required in this research for a 500 iteration simulation was 35 minutes; updating may only be required every three months. The initial input of data was time-consumsing but once the networked system was operational, manipulation of the data was minimal. If the family-mode (Moeller and Atzinger, 1983)[2] were used in future, the element sub networks could be re-simulated independently to cut the costs of a full re-run of the model simulation.

5.3.4 Similation does not pretent to substitute for human judgement (Flanagan, 1980 and Beattie & Reader, 1971) but VERT did successfully enable 'human uncertainties' to be modelled, the systemmatic consideration of potential errors, risk analysis and the identification and evaluation of potential variations to be assessed (Jelen and Black, 1983). The simulation of the mechanical and electrical services installations and the variables contained within the research, may not have improved the accuracy of pre-tender estimates but VERT was a quantitative technique which successfully combined the decision tree technique (which aided in the visualising of the array of possible installation choices) and the process of simulation, to provide the quantity surveyor with a fuller understanding of the selections available and their likely cost, time and performance factors.

5.4 Program output

5.4.1 The simulation process within VERT selected particular paths through the network which abstracted specific sample data from the nominated distributions on each arc. The iterations were aggregated and could be displayed in a number of resultant formats. Within the research the terminal node SUCCESS (see Figures 12 and 13) and all the element total nodes (for example: HOTWT, FIRE, ELECTRIC) were programmed to display the following measures for the time, cost and performance variables:

i) The relative frequency distribution, which displayed the range and concentration of time, cost and performance values observed at a given node.

ii) The cumulative frequency distribution, which allowed the deduction of confidence levels from the probabilities of exceeding certain value levels.

iii) The mean or average of all the iterations pertaining to the variable.

iv) The standard error, which measured the dispersion of data.

v) The coefficient of variation, which was an abstract measure of dispersion obtained from the data.

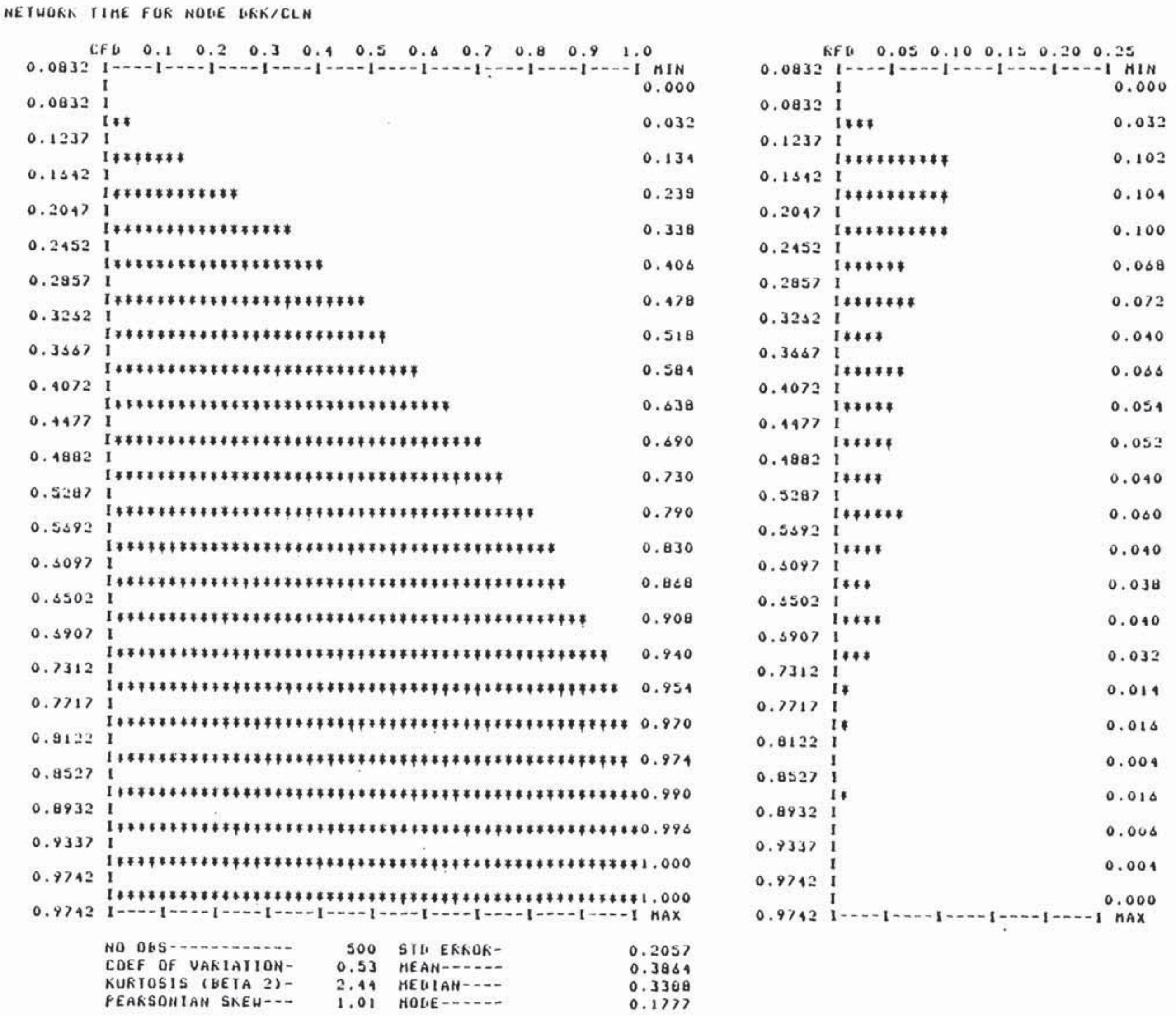
vi) The median or mid-point value observed from the iterations.

vii) The Beta 2 measure of Kurtosis, which measured the distribution's peakedness for comparison with the normal or mesokurtic distribution equal to three.

viii) The mode or greatest frequency value, which measured the central tendency or heaviest concentration of values within the distributions.

ix) The Pearsonian measure of skewness, which provided a comparison for central tendency.

The coefficient variation, the Beta 2 measure of kurtosis and the Pearsonian measure of skew allowed the distributions to be analysed in greater detail than other cost models. Figure 16: Network time for node DRK/CLN, illustrates an example print-out. The relative frequency distribution (RFD) is to the right of the cumulative frequency distribution (CFD). The statistics pertaining to the simulation distribution are given at the bottom of the page. Five hundred iterations or observations were processed. One sees that the kurtosis is less than three, therefore the distribution is platykurtic, and the Pearsonian skew indicates a slight measure of skewness to the right of the mean. The median and mode also both lie to the left of the mean.



```
NETWORK TIME FOR NODE DRK/CLN

      CFD  0.1  0.2  0.3  0.4  0.5  0.6  0.7  0.8  0.9  1.0                 RFD  0.05 0.10 0.15 0.20 0.25
0.0832 I----I----I----I----I----I----I----I----I----I----I MIN       0.0832 I----I----I----I----I----I MIN
       I                                                  0.000             I                         0.000
0.0832 I                                                             0.0832 I
       I**                                                0.032             I***                      0.032
0.1237 I                                                             0.1237 I
       I*******                                           0.134             I**********               0.102
0.1642 I                                                             0.1642 I
       I************                                      0.239             I**********               0.104
0.2047 I                                                             0.2047 I
       I*****************                                 0.338             I**********               0.100
0.2452 I                                                             0.2452 I
       I********************                              0.406             I******                   0.068
0.2857 I                                                             0.2857 I
       I************************                          0.478             I*******                  0.072
0.3262 I                                                             0.3262 I
       I**************************                        0.518             I****                     0.040
0.3667 I                                                             0.3667 I
       I*****************************                     0.584             I******                   0.066
0.4072 I                                                             0.4072 I
       I********************************                  0.638             I*****                    0.054
0.4477 I                                                             0.4477 I
       I***********************************               0.690             I*****                    0.052
0.4882 I                                                             0.4882 I
       I*************************************             0.730             I****                     0.040
0.5287 I                                                             0.5287 I
       I****************************************          0.790             I******                   0.060
0.5692 I                                                             0.5692 I
       I******************************************        0.830             I****                     0.040
0.6097 I                                                             0.6097 I
       I*******************************************       0.868             I***                      0.038
0.6502 I                                                             0.6502 I
       I*********************************************     0.908             I****                     0.040
0.6907 I                                                             0.6907 I
       I***********************************************   0.940             I***                      0.032
0.7312 I                                                             0.7312 I
       I************************************************  0.954             I*                        0.014
0.7717 I                                                             0.7717 I
       I************************************************* 0.970             I*                        0.016
0.8122 I                                                             0.8122 I
       I************************************************* 0.974             I                         0.004
0.8527 I                                                             0.8527 I
       I**************************************************0.990             I*                        0.016
0.8932 I                                                             0.8932 I
       I**************************************************0.996             I                         0.006
0.9337 I                                                             0.9337 I
       I**************************************************1.000             I                         0.004
0.9742 I                                                             0.9742 I
       I**************************************************1.000             I                         0.000
0.9742 I----I----I----I----I----I----I----I----I----I----I MAX       0.9742 I----I----I----I----I----I MAX

       NO OBS-----------      500  STD ERROR-          0.2057
       COEF OF VARIATION-     0.53  MEAN------          0.3864
       KURTOSIS (BETA 2)-     2.44  MEDIAN----          0.3308
       PEARSONIAN SKEW---     1.01  MODE------          0.1777
```

Figure 16.0 Network time for node DRK/CLN

```
CORE DATA STORAGE USAGE ANALYSIS

A1. CURRENT NUMBER OF ITERATIONS ALLOWED (VALUE OF MITER)-----------------  1000
A2. NUMBER OF ITERATIONS REQUESTED-----------------------------------------    10
A3. ITERATION STORAGE SPACE NOT USED ((A1-A2)*5)---------------------------        4950

B1. CURRENT NUMBER OF ARCS ALLOWED (VALUE OF MARC)-------------------------   250
B2. NUMBER OF ARCS ENTERED-------------------------------------------------    23
B3. ARC STORAGE SPACE NOT USED ((B1-B2)*16)--------------------------------        3632

C1. VARIABLE ARC STORAGE (ASTORE) AVAILABLE (VALUE OF LARC)----------------  2000
C2. VARIABLE ARC STORAGE USED----------------------------------------------   290
C3. VARIABLE ARC STORAGE SPACE NOT USED (C1-C2)----------------------------        1710

D1. CURRENT NUMBER OF NODES ALLOWED (VALUE OF MNODE)-----------------------   150
D2. NUMBER OF NODES ENTERED------------------------------------------------    12
D3. NODE STORAGE SPACE NOT USED ((D1-D2)*13)-------------------------------        1794

E1. VARIABLE NODE STORAGE (FRONT PART NSTORE) AVAILABLE (VALUE OF LNODE)--  1500
E2. VARIABLE NODE STORAGE USED---------------------------------------------    46
E3. VARIABLE NODE STORAGE SPACE NOT USED (E1-E2)---------------------------        1454

F1. COST-PERF VECTOR STORAGE (BACK PART NSTORE) AVAILABLE (VALUE OF NTAG)-  1500
F2. COST-PERF VECTOR STORAGE USED------------------------------------------     0
F3. COST-PERF VECTOR STORAGE SPACE NOT USED (F1-F2)------------------------        1500

G1. CURRENT NUMBER OF INTERNAL NODE STATISTICS ALLOWED (VALUE OF NHIST)---    20
G2. NUMBER OF INTERNAL NODE STATISTICS REQUESTED---------------------------     8
G3. INTERNAL NODE STATISTICS STORAGE SPACE NOT USED ((G1-G2)*141)---------        1692

H1. CURRENT NUMBER OF TERMINAL NODE HISTOGRAMS ALLOWED (VALUE OF NTERM)---     5
H2. NUMBER OF TERMINAL NODE HISTOGRAMS ENTERED-----------------------------     0
H3. TERMINAL NODE HISTOGRAM STORAGE SPACE NOT USED ((H1-H2)*9)------------          45

I1. CURRENT NUMBER OF SLACK HISTOGRAMS ALLOWED (VALUE OF NSLACK)----------    15
I2. NUMBER OF SLACK HISTOGRAMS REQUESTED-----------------------------------     0
I3. SLACK HISTOGRAM STORAGE SPACE NOT USED ((I1-I2)*6)--------------------          90

J1. CURRENT NUMBER OF COST-PERF TIME INTERVALS AVAILABLE (VALUE OF NCPGAP)    10
J2. NUMBER OF COST-PERF TIME INTERVALS REQUESTED---------------------------     0
J3. COST-PERF TIME INTERVALS NOT USED ((J1-J2)*7)-------------------------          70

K1. CURRENT NUMBER OF NETWORKS ALLOWED IN THE DATA BASE (VALUE OF NORD)---   150
K2. NUMBER OF NETWORKS ENTERED                                                  0
K3. NETWORK PARAMETER SPACE NOT USED ((K1-K2)*3)--------------------------         450

    TOTAL CORE STORAGE AVAILABLE------------------------------------------ 19425

    TOTAL CORE STORAGE NOT USED-------------------------------------------       17387

    OVERALL CORE STORAGE UTILIZATION--------------------------------------      10.49%

RECOMMENDED SIZES OF CHECK VARIABLES (A-K) FOR INPUT TO GINEN IN ORDER TO
CONFIGURE VERT-4 FOR OPTIMAL FUTURE PRODUCTION RUNS OF THIS NETWORK

    500    26    320    11    52    1    10    1    1    1    1

    LAST RANDOM NUMBER SEED =   1274383480
```

```
MITER    stores summary type information
         for each iteration

MARC     stores data for every component
         arc in the network

LARC     stores data associated with the
         various satellite arc records

MNODE    stores data for every node in
         the network

LNODE    partially stores input and output
         linkages for each node

NTAG     stores all the combinations of
         paths through the network

NHIST    stores time, path cost, overall
         cost and performance data for
         printed internal nodes

NTERM    stores time, path cost, overall
         cost and performance data for
         printed terminal nodes

NSLACK   stores arc and node slack data

NCPGAP   stores cost-performance time
         interval data

NORD     stores the family names and aids
         in the processing of the family
         mode
```

Figure 17.0 Core data storage usage analysis

```
ITER =     2 OPT TERMINAL NODE =SUCCESS  INIT SEED =  1668087743
TIME, PATH-COST, OVERALL-COST, PERFORMANCE =                  0.4832              16.3991                16.3991                0
                                                       TIME                                   COST                                 PERFORMANCE
ARC NAME   STATUS         SLACK          PRIMARY        CUMULATIVE           PRIMARY        CUMULATIVE            PRIMARY         CU
SANWCS          4                  0.103154052E-01  0.103154052E-01  0.477832735      0.477832735      0.000000000E+00  0.00000
SANWHBS         4                  0.314704105E-01  0.314704105E-01  0.770474051      0.770474851      0.000000000E+00  0.00000
SANOFS          4                  0.850679874E-01  0.850679874E-01   1.55435479       1.55135479      0.000000000E+00  0.00000
SANFTS     *    4                  0.469469696      0.469469696       2.98222828       2.98222828      0.000000000E+00  0.00000
URINALS    *    4                  0.708130095E-02  0.476550996      0.715760112       6.51066113      0.000000000E+00  0.00000
NDRKGFTN   *    4                  0.000000000E+00  0.476550995      0.000000000E+00   6.51066113      0.000000000E+00  0.00000
CLNRSSKS   *    4                  0.663718581E-02  0.483188182      0.868749783E-01   6.59734869      0.000000000E+00  0.00000
NMACS      *    4                  0.000000000E+00  0.483189182      0.000000000E+00   6.59734869      0.000000000E+00  0.00000
CWMAINS         4                  0.166024957E-01  0.166024957E-01  0.263143510      0.263113510      0.000000000E+00  0.00000
CWFTS           4                  0.287233472      0.287233472       1.10219514       1.10219514      0.000000000E+00  0.00000
CWSTORAG        4                  0.352601670E-01  0.352601670E-01   3.32975602       3.32975602      0.000000000E+00  0.00000
NINSULTN        4                  0.000000000E+00  0.287233472      0.000000000E+00   4.69509459      0.000000000E+00  0.00000
HWFTS           4                  0.756027922E-01  0.756027922E-01   2.49809575       2.49809575      0.000000000E+00  0.00000
STORAGE         4                  0.501857465E-02  0.806213692E-01   2.11150479       4.60960054      0.000000000E+00  0.00000
PUMPS           4                  0.209506624E-02  0.827164352E-01  0.213718012       4.82331848      0.000000000E+00  0.00000
HINSULTN        4                  0.000000000E+00  0.827164352E-01  0.283313930'      5.10663223      0.000000000E+00  0.00000
NODE NAME STATUS          SLACK             TIME             COST          PERFORMANCE
START1     *    4                  0.000000000E+00  0.000000000E+00  0.000000000E+00
SAN/URI    *    4                  0.469469696       5.79490099      0.000000000E+00
URI/DRK    *    4                  0.476550996       6.51066113      0.000000000E+00
DRK/CLN    *    4                  0.476550996       6.51066113      0.000000000E+00
CLN/MAC    *    4                  0.483188182       6.59734869      0.000000000E+00
START2          3                  0.000000000E+00  0.000000000E+00  0.000000000E+00
CW/INS          3                  0.287233472       4.69509459      0.000000000E+00
START3          3                  0.000000000E+00  0.000000000E+00  0.000000000E+00
HW/STO          3                  0.756027922E-01   2.49809575      0.000000000E+00
STO/PUM         3                  0.806213692E-01   4.60960054      0.000000000E+00
PUM/HIN         3                  0.827164352E-01   4.82331848      0.000000000E+00
SUCCESS    *    4                  0.483188182       16.3990765      0.000000000E+00
```

Figure 18.0 A listing of all flowcarrying arcs and nodes realised in each iteration

5.4.2 The VERT program can also be used to output:

i) A listing of the major variable storage arrays. Figure 17: Core Data Storage usage analysis, illustrates this facility.

ii) A listing of all the flow carrying arcs and nodes realised in each iteration. An iteration is a single network flow that traverses the network from the initial to the terminal nodes. Figure 18 illustrates the flow of all data through the arcs and nodes realised for iteration number 2, taken from the Public Health pilot study. Arcs and nodes are coded according to their processing status and stars indicate their presence on the critical path. Slack, primary and cumulative times, primary and cumulative costs, and primary and cumulative performance values are given for the flow carrying arcs. The primary value represents the value selected randomly from the defined distributions for each component. The cumulative value represents the total combined primary values of all the prior simulated components in the network flow. The longest times recorded, the cumulative costs and performance values are assigned to the flow carrying nodes.

iii) A one-line summary listing of the results of each iteration. Figure 19 illustrates this facility. The name of the winning nodes, its time, path cost, overall cost and performance values are listed.

iv) A listing of the mean, minimum and maximum for the time, path cost, overall cost and performance variables for terminal and requested internal nodes. Figure 20 illustrates an example of this output.

```
       TERMINAL     BEGINNING
COUNT    NODE          SEED                    TIME           PATH COST        OVERALL COST          PERFORMANCE
    1  SUCCESS        65539          0.622909367085       18.3250217438       18.3250198364      0.000000000000E+00
    2  SUCCESS   1668087743          0.483188182116       16.3990764618       16.3990745544      0.000000000000E+00
    3  SUCCESS   1584750789          0.488951653242       17.7131805420       17.7131805420      0.000000000000E+00
    4  SUCCESS   2132634548          0.639026641846       18.6834278107       18.6834259033      0.000000000000E+00
    5  SUCCESS   1827733111          0.564938426018       19.7425441742       19.7425441742      0.000000000000E+00
    6  SUCCESS   1855299806          0.248379603028       16.3927326202       16.3927326202      0.000000000000E+00
    7  SUCCESS   1726960611          0.305441379547       20.0862255096       20.0862255096      0.000000000000E+00
    8  SUCCESS    321184523          0.569229185581       13.4631919861       13.4631919861      0.000000000000E+00
    9  SUCCESS   1307339003          0.460211306810       11.7966241837       11.7966241837      0.000000000000E+00
   10  SUCCESS   1404858641          0.425910145044       19.5045814514       19.5045814514      0.000000000000E+00
   11  SUCCESS   1274383480          0.523815751076       10.7572984695       10.7572975159      0.000000000000E+00
   12  SUCCESS   1914655077          0.540321290493       18.2294139862       18.2294120789      0.000000000000E+00
   13  SUCCESS   1702606597          0.761167943478       17.4838352203       17.4838333130      0.000000000000E+00
   14  SUCCESS    348006481          0.264125525951       24.6138458252       24.6138458252      0.000000000000E+00
   15  SUCCESS   1322931827          0.150239720941       16.8156185150       16.8156185150      0.000000000000E+00
   16  SUCCESS    983910403          0.263321697712       18.5778751373       18.5778770447      0.000000000000E+00
   17  SUCCESS   1642116526          0.541292726994       18.3122119904       18.3122158051      0.000000000000E+00
   18  SUCCESS    358292191          0.439447134733       20.5673847198       20.5673847198      0.000000000000E+00
   19  SUCCESS    288717666          0.587111294270       18.1615200043       18.1615219116      0.000000000000E+00
   20  SUCCESS   1508320039          0.272090464830       14.5693979263       14.5693979263      0.000000000000E+00
   21  SUCCESS   2027458542          0.970798671246       12.0645685196       12.0645675659      0.000000000000E+00
   22  SUCCESS   1628790263          0.630116283894       22.9081306458       22.9081287384      0.000000000000E+00
   23  SUCCESS   1832106061          0.381652593613       18.8043098450       18.8043098450      0.000000000000E+00
   24  SUCCESS   2136008347          0.720496892929       12.0069179535       12.0069179535      0.000000000000E+00
   25  SUCCESS   1571811899          0.412950903177       22.4807510376       22.4807510376      0.000000000000E+00
   26  SUCCESS   1781578382          0.551490426064       27.4816532135       27.4816532135      0.000000000000E+00
   27  SUCCESS   2059640336          0.408396869898       15.7838764191       15.7838754654      0.000000000000E+00
   28  SUCCESS    195210980          0.471661955118       20.4817924500       20.4817905426      0.000000000000E+00
   29  SUCCESS   1767645302          0.637533485889       17.7123546600       17.7123546600      0.000000000000E+00
   30  SUCCESS   1659272156          0.570582985878       16.7478790283       16.7478828430      0.000000000000E+00
   31  SUCCESS   1386849104          0.651545286179       13.6727590561       13.6727590561      0.000000000000E+00
   32  SUCCESS   2046071790          0.153615474701       18.7150745392       18.7150745392      0.000000000000E+00
   33  SUCCESS    386845687          0.689409613609       17.1053447723       17.1053447723      0.000000000000E+00
   34  SUCCESS   2131540860          0.524073541164       16.1487655640       16.1487655640      0.000000000000E+00
   35  SUCCESS   1928097305          0.557025909424       20.5311031342       20.5311012268      0.000000000000E+00
   36  SUCCESS   2045417652          0.352673619986       18.4685497284       18.4685478210      0.000000000000E+00
   37  SUCCESS   1487031924          0.511251568794       16.8919334412       16.8919334412      0.000000000000E+00
   38  SUCCESS    121359573          0.553445041180       15.1695375443       15.1695375443      0.000000000000E+00
   39  SUCCESS   1132001554          0.528506398201       19.3345737457       19.3345737457      0.000000000000E+00
   40  SUCCESS   1616762420          0.405040800571       20.3445091248       20.3445091248      0.000000000000E+00
   41  SUCCESS    370931401          0.295135438442       18.8661422729       18.8661422729      0.000000000000E+00
   42  SUCCESS   1656812444          0.394285202026       21.8507537842       21.8507537842      0.000000000000E+00
   43  SUCCESS   1922833689          0.779524505138       17.9043273926       17.9043273926      0.000000000000E+00
   44  SUCCESS   2051705905          0.712318122387       16.2119483948       16.2119483948      0.000000000000E+00
   45  SUCCESS    111667354          0.348542779684       16.4560775757       16.4560775757      0.000000000000E+00
   46  SUCCESS    123614849          0.398253768682       17.8269119263       17.8269138336      0.000000000000E+00
   47  SUCCESS   1253733509          0.559901416302       17.0491752625       17.0491752625      0.000000000000E+00
   48  SUCCESS    695095306          0.734350979328       13.5935335159       13.5935335159      0.000000000000E+00
   49  SUCCESS   1739021880          0.765252351761       13.0757312775       13.0757312775      0.000000000000E+00
   50  SUCCESS   1945915531          0.360957890749       8.50410747528       8.50410652161      0.000000000000E+00
   51  SUCCESS   1977576336          0.566855847836       14.4120941162       14.4120941162      0.000000000000E+00
   52  SUCCESS    231948459          0.401803702116       25.8683910370       25.8683891296      0.000000000000E+00
   53  SUCCESS   1777421612          0.690018117428       16.4084491730       16.4084491730      0.000000000000E+00
   54  SUCCESS   2074699065          0.527334690094       17.1932888031       17.1932868958      0.000000000000E+00
   55  SUCCESS   1530473791          0.240731418133       22.4505004883       22.4505023956      0.000000000000E+00
   56  SUCCESS    861616343          0.323006272316       28.9509544373       28.9509563446      0.000000000000E+00
   57  SUCCESS   1278959629          0.710857285728       17.4694633484       17.4694652557      0.000000000000E+00
   58  SUCCESS    873309447          0.611028134823       15.3776292801       15.3776292801      0.000000000000E+00
   59  SUCCESS   1913192124          0.226705580950       17.5064754486       17.5064754486      0.000000000000E+00
   60  SUCCESS   1707203857          0.478522270918       14.0974197388       14.0974197308      0.000000000000E+00
   61  SUCCESS    138873123          0.584982216358       13.8045635223       13.8045644760      0.000000000000E+00
```

Figure 19.0 A one-line summary listing of the results of each iteration

```
         PATH COST FOR NODE HW/STO
NO OBS =                    500  AVE =              2.336064
MIN =                  0.151543  MAX =              6.322539

     OVERALL COST FOR NODE HW/STO
NO OBS =                    500  AVE =             16.222702
MIN =                  5.957469  MAX =             29.040327

     NETWORK TIME FOR NODE STO/PUM
NO OBS =                    368  AVE =              0.100461
MIN =                  0.013163  MAX =              0.266738

         PATH COST FOR NODE STO/PUM
NO OBS =                    368  AVE =              3.669730
MIN =                  0.609504  MAX =              8.150587

     OVERALL COST FOR NODE STO/PUM
NO OBS =                    368  AVE =             17.593498
MIN =                  6.957272  MAX =             30.234179

     NETWORK TIME FOR NODE PUM/HIN
NO OBS =                    210  AVE =              0.104142
MIN =                  0.018578  MAX =              0.239758

         PATH COST FOR NODE PUM/HIN
NO OBS =                    210  AVE =              3.931396
MIN =                  0.972082  MAX =              8.313585

     OVERALL COST FOR NODE PUM/HIN
NO OBS =                    210  AVE =             18.135811
MIN =                  9.737195  MAX =             30.706860

     NETWORK TIME FOR NODE SUCCESS
NO OBS =                    500  AVE =              0.467050
MIN =                  0.098238  MAX =              0.939643

         PATH COST FOR NODE SUCCESS
NO OBS =                    500  AVE =             18.688000
MIN =                  3.504107  MAX =             32.236626

     OVERALL COST FOR NODE SUCCESS
NO OBS =                    500  AVE =             18.688000
MIN =                  8.504107  MAX =             32.236626
```

Figure 20.0 A listing of the mean, minimum and maximum for the time, path cost, overall cost and performance for the terminal node and requested internal nodes

```
STARTI              0.0000              500
START2              0.0000              500
START3              0.0000              500
HW/STO              0.0846              500
STO/PUM             0.1005              368
PUM/HIN             0.1041              210
CW/INS              0.3131              500
SAN/URI             0.3681              500
URI/DRK             0.3308              500
DRK/CLN             0.3864              500
CLN/MAC             0.3906              500
SUCCESS             0.4670              500
```

Figure 21.0 Nodes mean completion time and realisation frequency

```
                     0.1  0.2  0.3  0.4  0.5  0.6  0.7  0.8  0.9  1.0
                 I----+----+----+----+----+----+----+----+----+----+I
START1    0.6400 I********************************                  I
                 I    +    +    +    +    +    +    +    +    +    +I
SAN/URI   0.6400 I********************************                  I
                 I    +    +    +    +    +    +    +    +    +    +I
URI/DRK   0.6400 I********************************                  I
                 I    +    +    +    +    +    +    +    +    +    +I
DRK/CLN   0.6400 I********************************                  I
                 I    +    +    +    +    +    +    +    +    +    +I
CLN/MAC   0.6400 I********************************                  I
                 I    +    +    +    +    +    +    +    +    +    +I
START2    0.3580 I******************                                I
                 I    +    +    +    +    +    +    +    +    +    +I
CW/INS    0.3580 I******************                                I
                 I    +    +    +    +    +    +    +    +    +    +I
START3    0.0020 I                                                  I
                 I    +    +    +    +    +    +    +    +    +    +I
HW/STO    0.0020 I                                                  I
                 I    +    +    +    +    +    +    +    +    +    +I
STO/PUM   0.0020 I                                                  I
                 I    +    +    +    +    +    +    +    +    +    +I
PUM/HIN   0.0020 I                                                  I
                 I    +    +    +    +    +    +    +    +    +    +I
SUCCESS   1.0000 I**************************************************I
                 I----+----+----+----+----+----+----+----+----+----+I
                     0.1  0.2  0.3  0.4  0.5  0.6  0.7  0.8  0.9  1.0
```

Figure 22.0 Nodes critical path index

```
                  .   0.1  0.2    3  0.4  0.5  0.6  0.7  0.8  0.9  1.0
                  I----+----+----+----+----+----+----+----+----+----+I
SANOFS    0.0020  I                                                  I
                  I    +    +    +    +    +    +    +    +    +    +I
SANPTS    0.6380  I********************************                  I
                  I    +    +    +    +    +    +    +    +    +    +I
URINALS   0.5660  I****************************                      I
                  I    +    +    +    +    +    +    +    +    +    +I
NURINALS  0.0740  I****                                              I
                  I    +    +    +    +    +    +    +    +    +    +I
DRKGFTNS  0.3040  I***************                                   I
                  I    +    +    +    +    +    +    +    +    +    +I
NDRKGFTN  0.3360  I*****************                                 I
                  I    +    +    +    +    +    +    +    +    +    +I
CLNRSSKS  0.5760  I*****************************                     I
                  I    +    +    +    +    +    +    +    +    +    +I
NCLNRSSK  0.0640  I***                                               I
                  I    +    +    +    +    +    +    +    +    +    +I
MACS      0.4100  I*********************                             I
                  I    +    +    +    +    +    +    +    +    +    +I
NMACS     0:2300  I************                                      I
                  I    +    +    +    +    +    +    +    +    +    +I
CWPTS     0.3580  I******************                                I
                  I    +    +    +    +    +    +    +    +    +    +I
INSULTN   0.2860  I**************                                    I
                  I    +    +    +    +    +    +    +    +    +    +I
NINSULTN  0.0720  I****                                              I
                  I    +    +    +    +    +    +    +    +    +    +I
HWPTS     0.0020  I                                                  I
                  I    +    +    +    +    +    +    +    +    +    +I
STORAGE   0.0020  I                                                  I
                  I    +    +    +    +    +    +    +    +    +    +I
PUMPS     0.0020  I                                                  I
                  I    +    +    +    +    +    +    +    +    +    +I
HINSULTN  0.0020  I                                                  I
                  I----+----+----+----+----+----+----+----+----+----+I
                      0.1  0.2  0.3  0.4  0.5  0.6  0.7  0.8  0.9  1.0

    LAST RANDOM NUMBER SEED =    1831695759
```

Figure 23.0 Arcs critical path index

v) Time, path cost and performance correlations.

vi) A listing of the optimum terminal node index and an arc and node critical path index. Figure 21 illustrates the nodes mean completion time and realisation frequency. Monte Carlo assigned probability checks can be made from the realisation frequencies. Figures 22 and 23 illustrate the nodes and arcs critical path indexes respectively. The VERT program computes the proportion of time each arc and node were on the critical path and illustrates the values in the form of bar charts. Within the research, the least desirable path or critical path through the network was considered to have the highest cost, longest time and lowest performance values. Component arcs and element total nodes which lay on the critical path were therefore considered as the most cost significant items and were closely examined.

5.4.3 VERT contains five combined output options. The user must select from the options in section 5.4.2, the most relevant outputs for the intended purpose of the results. The choice of combined output options are:

	Mode:	Field code:	Outputs as figs:
#1	Debug	0	17 & 18
#2	High Info.	1	16 (without the median), 19, 21, 22 & 23
		2	16 (without the RFD), 21, 22 & 23
		3	16, 19, 21, 22 & 23
#3	Fast Comp.	4	20, 21, 22 & 23
		5	16 (without the RFD), 21, 22 & 23.

Mode # 1 has a slow run speed and high volume output. Field code 0 or the debug mode was used to test the network logic and to assess the storage capacity.

Mode # 2 has a medium run speed and a high level of summary information. Field code 3 was selected for the resultant output of the mechanical and electrical services network.

Mode # 3 has a fast run speed and a low level of summary information. Field code 4 could be used in the future for sensitivity tests.

5.4.4 The VERT program displays a comprehensive array of output options, which were used successfully to test, research and assess the resultant cost models for mechanical and electrical services. VERT also contains 180 error and warning messages to help the quantity surveyor to identify problems when programming, coding and structuring the program; these were displayed, when appropriate output options were selected. Although the programming of VERT and the selection of the required output can be confusing to the novice, once the process has been understood, VERT can be easily operated and can produce the desired output.

6.0 RESULTS

6.0 Results

In order to make rational decisions, the quantity surveyor must have a detailed understanding of the historical data models upon which he bases the pre-tender cost estimates. The value of the models depends upon how well they describe the present and past situation, and how far all the major factors which influenced the historical projects have been identified and allowed for. The models themselves could not make judgements or take decisions, they merely reduced the complex mechanical and electrical choices to manageable proportions and, as a by-product, they laid the foundations for further research.

The models may be used in four ways. Primarily for the pre-tender cost estimating of mechanical and electrical installations for new office developments within London. Secondly, as a basis for cost design advice to the client. Thirdly as a monitoring device and research data base, to further examine the interrelationships between cost, time and performance criteria. And finally, as a trend monitor for changes in technologies, costs, design solutions and market forces. Information required outside the immediate estimating context, for example, statutory requirements and regulations could also be related to the component definitions (Appendix 9.3) and should be continually updated and monitored.

The quantity surveyor should be aware of the potentialities, failings and restrictions imposed when operating an historical data base model. The VERT program processed and printed out relative and cumulative frequency distributions, and a summary of the associated statistical measures. This chapter defines these statistics and uses examples to test the validity of the program results. Model verification using sampling theory, trace validation and goodness-of-fit tests have been used to provide quantitative analysis, which may improve decision analysis under uncertainties. The costing situation was so complex, and the adjustment factors and indices involved were imperfectly known, therefore the precise quantification of the results was not possible. The models show the effects of the significant factors, but do not aim to represent them exactly since they reflect the inherent uncertainties and opinion associated with cost data and estimating.

I was not involved in the removal of programming 'bugs' within VERT. The Management Centre at the University of Aston in Birmingham, under the guidance of Mrs V. Perks undertook this task. Problems were evidently encountered, as with any new computer program. Initially, the system refused to print-out histograms or provide assistance in FREE-FORMAT. Both of these problems were overcome. However, problems were persistent with the PLOT program which should have produced correlation plots of the VERT mechanical and electrical cost, time and performance variables (refer to 5.4.2v). Severe problems also existed when commanding programmer aid for the debugging mode. Despite these programming difficulties, VERT was successfully manipulated to produce the desired combined probabilistic time, cost and performance distributions or models.

6.1 Model verification and validation

Model verification and validation consists of three phases: model validation, computer model verification and operational validity (Cellier, 1982).

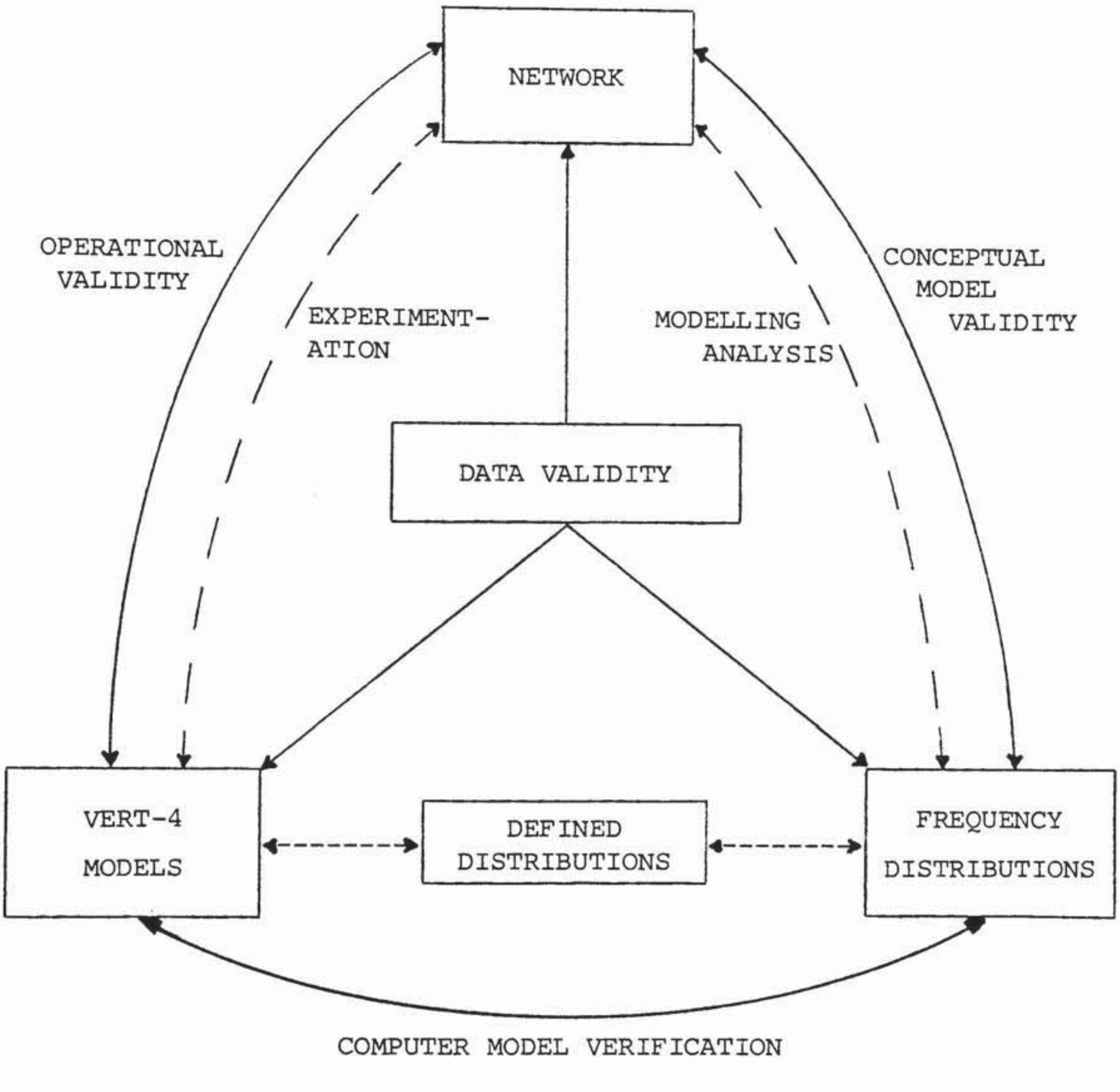


Figure 24 Model verification and validation

6.1.1 Sargent (1982) defined conceptual model validation as:

> "determining that the theories and assumptions are correct and the model representation of the problem entity is 'reasonable' for the intended use of the model."

Face validation and rules-of-thumb were used in this research to validate the conceptual model. Persons knowledgeable about the mechanical and electrical construction industry and the members of the ESD were asked if they could discriminate between current pre-tender estimates prepared using the traditional system and estimates, for the same project, based on the VERT models. In general the VERT models produced acceptable estimates, although depending on the quantity surveyor's expertise and knowledge of the particular projects, the random costings for some components were questioned. But the estimator was able to find an appropriate estimate within the ranges proposed by the VERT models. Extreme values were possible, but not always acceptable.

Discussions between myself, my industrial supervisor (Mr L. Coghill) and the members of the ESD were used to construct and evaluate the conceptual model network logic. Since the VERT program was very flexible, design options which were inconsistent with current practice were readily revised. Element and component logics were examined and assessed. The most troublesome aspect of the research was the definition of cost-design interrelationships. For example, the heat source components; only one boiler-plant room was required by most of the projects, but the size and cost of this component was very much dependent on the installations selected. Until rules-of-thumb could be defined, this problem was overcome by assigning a percentage of the heat source component to the installations defined in the project, based upon the serviced or treated floor area. This may not have been accurate, but as insufficient data was available, mathematical relationships and 'filter' logics (refer to 5.1.2) could not be utilised to provide a compound heat source element. The heat source element may also be dependent on the building parameters: shape, size, orientation and glazing areas (Garrett, 1975) but until the cost-design data becomes available and the specific algorithms are defined for combined installations, the network logic could not be designed to assess the cost-design interrelationships. Similar problems were also encountered with the electrical work in connection (EWIC) with mechanical installations (Flanagan, 1980 and Wood, 1975). Both of these problem areas, heat source and EWIC, were acknowledged within the research component definitions (Appendix 9.3) so that the quantity surveyor was aware of the procedures used to estimate these components, and could pay particular attention to these costs when preparing a pre-tender estimate.

6.1.2 To ensure that the computer programming and implementation of the network logic were correct, trace validation was used to verify the computerised models. This was necessary since problems had been experienced by the Management Centre staff when inputting the VERT program (refer to 6.0) and because the VERT program had not been used within the United Kingdom. Very little literature is available on this relatively new technique (refer to 3.6.6) and its reliability. A listing of all the active arcs and nodes for one hundred simulation iterations was used to indicate the paths taken through the network, and the values selected through the elements by way of the component arcs and decision nodes, to the terminal SUCCESS node. One hundred iterations were selected as a sizeable sample which could be manually manipulated and which represented sufficient quantities of data for all the design options in the network. The iterations were processed from the debug mode #1 (refer to 5.4.3) and were manually traced through the network. A trace validation sheet (Figure 25) was devised to aid with this time consuming task. The cost values, selected by the

COST ANALYSES Iteration No. Total Cost: £ ________

	Prestige				Prestige				Prestige			Comments:
Components	H	M	L	Components	H	M	L	Components	H	M	L	
ELEMENT 1												SANITARY INSTALLATTON
SANWCS				Urinals								
SANWHBS				Orkgftns								
SANOFS				Clnrsaks								
SANPTS				Macs								
ELEMENT 2												COLD WATER INSTALLATION
CWMAINS				Insultn								
CWPTS												
CWSTORAG												
ELEMENT 3												HOT WATER INSTALLATION
CHWPTS				Hwstorag								
				Shwht								
				Shwelc								
				Hinsultn								
				Pumps								
IHWPTS				ISTORAG				Ishwht				
								Ishwelc				
								Ihwht				
								Ihwelc				
ELEMENT 4												HEATING
FANCONV				Pwkfan								
				Htsfan								
				Elcfan								
PERCONV				Pwkper								
				Htsper								
				Elcper								
RADS				Pwkrad								
				Htsrad								
				Elcrad								
OPERFAN				Ofanper								
				Pwkper								
				Pwkdfan								
				Htsdpf								
				Elcdpf								
CAHU				Owkahu								AIR-CONDITIONING
				Terahu								
				Pwkahu								
				Htsahu								
				Elcanu								
VAV				Ahuvav								
				Owkvav								
				Tervav								
				Pwkvav								
				Htsvav								
				Elcvav								
VERSA				Ahuver								
				Owkver								
				Terver								
				Pwkver								
				Htsver								
				Elcver								
FANCOIL												
OVAVPER				Opervav								
				Pwkdper								
				Ahudvav								
				Owkdvav								
				Terdvav								
				Pwkdvav								
				Htsdvav								
				Elcdvav								
OVERSPER				Operver								
				Pwkdpc								
				Ahudver								
				Owkdver								
				Terdver								
				Pwkdver								
				Htsdver								
				Elcdver								
ELEMENT 5												VENTILATION
				EXTRACT				Exdwk				
								Exter				
								Exelc				
				SUPEXT				Sxdwk				
								Sxter				
								Sxelc				
				SUPPLY				Supdwk				
								Supter				
								Supelc				
ELEMENT 6												FIRE PROTECTION
HOSERLS				Spnklr								
				Lequip								
				Dryrsr								
				Alarms								
ELEMENT 7												LIFTS
				HLIFT				Hlftelc				
				ELIFT				Elftelc				
ELEMENT 8												ELECTRICAL INSTALLATIONS
EMAINS				600LUX				Spot				
ECABLE				500LUX				Gpo				
ETRUNK				300LUX				Ltng				
EMGNCY												
POWER												

Figure 25.0 Trace validation sheet

VERT program from the defined distributions for each component, were logged against a prestige level (High: H, Medium: M or Low: L) which were dependent upon which third of the distribution area, the costs were obtained. Appendix 9.7 illustrates some examples of mechanical and electrical cost analyses based upon the trace validation sheets. From these cost analyses, a deterministic estimating manual was created which enabled the quantity surveyor, with a specific budget per square metre, to ascertain the installation options available to the client and their relative prestige levels. Whenever a total cost per square metre was obtained from the VERT models, these could also be checked for content using the trace validation sheets.

Cost, time and performance values obtained from the one hundred iterations were also plotted manually and compared to the original sample data relative frequency distributions and the defined beta distributions (refer to 6.2: Statistical tests). The network logic and Monte Carlo selected probabilities were also checked from the iterations. A problem area identified in the network logic, which was not spotted by face validation tests, was that some iterations contained both air-conditioning and ventilation installations in the same serviced area. Unfortunately, there was not enough research time remaining in which to rectify this situation. However, in the future, a 'filter' option may be specified prior to the selection of the ventilation options which would eliminate their processing when any of the air-conditioning installations had been previously determined from the heating element. No iteration values were identical, so it was assumed that the random generators were not exhausted, however since the computer program was probably based on the multiplicative congurence method (Kohlas, 1982) it would be difficult to assess whether repetition had occurred for only one hundred iterations. The VERT manual (Moeller & Atzinger, 1983)[2] recommended that generally five hundred to one thousand iterations were more than adequate to ensure low estimation errors for final runs of the networks. The simulation functions or split-node logics functioned correctly, however the number of iterations affected the reliability of the percentage choices made at the Monte Carlo initiated nodes.

6.1.3 Operational validity could only be determined as new office development projects were estimated by the traditional techniques and compared to the VERT model estimates. Feedback would be essential to assess whether the pertinent characteristics of the model adequately represented the problem entity for the intended use of the model. Unfortunately there was insufficient time available to research into the model's operational validity since it may have been many months before a new office development project would discredit the VERT models. The models could have been executed under different conditions where critical or cost significant components could be reprogrammed or the network restructured. Again, time was too short but sensitivity analysis would be the next step to be taken in the research.

6.1.4 Data validity was contingent upon the raw data which was not held to be true with perfect certainty (refer to 4.4.4), therefore the resultant models could not be held with perfect certainty. The raw data was based on subjective judgement, expertise and opinion. The research models could not produce definitive answers. Component definitions, standardised cost analysis formats, adjustment factors and indices were all sources of data error (refer to 4.1.5). The accuracy of the data would be hard to define, but recognition of the existence of possible error margins within the structured framework may allow, with further research, accuracies to be determined. In essence this was one reason that stochastic networking was preferred to an analytical approach, because probabilistic estimating recognises the inherent uncertainties associated with cost, time and performance variables. As more data becomes available, the assumptions upon which the defined distributions were prepared can be rationalised, tuned and updated to produce a more valid picture of the situation and possible solutions. Rationalism of this sort, could be used as an historical method of validation.

6.2 Statistical tests

6.2.1 The mechanical and electrical estimates were researched on the assumption that the characteristics of the sample raw data on office projects would adequately reflect the characteristics of the aggregate or statistical population of all pre-tender estimates for mechanical and electrical installations within office developments. Although samples can not have precisely the same qualities as the population, statisticians have shown that in many circumstances the loss of precision does not take on large proportions. The larger the sample, the more realistic a representation of the population. Statistical sampling endeavours to determine how accurate a description of the population the sample and its properties can provide (Yeomans, 1968). A statistical population can be defined as every member of a group possessing the same basic and defined characteristics, but which vary in quantity or quality from each other. Statistical decisions are based upon tests of significance and hypotheses about the population (Spiegel & Bower, 1972). In general, a study of inferences made concerning a population by the examination of samples drawn from it, together with indications of the accuracy of such inferences using probability theory, is called statistical inference (Moore, 1979). In order that conclusions from sampling theory and statistical inference could be validated, in this research, the M&E samples were chosen randomly and were deemed to be representative of the population. The resultant probability distributions or models for time, cost and performance variables have been used to aid in the quantification of the data and opinion.

The Central Limit Theorem can be used to show that the arithmetic means of a large number of independent random variables converge with increasing observations ($N > 40$) to the standardised normal distribution (Kohlas, 1982) irrespective of the population; provided the population mean and variance are finite and the population size is at least twice the sample size. Given this knowledge, the standard deviation can be examined to find the sampling distribution of, for example, means, medians, standard deviations and variances. The standard deviation of a sampling distribution of a statistic is often called the standard error, which provides a measure of potential error involved in a population figure from a sample figure (Harper, 1982).

Two methods have been used within this research, large sampling methods ($N \geqslant 30$) and small sample or exact sampling methods ($N < 30$). The first method was used to compare the standard errors of the computer simulated distributions for one hundred and five hundred iterations (Footnote - Example A). The two methods were used to compare: the simulation distribution for one hundred iterations with the sample distribution (Footnote - Example B) and the resultant SUCCESS model from a five hundred iteration simulation with the sample distribution (Footnote - Example C). From the examples, it was shown that the precision of the sample statistic increased as the sample size was increased, in other words, for the fixed level of confidence (99%) the error intervals decreased as the number of iterations simulated were increased. Therefore, the quantity surveyor can be less certain of the accuracy of an estimated cost distribution, the fewer the number of project samples, and should examine closely those component distributions which were constructed from only a few office developments. Example B illustrated the two sampling methods. Example C showed that the estimated percentage error about the mean (at 99% confidence) for the resultant VERT mechanical and electrical cost model was 2%. However since the original component distributions were based on 35 or less office developments, the realistic percentage standard error about the mean was probably between 11-17% for most components. Platykurtic distributions with large standard errors, are less reliable estimators than leptokurtic distributions.

6.2.2 Models invariably incorporate associations and relationships between variables. Empirical testing of the VERT models required an appropriate statistical measure of association. Various techniques were available but the Chi-square test was considered the most appropriate, as a goodness-of-fit test, to compare one continuous distribution with another. Chi-square tests are not immune from criticism, as with null hypotheses testing (Phillips, 1973). Traditionally the variables should be independent, but as with most variables, a connection could probably be found. It is also an approximation technique, valid for moderate to large values of N, and should not be used where expected cell frequencies are less than five.

When the relative frequency distributions or probability density functions were defined from the raw data by the Beta family of distributions (refer to 4.4.6), the question arose as to whether the simulation iterations adequately represented the defined beta curves for the particular component arc's cost, time and performance variables. The Chi-square test was used to examine whether the differences between the expected and observed frequencies were genuine differences or whether they had arisen by chance (Beeston, 1983). Footnote - Example D examines the differences between the expected and observed frequencies for the arc 'wash hand basins' (SANWHBS). From the example it was shown that the departure of the observed data (Y_0) from the data expected (Y'_E)

under independence was not statistically significant, as the calculated value of Chi-square was less than the tabled values for 95% and 99% levels of confidence. It was concluded that the beta distribution mode 0.2, 3, 9 (p,q) defined had been adequately modelled by the VERT simulation at one hundred iterations. Therefore the differences between the defined beta frequency distributions and the VERT simulated beta frequency distributions were probably due solely to chance. However, this does not prove that there was no difference, in the case of the non-rejection of the null hypothesis, only that the figures did not prove a difference.

Other Chi-square significance tests indicated that the VERT program had accurately modelled the beta distributions defined from the sample data. Since it was shown through the use of face validation and trace verification techniques that the VERT program corrected simulated the mechanical and electrical networks (refer to 5.1.4) and that through large and small sampling techniques population error margins can be reduced using simulation, the only remaining computer output which required examination was the statistics computed from the VERT distributions.

6.2.3 The path costs for the Sanitary Fittings (SANFTG) element (refer to 5.1.4) were used to test the accuracy of the VERT simulated statistics. The distributions simulated for one hundred and five hundred iterations were shown to be derived from the same beta defined distribution using the Chi-square test. The statistics manually calculated for the one hundred iteration distribution (Appendix 9.8. 1) should therfore equal those calculated for the five hundred distribution by VERT (Appendix 9.9). Footnote examples E - K indicate the formulae used to test the VERT statistics. The results were tabulated:

STATISTIC	$\bar{X}$ £/m^2	$\tilde{X}$ £/m^2	$\hat{X}$ £/m^2	S £/m^2	V	SK	b_2
100 Iterations	3.4106	3.4 (3.4164)	3.6480	0.54 (0.5405)	0.16 (0.1585)	-0.44 (-0.4392)	3 (2.9749)
500 Iterations	3.4106	3.4 (3.4287)	3.6480	0.54 (0.5393)	0.16 (0.1581)	-0.44 (-0.4402)	3 (2.95)

Figure 26 Statistics for Sanitary Fittings (SANFTG)

where : $\bar{X}$ represents the arithmetic mean

$\tilde{X}$ represents the median

$\hat{X}$ represents the mode

S represents the standard deviation

V represents the coefficient of variation

SK represents the skewness

b_2 represents the Beta 2 measure of kurtosis.

From these results, it was shown that the VERT program calculated the resultant statistics correctly. The slight differences in the statistics: the median, standard deviation and kurtosis, may be due to the further refining four-hundred observations made by the simulation process and the significant number of decimal places used in the manual calculations. The median value was dependent on the observed 50th and 250th iteration values, when the observations were arranged in order of magnitude. Since it was shown (6.2.1) that standard errors were reduced when the simulation iterations were increased, likewise, the standard deviation may have been reduced due to the increased number of observations. I was, however, satisfied that VERT successfully calculated the resultant stochastic probability distribution's or model's statistics.

6.2.4 Before the analysis of the resultant models in terms of their practical use to the quantity surveyor, the value of the statistics supplied by VERT should be mentioned to guide the estimator. There are several types of averages that can be defined, the most common being the arithmetic mean, the median and the mode. (Geometric and harmonic means were not used in the research.) An average has a value which is regarded as typical or representative of a set of data. Each average or measure of central tendency has its advantages and disadvantages depending on the raw data, and the intended purpose of the statistic. Numerous statisticians (Spiegel, 1972; Harper, 1982 and Beeston, 1983) have commented on their relevant merits and demerits. The arithmetic mean is the best known and accepted of the averages. It is derived from every value in a given distribution and can be an actual observation value or technically impossible. The arithmetic mean can minimise squared errors in an estimate and be used for further statistical computations, but it can also be distorted by extreme values. The BCIS (1984) indicated that most building costs showed 'skewed' distributions and, in their opinion, the mode could give a better indication of typical costs. The mode can ignore the extreme values which distort the mean statistic, can be estimated from incomplete data and maximises the user's chance of being correct, but cannot be used for further statistical processing. The mode is affected by the choice of class or cell boundaries, which in turn can alter the shape of a distribution. Smoothing of a distribution can provide more stability, but this is dependent upon the opinion of the analyst, which can cause subjective results. The mode has been little used by quantity surveyors in the past because there was no guarantee that a mode would exist, or that there would be only one solution, causing discrepancies. Therefore, for practical purposes, the estimator would be well advised to ignor the mode unless it is distinct and definite, as in the case of ungrouped discrete data. The median could be used to minimise absolute error in estimates since there would be a fifty-fifty chance that the value would be equal or above the average. Harmer (1983) suggested that median rates should be preferred as the basis of an estimate. The median is unaffected by extreme values and can be computed from incomplete data, but it cannot be used for further statistical processing. When a choice of an average has to be made, for example, the cost of sanitary fittings for offices generally, the mean would supply an answer, since any typical office development would require a certain quantity of fittings at a mean cost. On the other hand, if an estimate were required for the overall cost of sanitaryware, the median may be the most useful, since the estimate would have a fifty-fifty chance of costing the median value. If, however, a client wished to tender keenly for an office development, the mode should be considered since it represents the cost of a typical office within the tendering environment and the cost most frequencly encountered in that environment.

The standard deviation measures the expected deviation of the values of a random variable from its expected value, the arithmetic mean (Kohlas, 1982). The VERT program defines the standard deviation as the standard error, which has great importance in statistical theory. However, since the standard deviation is an absolute measure of dispersion, comparisons cannot be made between the dispersions of various distributions that are in difference units of measurement but the coefficient of variation can be used, since this is generally expressed as a percentage. The greater the dispersion of a distribution, the higher the value of the standard deviation relative to the mean. The skewness statistic measures the distribution's departure from symmetry. A distribution is not markedly skewed when the Pearsons first coefficient of skew has an absolute value of less than one. VERT does not indicate the direction of skew from the statistic, but this may be observed from the relative frequency distribution. Kurtosis measures the degree of peakedness of a distribution relative to the normal distribution. For the normal distribution, kurtosis can be defined by $b_2 = 3$. Leptokurtic distributions have values of kurtosis greater than three and platykurtic less than three. When a distribution is defined as leptokurtic, it indicates that there is a high probability that costs for this component are close to the mean value; it may also indicate a relatively high degree of expertise and uniformity in costings. Platykurtic distributions may indicate that costs are uncertain or influenced by other factors, such as, quality or prestige.

To conclude, the validity of the VERT statistics were successfully tested. The resultant models enable the quantity surveyor to assess the costs of components and elements in the light of their distributions and statistics, before recommending an appropriate mechanical and electrical estimate for office developments. This probabilistic estimating technique has an advantage over deterministic methods since the quantity surveyor may consider alternative averages and the dispension of the data, rather than concentrating on the arithmetic mean. Professional interpretation can be applied with the full knowledge of the costing alternatives.

6.3 Element analysis

The VERT research program successfully produced the resultant combined cost, time and performance models (Appendix 9.9) for the eight main elements and the SUCCESS node (refer to 5.1.4) for mechanical and electrical engineering services installations in office developments. The simulation results provided unbiased distributions of the element and total costs, identified and evaluated the potential variations in statistics and indicated the criticality of the individual components. The summaries of the distributions and the statistics provided the quantity surveyor with comparative costs for alternative design solutions and provided measures of error or uncertainty associated with the various design proposals. However, the tender price for M&E engineering services has been shown to be affected by many parameters (for example, inflation indices, adjustment factors, errors and subjectivity). Consequently the costs predicted cannot be considered 'absolute values' since they were based on estimates with associated relative error bounds. The user of the models should be aware of their illusory accuracy, since the results were intimately bound by the raw data limitations (refer to 4.1), the judgements made at the time of classification (refer to 4.2) and cost analysis. The user may consider component distributions constructed from larger numbers of raw data projects as more accurate representations of reality and peaked distributions (refer to 4.4). However, this may also be misleading since some components may accurately command wide performance and prestige ranges (Cochran, 1976 and Southwell, 1968). To aid in the determination of the accuracy of the models, statutory and recognised rules-of-thumb were applied to examine whether the resultant costs and performance values reflected these accepted principles. The ESD also compared the resultant models with published cost data from pricing books and periodicals.

6.3.1 The eight resultant element cost models (sanitary fittings, cold water, hot water, heating, ventilating, fire protection, lifts and electrical installations) were examined individually to determine the practical implications of the network design logic and to assess the realism of the results.

i) The path cost for node SANFTG (Appendix 9.9) indicated that the total cost of sanitary fittings was not markedly skewed to the left, with a standard error of £0.54/m^2 and coefficient of variation of 16%. The 'averages' of £3.41/m^2, £3.43/m^2 and £3.65/m^2 were considered realistic and generally included for medium quality compulsory fittings (water closets, wash hand basins, overflows and sanitary points) and three out of four of the selected fittings (urinals, drinking fountains, cleaners sinks and macerators).

ii) The path cost for node COLDWT (Appendix 9.9) indicated that the total cost of cold water installations was not markedly skewed to the right, with a standard error of £0.76/m^2 and coefficient of variation of 24%. The 'averages' of £2.89/m^2, £3.07/m^2 and £3.15/m^2 were considered realistic and generally included for medium quality cold water points and cold water pipework insulation.

iii) The path cost for node HOTWT (Appendix 9.9) indicated that the total cost of hot water installations was markedly skewed to the right, with a standard error of £0.99/m^2 and coefficient of variation of 43%. The relative frequency distribution indicated two defined groupings of data. From an analysis of the iterations, it was shown that the lower valued group represented the costs for instantaneous non-storage and storage hot water installations, and the upper valued group represented the costs for centralised hot water installations. The associated statistics were, therefore, meaningless for the individual installation types. To correct this, the element would require alterations to be made to the network structure, although the quantity surveyor can observe the distinct distribution patterns for the instantaneous and centralised hot water systems. The iterations indicated that the instantaneous non-storage installations ranged from £0.41/m^2 - £1.28/m^2, the instantaneous storage installations ranged from £1.10/m^2 - £2.25/m^2 and centralised storage hot water systems ranged from £2.00/m^2 - £4.19/m^2. The nodes of £0.67/m^2, £1.36/m^2 and £2.90/m^2 observed from the relative frequency distributions were considered realistic for the respective installation types.

iv) The path cost for node HEATING (Appendix 9.9) indicated that the total cost of piped and air-conditioning installations was markedly skewed to the right, with a standard error of £25.54/m^2 and coefficient of variation of 70%. The relative frequency distribution indicated a distinct grouping of the data at the lower cost end of the range. This was due to the higher percentage of piped heating systems selected by the Monte Carlo initiated arcs. The statistics computed were not related to the individual installations, but gave an overview of heating systems in general. This element would require alterations to be made to the network structure (refer to 5.1.4) if the individual installations were required to be defined separately. The FAMILY MODE (Moeller & Atzinger, 1983)[2] alternative, available within VERT, would allow the quantity surveyor to overcome this problem and print-out models for more than the ten options currently available, however, the increase in program operating time would require financial consideration. The iterations indicated that radiator installations ranged from £7.83/m^2 - £62.97/m^2, fan convectors ranged from £7.83/m^2 - £37.90/m^2, perimeter convectors ranged from £15.00/m^2 - £42.92/m^2 and dual perimeter convectors and fan convectors ranged from £20.85/m^2 - £40.25/m^2. Hence the mode of £21.75/m^2 for piped heating systems. Dual Versatemp and perimeter convector systems represented the cheapest dual air-conditioning and piped heating system, at approximately £54.61/m^2. The central air handling air-conditioning system was represented as £57.64/m^2 and fancoil systems represented a constant at £68.31/m^2. Dual variable-air-volume and perimeter convectors ranged from £62.97/m^2 - £115.09/m^2, Versatemp systems ranged from £78.01/m^2 - £107.08/m^2 and variable-air-volume systems ranged from £111.09/m^2 - £118.10/m^2. The costs observed from the relative frequency distributions and the iterations were considered realistic for the respective installation types, however, due to the lack of data, cost predictions for fancoil units and dual systems were considered likely to be inaccurate.

v) The path cost for node VENTN (Appendix 9.9) indicated that the total cost of ventilation systems had a positive skew to the right, with a standard error of £29.76/m^2 and coefficient of variation of 1.16%. The statistics were rendered meaningless because of the inclusion of the 'no ventilation' or 'natural ventilation (NVENT) arc which particularly affected the calculation of the median and the mode. The network would require an alteration in the element structure to ensure that when the NVENT arc was selected, the arc input would bypass the total element node and enter directly the SUCCESS node (refer to 5.1.4), to overcome this problem. The relative frequency distribution indicated four distinct groups of data. From an analysis of the iterations it was shown that 50% of the processed arcs were for no ventilation, the cost of supply ventilation ranged from £4.33/m^2 - £21.64/m^2, extract ventilation ranged from £36.79/m^2 - £55.28/m^2 and, supply and extract ventilation systems ranged from £47.62/m^2 - £95.23/m^2. These were considered by the ESD to represent realistic cost ranges for each type of installation.

vi) The path cost for node FIRE (Appendix 9.9) indicated that the total cost of fire protection systems was markedly skewed to the left, with a kurtosis value of 5.45, indicating peakedness. The standard error was £5.00/m^2 and coefficient of variation 77%. From an analysis of the computer iterations the mean of £6.51/m^2, the mode of £4.70/m^2 and the median of £5.01/m^2 realistically represented the selection of hosereels, dry risers, loose equipment and alarms. Sprinkler installations ranged in cost from £8.96/m^2 - £25.15/m^2 and accounted for the long 'tail' to the right of the 'average' figures. The iterations also showed that sprinklers and dry riser installations were measured in the same area, which would be most unusual, therefore it was recommended that values above £18.47/m^2 were excluded from the models. The element network would require alteration, a FILTER option (Moeller and Atzinger, 1983)[2], to prohibit the combining of these two systems.

vii) The path cost for node LIFTS (Appendix 9.9) indicated that the total cost of lift installations had a negative skew to the left with a standard error of £9.99/m^2 and coefficient of variation of 72%. The statistics were rendered meaningless because of the inclusion of the 'no lifts' (NLIFT) arc which particularly affected the calculation of the median and the mode. The network would require an alteration in the element structure to ensure that when the

NLIFT arc was selected, the arc input would bypass the total element node and enter directly the SUCCESS node (refer to 5.1.4), to overcome this problem. The relative frequency distribution for the element indicated two distinct groupings of data for hydraulic and electric lift installations. From the iterations, it was shown that electric lifts ranged from £10.21/m^2 - £32.09/m^2 and hydraulic lifts ranged from £16.75/m^2 - £21.88/m^2. These were considered realistic cost ranges for each type of installation.

viii) The path cost for node ELECTRIC (Appendix 9.9) showed that the total cost of electrical installations was neither markedly skewed or peaked, although a slight positive skew to the right was observed since the mean > median > mode. The standard error was £5.09/m^2 and the coefficient of variation 16%. From an analysis of the iterations, the mode of £29.73/m^2 indicated a medium quality installation with 500 Lux lighting levels and two out of three of the selected components (spot lighting, telephone lines and lighning protection). The higher costs were generally incurred when the 600 Lux lighting fittings option was selected by the program. The resultant model was considered by the ESD to realistically represent the electrical installation cost range in the light of current knowledge.

The resultant element cost models were generally successful and representative of the current estimating knowledge of engineering services within Monk Dunstone Associates. They provided the quantity surveyor with an overview of all historical element costs and with the means to state confidence levels for alternative design installations; for example, the estimator may conclude from the models that the client has an 85% probability of successfully contracting the installation of a radiator system for £52.00/m^2 (plus mark-ups and profit - refer to 4.2.2) and may advise that perimeter convectors and fan convectors may provide an alternative heating installation for less than this cost yardstick. The quantity surveyor must, however, be aware of all the performance and time variables which may affect the choice of an installation type (refer to Appendix 9.3) and apply his/her expertise to assess an appropriate estimate within the installation range of costs.

6.3.2 Heuristics are commonly defined as the use of rules-of-thumb to solve problems (Meidan, 1981). Baumol and Quandt (1964) stated that rules-of-thumb were among the more efficient pieces of equipment used for optimal decision making and not evidence of sloppy workmanship. Rules-of-thumb can be objectively measured and communicable, they are usually simple, inexpensive and suitable for frequent repetition and for spot checking. Within the ESD (Engineering Services Division), quantity surveyors used rules-of-thumb to reason estimates for mechanical and electrical services, based on experience and statute guidelines. To aid in the examination of the reflected realism of the cost models, statutory and recognised rules-of-thumb were applied to a 'standardised' office development, observed from the raw data (refer to Footnote) and compared with the resultant performance models and raw data frequency distributions.

ELEMENT	COMPONENT	RULES-OF-THUMB	PERFORMANCE MODES
		(Footnote examples L - Q)	(Appendix 9.9)
Sanitary Fittings	Water Closets	0.004-0.005 Nr./m^2	0.005 Nr./m^2
	Urinals	0.001-0.002 Nr./m^2	0.001 Nr./m^2
	Wash hand basins	0.005 Nr./m^2	0.005 Nr./m^2
Cold Water Installations	Cold Water storage	3.5 litres/m^2	3-4 litres/m^2
Hot Water Installations	Hot water storage	0.45-0.50 litres/m^2	0.55 litres/m^2
	Heat source	0.010-0.012 KW/m^2	0.010 KW/m^2

Heating Installations	Heat source	0.10 KW/m^2	0.12 KW/m^2
	Cooling loads	0.045 tonnes (refrig.)/m^2 (MDA Rule-of-Thumb)	0.04 tonnes/m^2
Fire Protection Installations	Dry risers	0.0011 Nr./m^2	0.0012 Nr./m^2
	Hosereels	0.0125 Nr./m^2	0.0025 Nr./m^2
	Alarms	0.0333 Nr./m^2 (Fire Protection Assoc., National Fire Code and Burberry, 1977)	0.0006 Nr./m^2
Lift Installations	Lifts	0.0004-0.0009 Nr./m^2	0.0006 Nr./m^2
Electrical Installations	Light fittings:		
	300 Lux	0.123-0.302 Nr./m^2	0.195-0.268 Nr./m^2
	500 Lux	0.204-(0.213)-0.503Nr./m^2	0.164-0.270 Nr./m^2
	600 Lux	0.245-0.603 Nr./m^2	0.164-0.200 Nr./m^2

The performance models obtained from the raw data were shown, by comparison, to successfully reflect the rules-of-thumb used within the engineering services industry. However, it should be noted that the interrelationships between components and their performance is extremely complex, for example, the relationship between hot water storage and the heat source or boiler power components. Heating systems require a detailed knowledge of the shape of a building, the number of storeys, the building orientation, the percentage of glazing, the fabric construction, lighting levels, infiltration rates and whether the installation is to be centralised or decentralised (Wood, 1975 and Watson, 1980[2]). Unfortunately, at the pre-tender estimating stages, few of these details were known or recorded by the research historical cost analyses; consequently rules-of-thumb obtained for fuel storage capacities (Porges, 1982), heat gains and losses (Garrett, 1975 and 1981), cooling loads (Missenden, 1974), ductwork labour factors (Hall, 1984) and labour factors for the installation and erection of heating and ventilating equipment (Porges, 1982) were not compared in the research, due to the lack of performance details. Rules-of-thumb for ventilation requirements within office developments (Wise, 1979; Porges, 1982; Building Regulations, HMSO, 1976; Garrett, 1975 and Warren, 1984) indicated that there should be 1-3 air changes per hour of natural ventilation or 3-8 air changes per hour (21-22 m^3/hr) of mechanical ventilation. Since none of the historical projects indicated the number of air changes, no rules-of-thumb could be used to assess the performance of the ventilation element.

Lift installations are a major item of expenditure and are also dependent on a great number of factors: the height of the building, its shape, number of zones, population, the lift car capacity, speed, prestige levels, door operating times, traffic flow, passenger transfer and waiting intervals, the running time, number of floors and round trip times (Pinfold, 1966; B.S.5655, 1981; Boje, 1971; Cain, 1975; IHVE B15, CIBSE, 1972; Bedford & White, 1983; PSA, 1982 and Flanagan, 1980). Knight and Duck (1962) identified the major design-cost criteria as the number of lift cars, the number of floors served, the lift car speed, the type of control system, the size and specification of the lift car and the height of the building. Lift manufacturers were contacted and stated that the grouping of the lift cars, special conditions (exposed shaft to the weather, side hung lift cars and glass walled lifts) and the location of the lift motor room also influenced the costs. However it was shown by Bowen (1982) that there was a direct relationship between the gross floor area and the number of lifts.

Rules-of-thumb were also obtained for electrical design installations (Johnston, 1969; Butler, 1976; Butler, 1977; Burberry, 1977 and Bathurst, 1971). These were generally highly specialised, requiring details of a specific nature which were unobtainable from the historical pre-tender estimates.

6.3.3 The VERT research program produced the resultant models for the total cost (time and performance) of mechanical and electrical services within office developments. The overall SUCCESS models (Appendix 9.9) indicated that the total cost of the combined mechanical and electrical costs ranged between £51.38/m^2 - £265.75/m^2 with a distribution skewed to the right and approximately normal kurtosis. The standard error was shown to be £40.10/m^2 and the coefficient of variation, 33%. The stochastically calculated models combined the variabilities of the costs of the individual components and elements, and demonstrated the range of possible cost-design solutions for an M&E project. The models enabled the quantity surveyor to consider the full range of alternative designs (based on the historical data) in a probabilistic rather than deterministic manner and consider quantitatively the uncertainty or risk inherent in pre-tender estimates. The total cost of engineering services within office developments could, from the cumulative frequency distribution, be stated with an associated degree of confidence; for example, the estimator may state that there was a 90% chance that the total cost of M&E services, for a particular project, would not exceed £172.18/m^2. The quantity surveyor was, therefore, able to consider a far wider range of alternative designs, in a shorter space of time and with a specified measure of risk. In theory costs could also have been separated into labour and material costs, by the simple deduction of the labour distribution from the total cost distribution. At present however, due to the lack of labour factors within the research data, it would be unwise to rely on the resultant total time distribution until further data input, although the VERT research program does provide for this valuable facility in the future.

The VERT research program also produced the resultant nodes and arcs critical path indices, weighted for cost (refer to 5.2.1 : The control and problem options module, columns 51-53). These print-outs enabled the quantity surveyor to consider the cost significant components and elements within the engineering services network. Elements 4, 5 and 8: Heating, Ventilating and Electrical installations were considered the most cost significant elements. Within these elements i) perimeter convectors, radiators, the dual piped heating installation and all the air-conditioning installations, ii) all the ventilating installations, and iii) the electrical mains, trunking, power points and lighting installations, were the cost significant components. This broadly confirmed the belief that 80% of the value of mechanical and electrical services work was related to 20% of the items (Harmer, 1983 and Spooner, 1974). The quantity surveyor could, therefore, pay greater attention to these items when preparing an estimate and concentrate on the associated risks with those components.

Footnotes:

1. Example A

The Sanitary Fittings (SANFTG) element (refer to 5.1.4) was used to compare the standard errors about the mean for a one hundred iteration simulated distribution (Appendix 9.8.1: obtained from the trace validation sheets 6.1.2) and the resultant five hundred iteration simulated distribution produced by VERT (Appendix 9.9: Path cost for node SANFTG).

For large samples the confidence limits for the population mean are given by the formula:

$$\overline{X} \pm Z_c \frac{s}{\sqrt{N}} \qquad \text{or} \qquad \overline{X} \pm Z_c \sigma_{\overline{x}}$$

(Spiegel & Bower, 1972)

where: $\overline{X}$ = sample mean

Z_c = confidence coefficient (a confidence interval of 99% was used by the research, therefore $Z_c = 2.58$)

$\sigma_{\overline{x}}$ = standard error of the mean

s = standard deviation of the sample

N = number of observations or iterations.

Therefore the standard error about the mean for SANFTG at one hundred iterations was:

$$\overline{X} \pm Z_c \frac{s}{\sqrt{N}} \quad => \quad 3.4106 \pm 0.14$$

The standard error about the mean for SANFTG at five hundred iterations was:

$$\overline{X} \pm Z_c \frac{s}{\sqrt{N}} \quad => \quad 3.4106 \pm 0.06$$

Since the distribution range for SANFTG was from 5.2881 - 2.2293 £/m^2, in absolute terms £3.05/m^2. The estimated percentage error was reduced from ± 5% to ± 2%.

2. Example B

The Water Closets (SANWCS) component (refer to 5.1.4) was used to compare the standard errors about the mean for a one hundred iteration simulated distribution (Appendix 9.8.2: obtained from the validation sheets 6.1.2) and a sample distribution constructed from the raw data (Appendix 9.8.2: observed frequencies.

The standard error about the mean for SANWCS at one hundred iterations was:

$$\overline{X} \pm Z_c \frac{s}{\sqrt{N}} \qquad 0.62 \pm 0.05$$

The standard error about the mean for SANWCS observed from the raw data, a small sample ($N < 30$), was obtained from the formula:

$$\overline{X} \pm t \frac{s}{\sqrt{N-1}} \qquad \text{or} \qquad \overline{X} \pm t\sigma_{\overline{X}}$$

(Beeston, 1983 and
Harper, 1982)

where: t = confidence coefficient obtained from the students' 't' distribution at 99% level of confidence, with the relevant degrees of freedom.

Therefore the standard error about the mean for SANWCs obtained from the raw data was:

$$\overline{X} \pm t \frac{s}{\sqrt{N-1}} \quad \Rightarrow \quad 0.63 \pm 0.17$$

where the degrees of freedom (v) = 24 and $t = 2.81$.

Since the distribution range for SANWCS was from 0.15 - 1.34 £/m^2, in absolute terms £1.19/m^2. The estimated percentage error was reduced from ± 14% to ± 4%.

3. Example C

The SUCCESS terminal node (refer to 5.1.4) was used to compare the standard errors about the mean for a five hundred iteration simulated distribution (Appendix 9.9: Path cost for node SUCCESS) and a hypothetical combined distribution constructed from the raw data.

The standard error about the mean for SUCCESS at five hundred iterations was:

$$\overline{X} \pm Z_c \frac{s}{\sqrt{N}} \quad \Rightarrow \quad 123.0900 \pm 4.72 \text{ (or } \pm 2\%)$$

The standard error about the mean for the hypothetical combined mechanical and electrical distribution constructed from the raw data sample may have been:

$$\overline{X} \pm Z_c \frac{s}{\sqrt{N}} \quad \Rightarrow \quad 123.0900 \pm 18.10 \text{ (or } \pm 8\%)$$

If all 35 office developments were used.

However, since not all thirty-five office developments were used to construct the sample component distributions, because of the lack of data or choices involved, it was difficult to predict the standard error about the mean for the resultant model representing the overall costs of mechanical and electrical services, had the raw data sample distributions been combined. The small sample method can be used to indicate more realistic values for the standard errors about the mean. If twenty-four projects had been used:

$$\overline{X} \pm t \frac{s}{\sqrt{N-1}} \quad \Rightarrow \quad 123.0900 \pm 23.96 \text{ (or } \pm 11\%)$$

If thirteen projects had been used:

$$\overline{X} \pm t \frac{s}{\sqrt{N-1}} \qquad 123.0900 \pm 36.13 \text{ (or } \pm 17\%)$$

The estimated percentage error about the mean increased as the sample size decreased.

NOTE: The examples A - C only consider the confidence limits above and below the mean, but other intervals or standard errors can be calculated from the sample statistics.

4. Example D

The path cost for arc 'wash hand basins' (SANWHBS - refer to 5.1.4) was used to examine (using the Chi-square- χ^2-test) whether the differences between the defined beta curve for the component and the VERT simulated beta curve at one hundred iterations, were genuine differences or whether they had arisen by chance.

Chi-square was determined from the formula:

$$\chi^2 = \frac{\Sigma(\text{Actual - Expected value})^2}{\text{Expected value}} = \frac{\Sigma(0 - E)^2}{E}$$

(Harper, 1982 and Phillips, 1983)

$$= \frac{\Sigma(\text{Observed frequency - the normalised expected frequency})^2}{\text{Normalised expected frequency}}$$

$$= \frac{\Sigma(Y_0 - Y'_E)^2}{Y'_E}$$

(Refer to Appendix 9.8.3 for the calculations)

$\chi^2 = 6.62$

The degrees of freedom = The number of groups - 1 - the number of parameters
= 7 - 1 - 2 (p & q)
= 4

From χ^2 tables (Spiegel, 1972) at 0.95 and 0.99 levels of confidence, χ^2 equalled 9.49 and 13.30 respectively.

Therefore: $\chi_o^2 < \chi^2$ tabled since $6.62 < 9.49 < 13.30$.

NOTE: The following examples E - K indicate the formulae used to test the VERT statistics. Reference should be made to Appendix 9.8.1 for the one-hundred iteration manual statistics and Appendix 9.9: Path cost for node Sanitary Fittings (SANFTG) for the resultant VERT five-hundred iteration statistics.

5. Example E

The mean of a set of N observations is the arithmetic average. It is denoted by $\overline{X}$ and is the sum of the observations divided by the number of observations (Moore, 1979 and Spiegel, 1972).

$$\overline{X} = \frac{\Sigma fx}{\Sigma f} = \frac{\Sigma fx}{N}$$

where X denotes the observation or mid point of the class

f denotes the frequency

Σf represents the total frequency.

$$\overline{X}_{100} = \frac{3.4106}{1} = £3.4106/m^2$$ (Refer to Appendix 9.8.1)

$$\overline{X}_{500} = £3.4106/m^2$$ (Refer to Appendix 9.9)

Therefore $\overline{X}_{100} = \overline{X}_{500}$

6. Example F

The median can be described as the typical value, as it is the mid-point of the observations, when they are arranged in order of magnitude or the arithmetic mean of the two middle values. It is denoted by $\tilde{X}$ and divides a histogram or distribution into two parts which have equal areas.

$$\tilde{X} = L_1 + \left(\frac{\frac{N}{2} - (\Sigma f)_1}{f \text{ median}} \right) c$$ Spiegel, 1972

where L_1 denotes the lower class boundary of the median class

N denotes the total frequency

$(\Sigma f)_1$ = the sum of the frequencies lower than the median class

f_{median} = the frequency of the median class

c = the size of the median class interval.

$$\tilde{X}_{100} = 3.3390 + \left(\frac{0.5 - 0.442}{0.104}\right) 0.1388$$

$$= 3.4164 \doteq £3.4/m^2$$

$$\tilde{X}_{500} = 3.4287 \doteq £3.4/m^2$$

Therefore $\tilde{X}_{100} \doteq \tilde{X}_{500}$

7. Example G

The mode is the value which has the maximum frequency among the observations, that is, the most common value. It is denoted by $\hat{X}$ and defined by the formula:

$$\hat{X} = L_1 + \left(\frac{\Delta 1}{\Delta 1 + \Delta 2}\right) c$$

Spiegel, 1972

where L_1 denotes the lower class boundary of the modal class

$\Delta 1$ = excess of modal frequency over the frequency of the next lower class

$\Delta 2$ = excess of modal frequency over the frequency of the next higher class

c = the size of the modal class interval.

$$\hat{X}_{100} = 3.6165 + \left(\frac{0.01}{0.01 + 0.034}\right) 0.1387$$

$$= £3.6480/m^2$$

$$\hat{X}_{500} = £3.6480/m^2$$

Therefore $\hat{X}_{100} = \hat{X}_{500}$

8. Example H

The standard deviation measures the degree to which numerical data tends to spread about an average, or the dispersion of data. It is denoted by S and is defined by the formula:

$$S = \sqrt{\frac{\Sigma f\,(X - \bar{X})^2}{N}}$$ Spiegel, 1972

where X denotes the mid-point of the class

f denotes the frequency

$\bar{X}$ denotes the arithmetic mean

N represents the total frequency

$$S_{100} = \sqrt{0.2921} = 0.5405 \triangleq £0.54/m^2$$

$$S_{500} = 0.5393 \triangleq £0.54/m^2$$

Therefore $S_{100} \triangleq S_{500}$

9. Example I

The coefficient of variation is the ratio of the standard deviation to the mean and is an abstract measure of dispersion independent of the units of measurement. It is denoted by the letter V and can be defined by the formula:

$$V = \frac{S}{\bar{X}}$$ Spiegel, 1972

where s represents the standard deviation

$\bar{x}$ represents the arithmetic mean.

$$V_{100} = \frac{0.5405}{3.4106} = 0.1585 \triangleq 0.16$$

$$V_{500} = \frac{0.5393}{3.4106} = 0.1581 \triangleq 0.16$$

Therefore $V_{100} \triangleq V_{500}$

10. Example J

Skewness is the degree of asymmetry of a distribution. For skewed distributions the mean and mode are related to the direction of skew. Skewness is denoted by Sk and can be defined by:

$$SK - \frac{\bar{X} - \hat{X}}{s}$$ Spiegel, 1972
Pearson's first coefficient of skew.

where $\bar{X}$ represents the arithmetic mean

$\hat{X}$ represents the mode

s represents the standard deviation.

$$SK_{100} = \frac{3.4106 - 3.6480}{0.5405} = -0.4392 \hat{=} -0.44$$

$$SK_{500} = \frac{3.4106 - 3.6480}{0.5393} = -0.4402 \hat{=} -0.44$$

Therefore $SK_{100} \hat{=} SK_{500}$

11. Example K

Kurtosis measures the degree of peakedness of a distribution relative to the normal distribution. The Beta-2 measure of Kurtosis uses the fourth moment about the mean, expressed in a dimensionless form. It is usually denoted by b_2 and can be defined by:

$$b_2 = \frac{m_4}{s_4} = \frac{m_4}{m^2{}_2}$$ Spiegel, 1972

where the moments for grouped data are given by the formulae:

$$m_r = \frac{\Sigma f(X - \overline{X})^r}{N} = (X - \overline{X})^r$$

$$m_r' = \frac{\Sigma f(X - A)^r}{N} = (X - A)^r$$

The r^{th} moment about the mean $\overline{X}$ and about any origin A (an assumed mean). The relationships between the moments about the mean and about an arbitrary origin are:

$$m_2 = m_2' - m_1'^2$$

$$m_3 = m_3' - 3m_1' m_2' + 2m_1'^3$$

$$m_4 = m_4' - 4m_1' m_3' + 6m_1'^2 m_2' - 3m_1'^4$$

$$m_1' = \overline{X} - A = c \frac{\Sigma fu}{N}$$

$$m_2' = c^2 \frac{\Sigma fu^2}{N}$$

$$m_3' = c^3 \frac{\Sigma fu^3}{N}$$

$$m_4 = c^4 \frac{\Sigma fu^4}{N}$$

where $x_j = A + CU_j$

c = the class interval

U_j can be a positive or negative integer or zero.

For 100 iterations:

$$m_1' = 0.1387 \cdot \frac{0.016}{1} = 0.0022$$

$$m_2' = 0.1387^2 \cdot \frac{15.188}{1} = 0.2922$$

$$m_3' = 0.1387^3 \cdot \frac{14.716}{1} = 0.0393$$

$$m_4' = 0.1387^4 \cdot \frac{687.020}{1} = 0.2543$$

$$m_1 = 0$$

$$m_2 = 0.2922 - 0.0022^2 = 0.2922$$

$$m_3 = 0.0393 - 3(0.0022)(0.2922) + 2(0.0022)^3 = 0.0374$$

$$m_4 = 0.2543 - 4(0.0022)(0.0393) + 6(0.0022)^2(0.2922) - 3(0.0022)^4 = 0.2540$$

$$b_2 = \frac{0.2540}{(0.2922)^2} = 2.9749 \triangleq 3$$

For 500 iterations : $b_2 = 2.95 \triangleq 3$

Therefore $b_{2(100)} \triangleq b_{2(500)}$.

NOTE: The examples L - Q test the relationships between accepted rules-of-thumb for engineering services installations and the resultant performance models. The tests were based on the office developments selected from the research raw data (refer to 4.1.4) which were of a medium size, on average, five storeys high and had an 'average' gross floor area of 4600m^2. From the cost analyses, occupancy loads were based upon gross floor areas and varied between 5m^2 and 12m^2 per person, although they may be as high as 25m^2 per person (Scholfield, Raftery and Wilson, 1982). Based upon a rule-of-thumb of 10m^2 per person, there would be approximately 460 occupants (50% women and 50% men) within the 'typical' research office development.

12. Example L Sanitary Fittings

i) CP 305: Part 1: 1974 (BS 6465: 1984) BSI Catalogue (1985).

Women require : 5 Nr. WCs for 100 persons plus 1 for every additional 25 persons or part thereof.

Men require : 4 Nr. WCs for 100 persons plus 1 for every additional 25 persons or part thereof but 1 in 4 of the additional fitments may be a urinal. 4 Nr. urinals for 100 persons plus the number determined by the WCs.

There should be at least 1 WC per floor.

Therefore, for 230 female occupants: 11 Nr. WCs would be required and for 230 male occupants: 9 Nr. WCs would be required and 5 Nr. urinals. In total 20 Nr. WCs (0.004 Nr./m^2) plus 5 Nr. urinals (0.001 Nr./m^2) would be the required minimum.

ii) I.H.V.E. Guide B4-5 Table B4.3 (CIBSE: B4, 1972).

Women require : 1 Nr. WC plus 1 Nr. WC per 14 persons for up to 100 persons, plus 1 Nr. WC per 20 persons over 100 occupants.

Men require : 1 Nr. WC plus 1Nr. EC per 25 persons for up to 100 persons, plus 1 Nr. WC per 30 persons over 100 occupants.

Therefore, for 230 female occupants: 15 Nr. WCs would be required and for 230 male occupants: 10 Nr. WCs would be required. In total a minimum of 25 Nr. WCs (0.005 Nr./m^2) would be then required.

iii) The Offices, Shops and Railway Premises Act, 1963 (DOE, 1971).

Women require : 6 Nr. WCs for 100 persons, plus 1 for every additional 20 persons and 6 Nr. wash hand basins for 100 persons, plus 1 for every additional 20 persons.

Men require : 4 Nr. WCs for 100 persons, plus 1 for every additional 33 persons and 4 Nr. urinals for 100 persons, plus 1 for every additional 40 persons over 200 occupants. 5 Nr. wash hand basins for 100 persons, plus 1 for every additional 25 persons.

Therefore, for 230 female occupants: 13 Nr. WCs and 13 Nr. wash hand basins would be required. For 230 male occupants 8 Nr. WCs, 8Nr. urinals and 10 Nr. wash hand basins would be required. In total 21 Nr. WCs (0.005 Nr./m^2), 8 Nr. urinals (0.002 Nr./m^2) and 23 Nr. wash hand basins (0.005 Nr./m^2) would be the required minimum.

13. Example M Cold water installations.

Code of Practice 310 (BSI Catalogue, 1985) states that offices without canteens require 35 litres of cold water storage to be provided to cover 24 hours interruption of supply, per occupant. Since the 'typical' office development, observed in the raw data, allowed approximately 10 m^2 per occupant, 3.5 litres/m^2 of cold water storage was the required minimum.

14. Example N Hot water installations.

Rules-of-thumb for hot water storage:

i) 4.5 litres / person (The Institute of Plumbing, 1977)
ii) 4.6 litres / person (Burberry, 1977)
iii) 5.0 litres / person (BS 6465: 1984)

These represent a range of 0.45 - 0.50 litres/m^2 for the 'typical' office development observed in the raw data.

Rules-of-thumb for boiler power requirements range from 0.120 KW per person (Burberry, 1977) to 0.100 KW per person (BS 6465: 1984) or 0.012 - 0.010 KW/m^2.

15. Example O Heating installations.

Garrett (1981) gave a simple formula for the estimation of cooling loads, based on some assumptions regarding the building structure:

$$Q = 1.06 (K_1 (T_E + T_N + 1.5T_S + 3.5T_W) + F (Z + 25S) + 320P + 2V + E) \text{ watts.}$$

(for a building with one wall facing due south, single glazing)

where: T = total area of glass and wall (m^2)
F = total area of floor and roof (m^2)
V = volume of building (m^3)
P = number of occupants
S = number of storeys
E = heat from installed equipment
Q = heat load.

For the 'typical' observed office development with 66% glazing, 4600m^2 gross floor area, 5 storeys, 3.0m floor to ceiling height and 10m^2 per occupant, the formula reduced to:

$$Q = 1.06 (217350 + 1994 + 147200 + 27600 + 10\%)$$

$$= 459571.90 \text{ watts}$$

$$\hat{=} 0.10 \text{ KW/m}^2$$

16. Example P Lift installations

The following rules-of-thumb for lift installations were obtained for analysis with the raw data 'typical' office developments of five storeys and 4600m^2 gross floor area.

i) Smith and Julian (1976) stated that 4 Nr. 1150Kg (12 person) lifts at 2.5 m/s would be required if the office was zoned and 3 Nr. 900Kg (10 person) lifts at 1.5 m/s would be required for a single tenant office development.

ii) Hammond and Champness (1982) recommended 2 Nr. 12 person lifts at 0.75 m/s (hydraulic or electric).

iii) Williams (1974) recommended 2 Nr. 8-10 person lifts at 1.00 m/s.

iv) PSA (1975) recommended 2 Nr. 8-10 person lifts at 1.00 m/s based on BS 2655: 1971 (BSI Catalogue, 1985).

(All the information was taken from the tables provided by each reference.)

Therefore, the estimates indicated that 2-4 Nr. lifts (0.0004 - 0.0009 Nr./m^2) would be required, which should range between 8-12 persons capacity, travelling at between 0.75 - 2.5 m/s.

(CP 407: 1972 stated that it would be a 'poor' lift service if only one lift was provided for five floors.)

17. Example Q Electrical installations

i) The IHVE Guide B9.6 (1970) indicated the following rule-of-thumb for the estimation of light fittings.

$$\text{No. of luminaires} = \frac{\text{Area x lighting load/m}^2}{\text{Voltage x current load/luminaire}}$$

For the 'typical' office development (4600m^2, 500 Lux):

$$\text{No. of luminaires/m}^2 = \frac{60\text{W/m}^2}{415\text{V x } 0.68 \text{ amps}}$$

$$= 0.2126$$

ii) MDA applied the following table of fittings per m^2:

Lux level	Fluorescent fittings/m^2	Tungsten fittings/m^2
300	0.123	0.302
400	0.163	0.402
500	0.204	0.503
600	0.245	0.603
700	0.286	0.704

based on the formula

$$\text{Nr./m}^2 = \frac{E}{F \times UF \times MF} \qquad \text{(Burberry, 1977)}$$

where: Nr. = Number of fittings required

E = Illuminance level required (Lux)

F = Average luminous flux from each lamp (lm)

UF = Utilisation factor

MF = Maintenance factor.

For example:

Nr. of 80W fluorescent lamps/m^2

$$= \frac{\text{Lux level}}{4800 \times 0.60 \times 0.85}$$

$$= \frac{\text{Lux Level}}{2448}$$

and

Nr. of 150W tungsten fittings/m^2

$$= \frac{\text{Lux level}}{1950 \times 0.60 \times 0.85}$$

$$= \frac{\text{Lux level}}{994.5}$$

7.0 Further research

Further research into many of the subject areas examined by this project could be undertaken. Initially research into estimating methods, alternative techniques for presenting cost data and the relationship between costs and gross floor areas should be examined. The methodology used by the BCIS (Building Cost Information Service) to construct its tender price index has been questioned (Ferry & Hunter, 1986) recently, therefore the reliability and production of an M&E tender price index should be researched. Analysis into the influence of the construction duration, the resources involved and the operational sequence of construction versus the complexity of the components within a project should be examined. Alternative adjustment factors should be researched such as length/breadth indices, plan/shape indices, internal building lay-out factors (cellular vs open plan offices, for example), wall/roof ratios and contract period factors. Further research into the relationship between tender prices and performance factors would prove valuable, as estimators may indicate higher costs to reflect high qualities or prestige levels, greater margins on plant and equipment sizing to allow for future demands and increased standby facilities. It may be cost effective to the client, in the long term, if a longer life were achieved for plant items, components were better co-ordinated and lower running costs were achieved through greater control and energy management systems. The quantity surveyor should be aware of the capital and costs-in-use in the short and long term, also the relationships between energy, fabric, heat losses, quality, quantity and cost. Unfortunately, at present, due to the lack of data supplied with estimates, it would be difficult to analyse the cost data in relation to all the design parameters, and as such, models can only remain as checking tools rather than adequate design-cost estimators. The inter-active nature of services installations and the building structure necessitates co-ordination. Further research into component definitions and resources would also improve the quantity surveyor's understanding of services installations. Research must aim to go beyond the description of the variability in costs and strive towards a more meaningful analysis of the reasons for cost variability.

Within this project, no account could be taken of the interrelationships between some components, which may be remedied in the future by rule-of-thumb algorithms and VERT's network filters. The development of algorithms from experience, regulations and statutory requirements (as they change) would keep the data base up-to-date technologically and represent more realistically component interdependence. The PLOT function, available within VERT, may aid in their identification. Tests indicated that some minor changes to the mechanical and electrical network were required; ventilation and air conditioning systems were present in the same area, so were dry risers and sprinklers, both could be rectified, in the future, by the implementation of the FILTER option; also to improve the accuracy of the statistics, some non-selected installations (NLIFT and NVENT) would be directly inputted into the terminal node rather than the element nodes. The network provided a framework for further research into alternative design installation, elements, components, definitions and indices. In the future other building types and alternative M&E installations may be considered, for example, rainwater installations, external drainage and disposal services. Because VERT is so flexible components may also be sub-divided, if necessary, to reflect graded outputs, prestige levels and other influencing factors. One problem encountered, when using VERT, was the isolation of the total accumulated times (SUCCESS time distribution) so that labour factors could be costed independently and combined with the material costs. This was not possible within the research since the VERT program only combined time factors for those arcs on the critical path. It may however be possible to overcome this problem with the use of one of the many mathematical functions available within the program. Research into the labour factors associated with mechanical and electrical installations should be a priority undertaking.

In the future, more data will become available, therefore the operational validity of the resultant models may be evaluated in conjunction with the more conventional or traditional estimating techniques, over a period of time. Sensitivity tests may also be undertaken to examine the cost significance of components in greater depth and the Monte Carlo selected percentages. Perhaps trend control charts and deviation cost analyses may be used to monitor the changes in costs and the technological data. VERT paid little attention to aiding the modeller with the handling of the raw data, as it was assumed that the data had been previously analysed prior to input. Histogram satellite arc records could have been used to input data in the form of frequency graphs but these occupy large amounts of computer storage space, are time consuming to input, ignore opinion analysis and would have created deterministic resultant models. A tag-on statistical computer package would have helped to meet these data management needs and would also have aided in distribution modification and validation techniques. A VERT tag-on network for the addition of mark-ups, preliminaries, profit, commissioning and prime costs would also be invaluable for the production of the gross cost of engineering services installations. Generally, because of the lack of computer expertise and suitable programs within the quantity surveying profession, further research into the development, testing and integration of computers plus increased computer training should be encouraged. A pool of computerised probabilistic data could provide the framework for further research and improve the service offered by the quantity surveying profession to both clients and engineers.

8.0 Conclusions

The stochastic networking technique VERT (Venture Evaluation and Review Technique) was successfully utilised to model the pre-tender costs of public health (sanitary, hot and cold water installations), heating, ventilating, air conditioning, fire protection, lifts and electrical installations within office developments. This computerised technique enabled the quantity surveyor to analyse, manipulate and explore complex scenarios which had previously defied ready mathematical analysis. Cost, time and performance factors were systematically processed and defined for alternative design options in a flexible and probabilistic manner. The cost models were designed specifically to suit the requirements of the Engineering Services Division (ESD) within Monk Dunstone Associates (MDA) and were presented in a format which was conducive to the in-house current methods of estimating.

From the literature review it was shown that the lack of research undertaken by the quantity surveying profession into the cost estimation of mechanical and electrical services installations, the lack of trained surveyors with an appropriate technical knowledge coupled with the absence of a reliable historical cost data base, had all contributed to the failure of the profession to accurately cost pre-tender estimates for engineering services installations. Quantity surveyors, within MDA, were unwilling to rely on published deterministic cost data and the limited in-house historical costs obtained from bills of quantities. The literature review examined the various methods of pre-tender estimating and the previous research into cost models. The 'floor area' method of estimating and elemental comparative cost techniques were suggested by the research, despite their limitations, because of the historical data restrictions. Computerised cost models were proposed in order that future estimates could be inferred from the historical data and expertise within the ESD. The research refuted the claim that costs were deterministic and put forward the use of probabilistic techniques which would recognise cost ranges and the inherent uncertainties associated with pre-tender estimates. Criteria for the selection of a flexible computer program were developed since a methodology was required which could systematically reduce and combine the historical interdependent cost, time and design (performance) parameters in a probabilistic manner. The selected program had to allow for large amounts of data to be stored, easily retrieved, updated and edited, allow the interrelationships between the parameters to be realistically processed, indicate the cost sequences of alternative design options and produce an output immediately legible to the services quantity surveyor. The development of the VERT program was researched as an approach which appeared to be able to provide the structure required to produce a flexible, applicable and comprehensive solution. It was a stochastic networking technique which contained enough features to effectively model the pre-tender estimating decision situation, however, as a relatively new risk analysis method, it required time and empirical research before its usefulness could be validated.

The collection, verification and presentation of the raw data required much research effort since there was a lack of reliable services cost data in a readily available, consistent format. Cost analyses for office developments were painstakingly collated using research designed analysis sheets and component definitions. It was proposed that if it were possible to isolate the direct labour and material costs from the other cost factors of overheads, mark-ups and profit, it may be possible to establish the net cost of production and design alternatives. In order to compare cost analyses from a variety of locations, with alternative specifications, qualities, prestige levels, building shapes and heights, adjustment factors were investigated and implemented. Tender price indices were used to account for market conditions, tendering climates and inflation rates. The homogeneous research data was then presented in the form of relative frequency distributions which highlighted the uncertain, unpredictable and random factors which affect engineering services installations. The ranges indicated the dispersion of data for similar components and elements. These relative frequency distributions were modified, where necessary, using opinion analysis since the variability in estimates could be related to the 'expert' opinion or quantity surveyor's professional judgement. Three types of distributions were identified from the raw data: uniform, triangular, normal and Beta distributions, which were considered to reflect the ESD's subjective uncertainty about the component distributions.

A decision tree diagram was produced from the cost analyses and component definitions, which structured the possible mechanical and electrical design alternatives. This was coded using the VERT logic operands to produce a generalised flow network for engineering services. The VERT program contained a comprehensive array of logical, statistical and mathematical features which were used to program into the computer the network structure and probability density functions. The formulation of the pictorial network required a knowledge of the installation types and their components, and was based on the probabilities contained within the historical raw data.

The representative mechanical and electrical pre-tender estimates were researched on the assumption that they would reflect the characteristics of the total statistical population of all pre-tender estimates for M&E installations within office developments. VERT simulated the possible values of the population and the values of the population parameters. Model verification, validation and statistical tests indicated that VERT had successfully modelled the defined network and the distribution statistics. It enabled 'human uncertainties' to be modelled, the systematic consideration of potential errors, risk analysis and the identification and evaluation of potential cost, time and performance variations to be assessed. Rules-of-thumb were also compared to the resultant models which demonstrated the practical acceptability of the models. VERT had successfully combined the decision tree technique, critical path analysis and the process of simulation to provide the quantity surveyor with a fuller understanding of the selections available and the probable cost, time and performance factors.

Further research into many of the subject areas within the project is still required since the raw data, adjustment factors and indices were not held to be true with perfect certainty, the resultant models could not be held with perfect certainty. As more data becomes available the assumptions upon which the defined distributions were based can be rationalised, tuned and updated to produce a more valid and current picture of the possible engineering services pre-tender costs and alternative design solutions. The resultant models, however, reflected the current estimating knowledge of engineering services within Monk Dunstone Associates.

It is unlikely that the full benefits and implications of the VERT program will be fully appreciated for some time since they tend to be intangible and difficult to quantify. The quantity surveyor should be satisfied that the engineering services designs meet the needs of the clients and satisfy any planning and statutory regulations which are applicable. The research produced a defined catalogue of element requirements and attempted to provide the quantity surveyor with an appreciation of the technology of the design options. The responsibility for the services design rests with the engineer, but the quantity surveyor must be aware of the cost-design implications and inform the designer of the probable costs of his decisions. The quantity surveyor should not only provide the client with the minimum costs but provide value for money accounts, encourage alternative designs at the feasibility stage and recognise the costs to the environment of the proposed projects.

VERT has the ability to combine probabilistic data and provides the user with a flexible tool for the integration of cost, time and performance criteria. It allowed the quantity surveyor to quote costs with associated degrees of confidence. The complexities and uncertainties contained within estimates were placed in a logical and consistent framework, amenable to further manipulation and research. This may not necessarily improve the accuracy of the pre-tender estimates but it does permit the systematic identification and evaluation of potential variations, risks and uncertainties which may avoid abortive detailed designs and estimates before the feasibility of the design alternatives have been considered. VERT cannot be viewed as an immediate saving in manpower, although it may sharpen the estimator's thinking, but more as a tool which may gain extra projects through reputation which may justify the cost of the system operation. More up-to-date in-house information could be provided at speed, at an earlier stage in the design process, so that more informed decisions could be made therefore improving the cost consultancy service offered to the client. The resultant VERT cost models suggest alternative cost-design solutions which may be used as a starting point for professional judgement, experience and intuition. They are not meant to substitute for estimating decisions but to compliment them.

9.0 Appendices

APPENDIX 9.1

THE DEVELOPMENT OF COST MODELS FOR CONSTRUCTION

THE DEVELOPMENT OF COST MODELS FOR CONSTRUCTION

REFERENCES	TECHNIQUES	DESCRIPTION AND COMMENTS
Knight & Duck (1962)	REGRESSION ANALYSIS	Knight & Duck (1962) identified the major cost components of a lift installation and considered the effects of height, the population per floor and other design parameters on the cost of components. A tabulated cost model was produced and the results of the model tested using regression analysis against historical costs. Rules of thumb were then diagnosed by relating cost to one variable (the capacity of the lift) as an approximate estimate at the initial stages of design.
The Wilderness Cost of Building Study Group (1964) (Townsend, 1977; Southwell, 1968; Kelly, 1982)		An investigation into the effects of altering basic variables, storey heights, column spacings, floor loadings and the number of storeys, in the design and cost relationship for a steel framed building. The research, funded by the RICS, failed to make a definitive decision on how to treat the effects of design variables on cost. It was a limited study as it only examined one element of the building.
Draper & Smith (1966)	REGRESSION ANALYSIS	Suggest the use of regression techniques for cost models
Buchanan (1969)	REGRESSION ANALYSIS	The study of the cost of reinforced concrete structures. Production of a cost model for estimating the frame using such variables as the floor area, average loading, floor span and the number of floors. Criticised by Bowen (1982) as being 'force-fitted'.
		During the 1970s an approach which attracted much development time was multiple regression analysis (MRA). The main thrust of the research being carried out by Loughborough University.

REFERENCES	TECHNIQUES	DESCRIPTION AND COMMENTS
Gould (1970)	REGRESSION ANALYSIS (Multiple linear regression)	Gould (1970) determines some of the design/cost relationships for heating, ventilating and air-conditioning installations in various types of buildings. He suggests a general framework within which relationships could be analysed. Gould related cost variability to heat flow and air flow, on the assumption that cost was partially dependant on the systems workload. He attempts to provide a measure of the cost of ducting, pipework and wiring associated with the volume of the building and some central power source. He expected that some cost variability would be explained by the effect of the shape of the building and considers the complexity of distribution. His results showed high correlation coefficients (99.8%) for large projects but suffered from a lack of raw data.
Maver (1970)	SIMULATION LINEAR PROGRAMMING	Maver (1970) considered the serious limitations of models. He stated that the confidence with which one could predict, from regression analysis based on historical data, was not high and the number of occasions where an objective function could be formulated, without over simplifying the problem to a level which contravenes realism, were few. Maver proposed a mechanism for each stage of the design morphology, using a suite of appraisal programs covering cost and performance variables. A large number of simulated solutions were analysed using linear programming to generate the functional relationship between the design variables.
Badby (1971)	REGRESSION ANALYSIS	Badby (1971) attempted to develop a cost model for the external walls, internal partitions, windows and doors of a building, irrespective of occupancy. This research proved to be unsatisfactory because the standard errors of the models were very large.

REFERENCES	TECHNIQUES	DESCRIPTION AND COMMENTS
Buchanan (1971)	REGRESSION ANALYSIS	Buchanan (1971) used regression analysis to develop a model which could estimate the cost of reinforced concrete frames of buildings.
Wilson (1973)	REGRESSION ANALYSIS	Wilson (1973) proposed the use of multiple regression analysis (MRA) in conjunction with cost optimisation for computer aided building design.
Maver (1973)	REGRESSION ANALYSIS	Maver (1973) proposed the use of multiple regression analysis (MRA) to compare various forms of designs. He used the PACE program.
PSA (1973)	SIMULATION	The PSA (1973) derived the COCO (Cost of Contractors' Operations) model by simulating the sequence of decisions made by the contractor when compiling a tender. The research represents one of the few attempts to analyse the effect on prices of the contractors method of construction. Does not consider M&E costings however.
Moyles (1973)	REGRESSION ANALYSIS	Moyles (1973) designed a successful cost model for schools using particular building systems. Variables measured included the floor area, wall area, a plan shape factor and the number of rooms.
Trimble (1974)	REGRESSION ANALYSIS	Trimble (1974) and his colleagues at Loughborough University of Technology considered the benefits of using regression analysis for various facets of building work.
Wood (1975)	REGRESSION ANALYSIS	Wood (1975) used a modified standard statistical computer program to develop multiple linear regression models for estimating the cost of piped heating systems in buildings.

REFERENCES	TECHNIQUES	DESCRIPTION AND COMMENTS
McCaffer (1975)	REGRESSION ANALYSIS	McCaffer (1975) produced research which indicated links between costs and heat and air flow, heat sources, the distance heat had to travel, and shape variables using linear regression techniques. An accuracy of 10-20% was claimed as opposed to 26% for traditional methods of estimating, but the results were not explicit. An electrical model gave an accuracy of 20% compared to 34% for traditional methods.
Morris (1976)	REGRESSION ANALYSIS	Morris (1976) used regression analysis for the early forecasting of construction prices.
Wiles (1976)	REGRESSION ANALYSIS	Wiles (1976) used regression techniques for the analysis of lift installations.
Wilson (1977)	SIMULATION	Wilson (1977) outlines the approaches adopted to produce a cost model, their advantages and disadvantages. He recognises the fruitfulness of simulation techniques and states that there will always be human qualitative factors which cannot be quantified and which demand insight.
Beeston (1977)	SIMULATION	Beeston (1977) discusses the merits of simulation techniques as opposed to regression models. He states his preference for simulation methods largely due to their ease of updating and improvement, as more knowledge becomes available. The statistical analysis of simulation model output could, he proposed, be used to provide early cost advice data.
Flanagan & Norman (1977)	REGRESSION ANALYSIS	Flanagan & Norman (1977) used regression analysis to estimate the relationship between the price and height.

REFERENCES	TECHNIQUES	DESCRIPTION AND COMMENTS
Brandon (1977)	DETERMINISTIC COST MAPS	Brandon (1977) studied a framework for cost exploration and strategic cost planning in design. He produced a dynamic cost model which provided deterministic cost maps. These identify limited cost strategies for building design. Brandon noted the inherent time constraints on producing enormous numbers of potentially feasible design solutions and the lack of available techniques for their measurement. He also developed EXPLORA which was an empirical model for the calculation of lift costs.
Townsend (1977)	DETERMINISTIC COST MODELS	Townsend (1977) indicated the effect of design decisions on the cost of an office development. He researched into the effect that land cost has upon the utilisation of the land, the effects of altering the plan: shape index, the effect on cost of glazing related to daylight factors, the optimum spacing of floor trunking and slab span. Townsend proposed that when alternative design costs were calculated, the client should be able to decide between the alternatives. His research suffers from price levels obtained from Spons with no regard to the tendering climate or professional reputation.
Reynolds (1978)		Reynolds (1978) described how cost models can aid in comparing alternative design solutions for building projects at an early stage, when information available is minimal.
Maybeck (1979)	STOCHASTIC MODELS	Maybeck (1979) investigates the theory of stochastic models and derives practical designs for estimators and stochastic controllers.
Maver (1979)		Maver (1979) discusses how the incoming generation of computer based design models promise to transform the practice of architectural design.

REFERENCES	TECHNIQUES	DESCRIPTION AND COMMENTS
Agugua (1979)	REGRESSION ANALYSIS	Agugua (1979) used multiple regression analysis (MRA) to analyse the building envelope, roof finishes, external walls, windows and external doors, of inpatient hospital buildings.
Finch & Postula (1979)	PROBABILISTIC MODELS	Finch & Postula (1979) discuss some of the benefits of probabilistic cost estimating.
Ashworth, Neale & Trimble (1980)	REGRESSION ANALYSIS	The development of a regression analysis model for the production of the total number of manhours required to complete the brickwork on a project. Bowen (1982) criticised the research as being 'force-fitted'.
Bowen (1980)	REGRESSION ANALYSIS	Bowen (1980) investigated into the feasibility of producing an econometric cost model for framed structures. Including a survey on the acceptance of regression analysis within the profession.
Reynolds (1980)	REGRESSION ANALYSIS	Reynolds' (1980) research showed a strong functional relationship between floor area and total services costs, and between total unit area costs and unit area costs of sections of elements and group elements. There was limited evidence of a functional relationship between total unit area costs and unit area costs of components. This research was based on 18 government office blocks which may have produced bias results because of the similarities in building specification and client requirements.

REFERENCES	TECHNIQUES	DESCRIPTION AND COMMENTS
Flanagan (1980)	SIMULATION	Flanagan (1980) investigated design parameters and their effect on price. He discusses the various types of models and considers the reliability and accuracy of price predictions. Flanagan developed a dynamic lift installation cost model based on the simulation of the design process. Risk analysis techniques, beta distributions and PERT were used to reduce the variability within selected elemental categories. He suggests the use of Monte Carlo simulation to study the relationship between an estimated price and the chance or probability of the tender price deviating from that amount, to study the relationships between room functions and costs, the construction time, operational sequence of construction and the construction complexity of historical projects.
SPATS	SIMULATION	M.A.B. Murray and B.A.V. Hanby developed a research tool for the analysis of component-based system simulation at the University of Technology in Loughborough. It includes routines for the interactive definition of hvac systems with a specification of simulation of bad profiles and utility programs for data management of both systems and components.
Morrison & Stevens (1980)		Morrison & Stevens (1980) researched into cost data bases. They identified the general nature of estimating, its organisation and arrangement. A list of the 100 most cost significant items was produced, analysed, matched and compared to provide sets of unit rates which were, they claimed, easier to use. They showed that cost data and estimating methods should grow and develop in response to changes in design and construction costs, and that the most accurate method of estimating in theory was when estimates were based on resources and costs based on contractors estimating methods.

REFERENCES	TECHNIQUES	DESCRIPTION AND COMMENTS
Ferry (1980)	SIMULATION	Ferry (1980) illustrates the use of Monte Carlo Simulation with costs-in-use studies. He suggests that simulation could be used to search for the optimum solution to a design problem, guided by rules-of-thumb established from the practical experience of the users.
Fine (1982)	SIMULATION	Fine (1982) considered the need and use of simulation as a research tool, as he insists that to make progress, models must incorporate uncertainty. The successes of simulation are few, he states, but they are significant in producing understanding and improved performance. Most models of construction processes assume that the cost of a project is the sum of the costs of the activities. Fine indicates that costs are largely due to interferences and uncertainties, and that simple additive models seriously under-estimate costs.
Wilson (1982)	SIMULATION	Wilson (1982) discusses some preliminary results from a major research project undertaken at Liverpool Polytechnic, into the design, development and testing of models for predicting the economic consequences of building design decisions. He examined the general area of data acquisition for probabilistic design cost models, used Monte Carlo Simulation to combine the triangular uncertainty distributions to discover their influence on the total costs of a concrete slab, and examined the treatment of convariance. Wilson noted that the assumption that cost uncertainties were always symmetrical was an over-simplification, he argued that although the central limit theorem was applicable to models with large numbers of constituent variables, it was foolish to apply the same criteria to models with few constituents. The results of his research indicated that for both labour and materials, a pronounced and consistent skewness to the right existed in all cases. Labour appeared to have a wider uncertainty range and higher skewness levels. Wilson's research relied on the Delphi Method which in this case relied on the subjective judgement of the panels of estimators chosen and the format of the questionnaire.

REFERENCES	TECHNIQUES	DESCRIPTION AND COMMENTS
Townsend (1982)		Townsend (1982) showed that cost modelling by computer can be effectively used from the time of the client's brief until the time for the return of tenders.
Hardcastle (1982)		Hardcastle (1982) examined capital cost estimating and the methods of presenting cost information. He stated that it was possible to identify over 80% of the cost of a space with only 24% of the items currently used.
Holes & Thomas (1982)		This research into general purpose cost models concentrated on resource allocation and regarded cost as largely derivative of construction processes.
Morris (1982)	REGRESSION ANALYSIS	Morris (1982) considered algorithms and price models suitable for modelling the cost of housing for the disabled.
Mathur (1982)	SIMULATION	Mathur (1982) proposed the probabilistic approach for cost modelling using normal distributions, to obtain the cost of all elements by way of the Monte Carlo Technique. He suggests the use of a simulation approach where, in the absence of a large amount of historical data, a random number may be used to select a value from a probability distribution which would be as likely a cost as any other in the distribution of cost and therefore taken to be the predicted cost of the element in one event.
Brandon (1982)		Brandon (1982) stated that there was a fundamental need to establish a more substantial body of theory and better cost models. He notes the apparent unwillingness of the RICS and QS profession to invest in research and to extend their knowledge and improve methodologies.

REFERENCES	TECHNIQUES	DESCRIPTION AND COMMENTS
Newton (1982)	SIMULATION	Newton (1982) analysed the performance of existing cost modelling techniques and their failure to meet the requirements of design. He criticises GOAL a sophisticated modelling technique which simulates the cost procedures used by the quantity surveyor by the insertion of unit rates. He states that cost models which assume single rate costs or static cost relationships are oversimplified and will rapidly become obsolete. He discusses ACE (Analysis of Construction Economics) simulation approach which uses approximate quantities and unit costs for alternative designs.
Kelly (1982)	LINEAR PROGRAMMING DECISION TREES SIMULATION CRITICAL PATH QUEUEING THEORY	Kelly (1982) compares the various techniques available in operational research for comparative costings: linear programming, decision trees, simulation methods, critical and queueing theory. He states that a cost solution draws upon a data base of intuition, experience and rules of thumb. He suggests that little cost advice is offered to the designer at the early sketch stages when a large proportion of project costs are committed. He refers to Vilfredo Pareto and his law of distribution to explain that 20% of the design elements contain 80% of the costs.
Wilson (1985)	PROBABILISTIC COST MODELLING	Wilson (1984) used risk analysis in the design of commercial buildings. He makes a plea for the wider use of probabilistic techniques, risk analysis and simulation for decision analysis, and recommends the use of Monte Carlo Simulation as a sampling technique. He notes the marked reluctance to abandon deterministic techniques but states that most people respond favourably to expressing their feelings probabilistically after a while, since they are no longer restrained by the need for a single point estimate. He describes the major uncertainties associated with estimates and suggests decision analysis as a technique which would allow for a clearer understanding of the problems associated with building design.

REFERENCES	TECHNIQUES	DESCRIPTION AND COMMENTS
Drake (1984)		Drake (1984) maintains that building costs are more or less directly proportioned to quantity, whereas civil engineering costs are process determined. He does not discuss whether M & E engineering services are quantity or process related.
CIBSE (1985)	SIMULATION	The CIBSE (1985) state two aspects of computer modelling building services installations: firstly, to model the interrelationship between the services and the structure, and secondly to model the components comprising the installation. Neither are mutually exclusive. They criticise the choice of designs currently available on hvac simulation systems. Murray & Handby propose attributes of a simulation methodology that could overcome the limitations of currently available hvac simulation programs.

APPENDIX 9.2

ESD SERVICES COST ANALYSIS SHEETS

APPENDIX 9.3

COMPONENT DEFINITIONS

NOTE:

One of the most difficult problems involved in the research of the component definitions was that of locating and isolating marginal sub-components such as motors, fans, traps and the variables which affected the cost of the projects. The test was normally the function that the component performed or its relative position within an installation; but this was not always easy to apply. Whatever was decided was consistently documented and applied, although the values of such marginal items were usually not of great consequence. Insulation and ductwork components were kept separate for prime cost sub-contractor costings when required. Plant room or heat source components were extremely difficult to determine and categorise because of their close interrelationships with the design of the building and the selected installations. The heat source item was sub-divided into the fuel installations, boilers, pumps, motors, pressurisation plants, water treatment and refrigeration plants. A percentage of the heat source was attributed to the installations involved and the treated or serviced floor area. Electrical work in connection (EWIC) was also apportioned in the same manner.

ELEMENT 1 SANITARY FITTINGS

COMPONENT	ARC	GENERAL SPECIFICATIONS	REGULATIONS	GUIDANCE NOTES
General		Total number of projects analysed: 24		BRE Current paper CP35:1976 BRE Digests: 249 and 248 Building Regulations 1976
		50% white 50% coloured fittings No correlation apparent between cost and white/coloured fittings contrary to 'Extra-over' costs entered in the estimates.	BS 6465: 1984 BS 3402: 1969	Code of practice for scale of provision, selection and installation of sanitary appliances. Quality of vitreous china sanitary appliances.
		Exclusions: Baths Showers Bidets Toilet roll holders Towel rails	BS 4118: 1981	Glossary of sanitation terms. NOTE: No references were noted for special provisions for disabled persons.
		Dependant on the number and sex of occupants; building type and shape; particular requirements.		Wise (1985) CIBSE Guide (1972) Volume B Section B8. Sanitation and waste disposal.
Water Closets	SANWCS	Number of projects: 24 100% Definition:	BS 1125: 1973	WC flushing cisterns (including dual flush cisterns and flush pipes).
(Siphonic cisterns or water waste preventors)		A water closet removes human wastes, solid or liquid. It is connected to a drainage system and has provision for flushing from a clean supply of water either by the operation of a mechanism or by automatic action. The integral P, Q or S trap acts as a connection to the soil branch or stack. It can be floor mounted or wall hung and have visible or concealed cisterns.	BS 1254: 1981 BS 5503: 1977 BS 5504: 1977 BS 5627: 1984	Specification for WC seats (plastic). Specification for vitreous china washdown WC pans with horizontal outlet. Specification for wall hung WC pan. Specification for plastics connectors for use with horizontal outlet vitreous china WC pans.
		Types: 1. Pedestal type, washdown 2. Pedestal type, suphonic 3. Corbal type.	BS 6465: 1984	Code of practice for scale of provision, selection and installation of sanitary appliances.
		Components: Cistern Ball valve Flush pipe Non-return valve Flushing valve/apparatus Water closet pan and trap Seat and cover	Offices, shops and Railway Premises Act; 1963	See Cave (1974) CIBSE Guide Book (1972) Volume B Sections B4, B8 The Institute of Plumbing (1977)
		Materials: Ceramics: Earthenware Fireclay Vitreous China Cast iron Pressed steel Stainless steel Plastics: Perspex Terazzo : Specials		

ELEMENT 1 SANITARY FITTINGS

COMPONENT	ARC	GENERAL SPECIFICATIONS	REGULATIONS	GUIDANCE NOTES
Wash Hand Basins	SANWHBS	Number of projects: 24 100% Definition: A wash hand basin is intended for washing the upper parts of the body. It has a waste connection pipe, clean piped water supply (cold and/or hot), a plug and taps. It is generally ceramic but can also be metal or plastic.	BS 1188: 1974	Ceramic wash basins and pedestals
			BS 1329: 1974	Metal hand rinse basins.
			BS 5506: 1977	Specification for wash basins.
			BS 6465: 1984	Code of practice for scale of provision, selection and installation of sanitary appliances.
		Types: 1. Individual basins 2. Range of basins 3. Hand spray basins 4. Fountains and troughs.		CIBSE Guide Book (1972) Volume B Section B4 The Institute of Plumbing (1977)
		Components: Basin Pedestal/brackets Trap Overflow (integral) Taps Plug and chain/connector	BS 5412: 1976	Specification for the performance of arrow-off taps with metal bodies for water services.
		Materials: Earthenware Fireclay Stoneware Vitreous China (heavy or ordinary duty grades) Plastic	The Offices, Shops and Railway Premises Act; 1963	NOTE: Metal lavatory basins excluded.
Overflows	SANOFS	Number of projects: 21 88% Three projects did not specify overflows within the estimate.		See SANWOS and URINALS
		Definition: An overflow is a pipe connected to a water closet or urinal cistern to discharge excess water.		The number of overflow points is related to the number of WCs and urinals. However, where grouping of sanitary fittings occur, one overflow point may service several fittings using a single cistern.
		Components: Pipe (usually PVC) Support brackets, clipping, sockets, connectors, elbows and tees.	DAS 61: 1982	Cold water storage cisterns: overflow pipes.
		Materials: PVC Galvanised mild steel Copper Plastics		
Sanitary Points	SANPTS	Number of projects: 22 92% One project used a total unit rate for disposal and another used a combined system with shops. Both were discounted.	BS 5572: 1978	Code of practice for sanitary pipework (formerly CP 304)
			CP 312 : 1973	Plastics pipework (thermoplastics materials).
			BS 416 : 1973	Cast iron spigot and socket soil, waste and ventilating pipes (sand cast and spun) and fittings.

COMPONENT	ARC	GENERAL SPECIFICATIONS	REGULATIONS	GUIDANCE NOTES
	SANPTS	Definition:		
		The sanitary pipework removes foul water from the sanitary fittings and is therefore related to the number of discharge points. The sanitary point provides drainage from the sanitary fitting trap to the lower slab level or ground level and includes wastes and vent pipes where required. Soil pipes discharge into the external foul drainage system.	BS 2035: 1966 (1981)	Cast iron flanged pipes and flanged fittings
			BS 2760: 1973	Pitch-impregnated fibre pipes and fittings for below and above ground drainage.
			BS 1184: 1976 (1981)	Copper and copperalloy traps.
			BS 3380: 1982	Specification for wastes (excluding skeleton sink wastes) and bath overflows.
		Types: Two pipe system Fully ventilated one-pipe system Modified one-pipe system Modified one-pipe vented stack system Single stack system.	BS 3868: 1973 (1980)	Prefabricated drainage stack units: galvanised steel.
			BS 3943: 1979	Specification for plastics waste traps.
		Components: WC and urinal connections WHBS, DRKGFTNS and CLNRSSKS waste pipe connections Pipework including sockets, brackets, bosses, branches, plugs, saddles, caps, bends, connectors, gaskets, reducers, offsets, access points for rodding, rodding eyes, non-return ventilation valves, fire stop collars, roof connectors Galvanised wire balloons or vent cowls and all necessary fittings and fixings, holderbates and/or floor supports.	BS 3974: 1974	Pipe supports.
			BS 4514: 1983	Specification for unplasticized PVC soil and ventilating pipes, fittings and accessories.
			BS 5254: 1976	Polypropylene waste pipe and fittings.
			BS 5255: 1976	Plastics waste pipe and fittings.
			BS 6087: 1981	Specification for flexible joints for cast iron drain pipes and fittings and for cast iron soil, waste and ventilating pipes and fittings.
				CIBSE Guide Book (1972) Volume B Section B4
				The Institute of Plumbing (1977)
		80% of the projects had cast iron stacks and copper wastes provided within ducts located in core areas of each floor level. They were generally estimated on the basis of a fully ventilated 'one pipe' system. UPVC systems were becoming more popular but the higher costs of fire resisting ducts should be examined. Stacks of 100 or 150mm diameter were usual.		Jackson (1985)
				Wise (1979)
				Design of stacks and ancillary venting.
			BRE No. 115	Soil and waste pipe systems for office buildings.
			BRE No. S248-9	Sanitary pipework design: basis and pipework.
			Building Regulations Section E12.	
		Materials: Cast iron Copper Steel Pitch fibre UPVC Polythene: Types 32 and 50 Plastics.		

ELEMENT 1 SANITARY FITTINGS

COMPONENT	ARC	GENERAL SPECIFICATIONS	REGULATIONS	GUIDANCE NOTES
Urinals	URINALS	Number of projects: 21 88% Definition: A urinal removes human male liquid waste. It is connected to the drainage system and has provision for flushing from a supply of clean water, either by operaton of a mechanism or by automatic action. Types: 1. Bowl/Basin 2. Slab 3. Stall. Components: Cistern and supports Ball valve Flushing valve (automatic or manual)/apparatus Flush pipe and spreader Urinal Trap (integral) Outlet grating (Sparge pipe and clips) Materials: Cast iron Ceramic ware Pressed steel Plastic Glazed ware Enamelled fireclay Stainless steel Porcelain.	BS 6465: 1984	Code of practice for scale of provision, selection and installation of sanitary appliances.
			BS 1876: 1972 (1977)	Automatic flushing cisterns for urinals.
			BS 4880: 1973	Stainless steel slab urinals.
			BS 5520: 1977	Specification for vitreous china bowl urinals. Rimless type
				CIBSE Guide Book (1972) Volume B Section B4.
				NOTE The cost was adjusted to correspond with a single urinal. For example: 2 No. 2 stall urinals at £175.00 each were adjusged to read 4 No. urinals at £87.50 each. This enabled rules of thumb for the provision of urinals to be checked with regulations. However, the larger the number of urinals required, the lower the cost.
No urinals provided	NURINALS	Number of projects: 3 12% WCs were provided instead of urinals.		
Drinking Fountains	DRKGFTNS	Number of projects: 12 50% Definition: A supply of drinking water directly from a jet, in a wall or pedestal mounted fitting. The drinking water supplies are met from the incoming water main up to a level compatible with the pressures available. Points above the critical pressure level are serviced from a drinking water header, adjacent to the roof break tank, serviced from the cold water booster pumps. Components: Inlet valve/apparatus Fountain fitting/basin Trap Materials: Ceramic Enamelled cast iron Brass chrome plated.	CP 310: 1965	Water supply
				Wise (1979)
				Exclusion: Cold water/drinking water points have not been included for vending machines.

ELEMENT 1 SANITARY FITTINGS

COMPONENT	ARC	GENERAL SPECIFICATIONS	REGULATIONS	GUIDANCE NOTES
No Drinking Fountains provided	NDRKGFTN	Number of projects: 12 50% An adequate supply of drinking water must be provided, but where no fountains are installed, drinking water taps may be provided. Cold water taps directly off the mains supply may also be used.	The Offices, Shops and Railway Premises Act; 1963.	
Cleaners sinks	CLNRSSKS	Number of projects: 22 92%	BS 6465: 1984	Code of practice for scale of provision, selection and installation of sanitary appliances.
		Definition: A sink unit is provided for laundry and domestic cleaning purposes.	BS 1206: 1974	Fireclay sinks.
		It has a waste connection pipe, clean piped water supply (cold and/or hot), a plug, taps and drainage work top(s).	BS 1244: 1956 (1977)	Metal sinks for domestic purposes.
		Types: Single bowl, single drainer Single bowl, double drainer Double bowl, single drainer Other types/variations.	BS 1244: 1982	Specification for stainless steel sink tops.
		Components: Bowl with integral overflow Drainer(s) Brackets/support Trap Taps Plug and chain/connector		NOTE Solid waste disposal such as grinders or the Garchey system, have not been included in the research.
		Materials: Perspex Acrylic sheet Polypropylene Fireclay Cast iron Pressed steel - porcelain enamelled Stainless steel.		
No Cleaners sinks provided	NCLNRSSK	Number of projects: 2 8%		
Macerators	MACS	Number of projects: 15 63%	BS 6465: 1984	Code of practice for scale of provision, selection and installation of sanitary appliances.
		Definition: Macerators provide a suitable and effective means of disposal for sanitary dressings.		
		Types: After flushing, the macerator reduces the sanitary dressings to a slurry which are pumped into the soil and waste system.	BS 3107: 1973	NOTE: Incinerators were not used. Small incinerators.
		Components: Specialist electrical appliance Water and waste connections Including all associated fixings and fittings.		Electrical work in connection included in power points see 'POWER' section.

ELEMENT 1 SANITARY FITTINGS

COMPONENT	ARC	GENERAL SPECIFICATIONS	REGULATIONS	GUIDANCE NOTES
No macerators provided	NMACS	Number of projects: 9 37%		

ELEMENT 2 COLD WATER

COMPONENT	ARC	GENERAL SPECIFICATIONS	REGULATIONS	GUIDANCE NOTES
General		Total number of projects: 26		
Cold Water Mains	CWMAINS	Number of projects: 13		CIBSE Guide Book (1972) Volume B Section B4
		50% of projects did not specify a mains or connection charge.	CP 310 : 1965	Water supply.
		Definition:	DD 82 : 1982	Drafts for Development (BSI) Specification of requirements for suitability of materials for use in contact with water for human consumption with regard to their effect on the quality of water.
		Mains cold water is obtained from the Water Authorities main supply, for which there is a connection charge. Water is then distributed through the rising main pipework to the cold water storage tanks, the pressumption unit feed and break tank, and various drinking/cold water outlets. Some installations require pumps or boosters to augment the mains pressure.	BS 534 : 1981	Specification for steel pipes and specials for water and sewage.
			BS 5480: 1977 (1984)	Specification for glass reinforced plastics (GRP) pipes and fittings for use for water supply or sewerage.
			BS 2871: 1971	Copper tubes for water, gas and sanitation.
			BS 5412: 1976	Specification for the performance of draw-off taps with metal bodies for water services.
		Components: Water Authority connection charge (screw ferrule and union)	BS 5413: 1976	Specification for the performance of draw-off taps with plastic bodies for water services.
		Stopcock(s) Rising main pipework		See 'pipework general'.
		Mains water booster plant (auto-pneumatic pressurisation unit incorporating direct coupled centrifugal pumps, air compressors, pressure vessel, break pressure cistern and control panel)		Wise (1979) pp26-30. See 'pressurisation'.
			BS 5276: 1977	Specification for pressure vessel details.
		Draw-off taps Connections and valves Fittings and fixings.	BS 3284: 1967	Polythene pipes (Type 50) for cold water services.
		Materials:	BS 1972: 1967	Polythene pipe (Type 32) for cold water services.
		Steel Copper Polythene PVC Plastics Cast iron	CP 312 : 1973	Plastics pipework (thermosplastics materials).
				The mains pipework and storage capacity are determined predominantly by the building type, height and number of occupants.

ELEMENT 2 COLD WATER

COMPONENT	ARC	GENERAL SPECIFICATIONS	REGULATIONS	GUIDANCE NOTES
Cold Water Points	CWPTS	Number of projects: 26		CIBSE Guide Book (1972) Volume B Section B4
		Definition:	Water Byelaws	
		Cold water distribution pipes from cold water storage to draw-off taps over sanitary fittings, instantaneous hot water points, feed(s) to hot water circulating system(s), air conditioning system and fire protection hose reels. Taps, valves, cocks etc. control the water flow.	CP 310 : 1965	Water supply. See 'CWMAINS' section.
			BS 3505: 1968 (1982)	Unplasticized PVC pipe for cold water services.
			BS 1010: 1973	Draw-off taps and above ground stopvalves.
			BS 3457: 1973	Materials for water tap and stopvalve seat washers.
			BS 5388: 1976 (1981)	Specification for spray taps.
			BS 5412: 1976	Metal draw-off taps.
			BS 5413: 1976	Plastics draw-off taps.
		Components:		
		Distribution pipework		See 'pipework general'.
		(Pumps/Pressurisation)		
		Taps, valves, cocks		The Institute of Plumbing Guide (1977)
		Supports and fixings		
		Flanges and joints		
		Fittings and connections	BS 5779: 1979	Specification for spray mixing taps.
		Materials:		
		Polythene (Type 32) Polythene (Type 50) UPVC Copper (light gauge) Stainless steel Steel Copper (heavy guage) Cast or spun iron.		The cold water distribution depends on the rationalisation of services (Wise, 1979); decentralisation or cored systems. Building shape, type, size and number of occupants.
Cold Water Storage	CWSTORAG	Number of projects: 24		
		Definition:		
		Cold water storage tanks can be fitted in the roof void or the basement. They provide water to the sanitary fittings, hot water system, fire-fighting systems and the air-conditioning system (when required). Plastic cisterns were most popular (Hampshire, 1985). Covers, overflows and venting arrangements varied considerably from the loose lid to a well sealed cover with trapped overflow and filtered air inlet. Ball valves may be linked to float switches, probes or pressure switches. Insulation or lagging was provided to prevent frost action in the roof space.		92% of projects had storage tanks in the roof. 2 projects were inspecific.
			BS 6465: 1984	Code of practice for scale of provision, selection and installation of sanitary appliances.
			BS 1563: 1949 (1964)	Cast iron sectional tanks (rectangular).
			BS 1564: 1975 (1983)	Pressed steel sectional rectangular tanks.
			BS 417 : 1973	Galvanised mild steel cisterns and covers, tanks and cylinders.
			BS 2594: 1975	Carbon steel welded horizontal cylindrical storage tanks.

ELEMENT 2 COLD WATER

COMPONENT	ARC	GENERAL SPECIFICATIONS	REGULATIONS	GUIDANCE NOTES
	CWSTORAG		BS 4213: 1975	Cold water storage cisterns (polyolefin or olefin copolymer) and cistern covers.
		Types:	BS 4994: 1973	Vessels and tanks in reinforced plastics.
		The size and type of storage provided depends on the water usage and load estimation.		Wise (1979), Maver (1966), McKay (1974).
		(Rates of heating for hot water and rates of supply of cold water with respect to time and probable usage). 'Reserve' storage provides a reserve of water in the event of mains supply failure.	BS 3792: 1964	Recommendations for the installation of automatic liquid level and temperature measuring instruments on storage tanks.
		'Buffer' storage limits the maximum rate of mains draw-off whilst maintaining a required	BS 1212: 1979	Specification for float operated valves (excluding floats)
		volume of storage under all conditions.	BS 1968: 1953	Floats for ball valves (copper).
			BS 2456: 1973	Floats (plastics) for ball valves for hot and cold water.
		Fixture unit methods and probability analyses can be used for advanced methods of load estimation, but for 'rules of thumb' for the provision of cold water storage to cover 24 hours interruption of supply, a fixed volume per head was used.	The Water Byelaws	
			CP 310 : 1965	Water Supply.
				The Institute of Plumbing (1977)
			BS 2879 : 1980	Cast iron and carbon steel ball valves for general purposes.
		Components:		
		Storage cistern(s) (Removable) cover Overflow pipe (warning pipe) Stop valve Ball valve Draining tap Vent pipe (Access ladders, manholes etc.) Connectors, fitting and fixings Insulation (lagging) Switches	BS 2879 : 1980	Specification for draining taps (screw-down pattern) Courtney (1977) Spink (1973)
		Materials		
		Plastic Galvanised steel Welded or riveted mild steel Pressed steel sectional Cast iron sectional.		
Insulation	INSULTN	Number of projects: 20 74%		
		Definition:		
		Insulation to cold water pipework, valves and flauges in ducts, chases, roof spaces, ventilated		See 'Insulation General' section
		floor spaces and shere cold water pipes run in close proximity to hot water services. To prevent	BS 5422 : 1977	Specification for the use of thermal insulating materials.
		freezing, condensation and warming.	BS 5970 : 1981	Code of practice for thermal insulation of pipework and equipment (in the temperature range of -100°C to +870°C).

ELEMENT 2 COLD WATER

COMPONENT	ARC	GENERAL SPECIFICATIONS	REGULATIONS	GUIDANCE NOTES
			CP 99 : 1972	Frost precautions for water services.
No insulation provided	NINSULTN	Number of projects: 7 26% Seven projects did not specify insulation to pipework.		

ELEMENT 3 HOT WATER

COMPONENT	ARC	GENERAL SPECIFICATIONS	REGULATIONS	GUIDANCE NOTES
General		Total number of projects: 27 Dependant on: 1. Height and shape of building 2. Location of the heat source 3. Economics and operating costs 4. Maintenance and service requirements.	CP 342 : 1974	Centralized hot water supply.
		Types: 1. Centralised: CHW (storage) 2. Decentralised systems or localised: IHW (storage or non-storage/instantaneous).		In large building complexes consideration should be given to the provision of several calorifier each serving a zone as opposed to one centrally located calorifier (Maver, 1971).
Centralised hot water point	CHWPTS	Number of projects: 16 60%	CP 342 : 1974	Centralized hot water supply.
		Definition: Hot water distribution pipes from centralised hot water heat source to draw-off taps over sanitary fittings.		The Institute of Plumbing Guide (1977)
		Types: 1. Direct from boiler 2. Indirect via calorifier and secondary pipework.		Burberry (1977) CIBSE Guide (1972) Volume B Tables VIII and IX
		The sizing of hot water pipework and calorifiers is related to the 'probable simultaneous demand'.		Water Byelaws.
		Components: Pipework (including fittings and fixings)		See 'pipework general' section.
		Safety devices: expansion valves, temperature relief valves, pressure valves and pressure reducing valves	BS 6283: 1982	Safety devices for use in hot water systems.
		Taps	BS 1010: 1973	Draw-off taps and above ground stop valves.
		Materials:	BS 3457: 1973	Materials for water tap and stop valve seat washers.
		Copper (light and heavy gauge) Stainless steel Steel Cast or spun iron.	BS 5388: 1976 (1981)	Specification for spray taps.
			BS 5412: 1976	Specification for metal draw-off taps.
			BS 5413: 1976	Specification for plastic draw-off taps.
			BS 5779: 1979	Specification for spray mixing taps.

ELEMENT 3 HOT WATER

COMPONENT	ARC	GENERAL SPECIFICATIONS	REGULATIONS	GUIDANCE NOTES
Centralised hot water storage calorifier (s)	HWSTORAG	Number of projects: 16		CIBSE Guide Book (1972) Volume B Section B4.8
		Definition: A calorifier is a hot water storage vessel, not open to the atmosphere, in which a supply of water is heated. The vessel contains an element, such as a coil of pipe, through which is passed a supply of hot water or steam. Heat is transferred through the element to the stored water. Stored hot water reduces the instantaneous demand on the boiler. Insulation is provided in the form of a jacket.	BS 6465: 1984	Code of practice for scale of provision, selection and installation of sanitary appliances.
				Kut (1968)
			BS 853 : 1981	Specification for calorifiers and storage vessels for central heating and hot water supply.
			BS 843 : 1976	Specification for thermal-storage electric water heaters (constructional and water requirements).
			BS 417 : 1973	Galvanised mild steel cisterns and covers, tanks and cylinders.
		Types:		The Institution of Plumbing Guide (1977)
		Water to water calorifiers Steam to water calorifiers Direct cylinders (alternative hot water storage direct from boiler).	BS 699 : 1984	Specification for copper direct cylinders for domestic purposes.
		Components:	BS 1566: 1984	Copper indirect cylinders for domestic purposes.
		Calorifier(s) Thermometer Pressure relief valve or safety valve Discharge pipe connection Pressure gauge Stopcock and drain cock Altitude gauge Temperature control: self acting, pneumatic or electric thermostats Vent Access joints Insulating jacket	BS 1565: 1973	Galvanised mild steel indirect cylinders, annual or saddle-back type.
			BS 3198: 1981	Specification for copper hot water storage combination units for domestic purposes.
			BS 6283: 1982	Safety devices for use in hot water systems.
				See 'insulation general' section.
			BS 5615: 1978	Specification for insulating jackets for hot water storage cylinders.
		Materials:		
		Copper Copper alloy Galvanised mild steel.		See 'heating' section for primaries and feed and expansion tanks.
				NOTE An adjustment was made to the insulating jackets because sub/sub-contract work not required. Therefore sub/sub-contract material cost multiplied by sub-contractor mark-up minus material mark-up equalled the cost to main contractor.

ELEMENT 3 HOT WATER

COMPONENT	ARC	GENERAL SPECIFICATIONS	REGULATIONS	GUIDANCE NOTES
Centralised hot water heat source	SHWHT	Number of projects: 14 Definition: A percentage of the total plant heat source associated with hot water for sanitary fittings i.e. boiler plant including hot water primaries, fittings and fixings.		See 'Heat source general' section. See 'pipework general' section.
Centralised hot water electrical work in connection	SHWELC	Number of projects: 12 Definition: Electrical work in connection with hot water calorifiers, pumps, starters and controls: Immersion sensors Contact sensors Mixers Programmable controllers % of plant room EWIC.		See 'EWIC General' section.
Hot water insulation	HINSULTN	Number of projects: 11 Definition: Insulation to hot water pipework, valves and flauges in ducts, chases, roof spaces, ventilated floor spaces and where cold water pipes run in close proximity. To prevent heat losses and condensation.	BS 5422 : 1977 BS 5970: 1981	See 'insulation general' section. Specification for the use of thermal insulating materials. Code of practice for thermal insulation of pipework and equipment (in the temperature range of -100°C to +870°C).
Centralised hot water pumps	PUMPS	Number of projects: 16 Definition: Hot water circulating pumps maintain flow to hot water points. Including valves, gauges, seals, flexible connections, motor and starter, switchgear and mountings.	BS 1394: 1971	See 'pumps general' section. Power driven circulators.
Instantaneous hot water points	IHWPTS	Number of projects: 11 40% Definition: Hot water distribution pipes from localised instantaneous heat source to draw-off points.taps over sanitary fittings. Types: 1. Storage: multipoint 2. Non-storage: single point. Non-storage systems include the cost of instantaneous heaters within the cost of IHWPTS, since	CP 324: 1951	See 'pipework general'. See 'Centralised hot water points'. Rowell (1985) Provision of domestic electric water-heating installations.

COMPONENT	ARC	GENERAL SPECIFICATIONS	REGULATIONS	GUIDANCE NOTES
	IHWPTS	the fitting is combined, usually with swivel spouts (hot water points).		
		Components:		
		Pipework, fittings and fixings (if required)		See 'pipework general'.
		Water heaters where no storage required Cold water inlet valves Insulation.		See 'insulation general'.
Instantaneous storage hot water heaters	ISTORAG	Number of projects: 7 64%		
		Definition:		
		Instantaneous hot water heaters with storage provision using off-peak electricity, gas or unrestricted electricity to meet expected and instant demands.	BS 843 : 1976	Specification for thermal storage electric water heaters (constructional and water requirements).
			BS 3456: 1970	Stationary non-instantaneous water heaters.
		Types and components:	BS 3456: 1979	Stationary instantaneous water heaters.
		1. Electrical water heaters Copper or galvanised hot water Storage cylinder/pressure vessel Electric immersion heater Control thermostat Cold water inlet Thermal insulation jacket Connectors Vent	BS 3999: 1967 (1978)	Thermal-storage electric water heaters. Immersions may be used during the summer months when the boiler plant has been shut down ('Primatic' system). Burberry (1977).
		2. Gas-fired water heaters Copper, coil-cooled combustion chamber	BS 5440: 1978	Flues.
		Single-stage heat exchanger	BS 5440: 1976	Air Supply.
		Connections-input and outlet Flue	BS 5546: 1979	Code of practice for installation of gas hot water supplies for domestic purposes. Burberry (1977)
			BS 3274: 1960	Tubular heat exchanges for general purposes.
			BS 5258: 1977	Storage water heaters.
			CP 335 : 1973	Domestic laundering and miscellaneous appliances.
			BS 5386: 1976	Gas burning appliances for instantaneous production of hot water for domestic use.
			BS 5386: 1981	Mini water heaters.
			HMSO (1976)	Building Regulations.
Instantaneous storage hot water heat source	ISHWHT	Number of projects: 5		
		Definition:		
		Percentage of heat source plant room (fuel) associated with storage hot water heaters. Some systems may rely on primary flow and return hot water or steam from the boiler (indirect system).	CP 331 : 1974	Low pressure installation pipes (gas).

ELEMENT 3 HOT WATER

COMPONENT	ARC	GENERAL SPECIFICATIONS	REGULATIONS	GUIDANCE NOTES
Instantaneous storage hot water electrical work in connection	ISHWELC	Number of projects: 3 Definition: Electrical work in connection with instantaneous storage hot water heaters.		See 'EWIC general'.
No storage provided for instantaneous hot water heaters	NSTORAG	Number of projects: 4 36% Definition: Instantaneous hot water heaters without storage using unrestricted electricity to meet instant demand.		
		Components:		All components included under IHWPTS.
		Electric immersion heater (usually 1KW) plus safety devices Swivel hot water outlet pipe Control valve on cold water supply inlet Thermostatic controls Diaphragm pressure switch	BS 3456: 1980	Appliances for heating liquids.
Non-storage instantaneous hot water electrical work in connection	IHWELC	Number of projects: 2 Definition: Electrical work in connection with instantaneous non-storage hot water heaters.		See 'EWIC general'.

ELEMENT 4 HEATING

COMPONENT	ARC	GENERAL SPECIFICATIONS	REGULATIONS	GUIDANCE NOTES
General		Total number of projects: 43		Porges (1982) Morgan (1985)
		Space heating was divided into two categories:		Watson (1980) Faber & Kell (1979)
		1. Piped heating systems: fan convectors, penmeter convectors and radiators.		Jaros (1961) CIBSE Guide (1972) Volume B Sections B1, 2, 3 & 14.
		2. Air-conditioning systems: central air-handling units, variable air volume, 'Versatemp' and fan coil installations.		CIBSE Guide (1978) Volume A Section A1.
		Dual systems, where piped and air-conditioning systems were used in the same space or two-types of piped systems in the same space, were also considered.		CIBSE (1984) Application Manual: Automatic controls and their implications for systems design. CIBSE (1974) Technical Memoranda: recommendations relating the design of air handling systems to gire and smoke control in buildings.
		PIPED HEATING SYSTEMS		CIBSE (1983) Technical Memoranda: Design notes for ductwork.
		Hot water is used to transmit heat through pipework from the boiler(s) to the room heaters or space emitters. Systems can be classified by pressure:	London Building By-Laws. ASHRAE	American Society of Heating, Refrigerating and Air-Conditioning Engineers.
		1. Low pressure hot water heating (LPHW), which can be sub-divided into pumped or gravity circulated systems. Gravity systems were most popular where circulation was produced by natural gravity action in temperature between the flow and return. This system was most suitable for offices which were concentrated in plan. Pumped systems were also popular requiring electrically driven centrifugal pumps to circulate the hot water. Pipe sizes seemed to be reduced due to the increased circulation rate but plant costs were higher.	HMSO: Building Regulations, 1976 Gas Regulations, 1984 Electrical Equipment (Safety) Regs; 1975	(up to 100°C). Sanford (1985) Burberry (1977) Garrett (1975) Parts: F, FF, Q, R, L and M. Building Services Research and Information Association (BSRIA) Product Profile (1985)
		2. Medium pressure hot water heating (MPHW).		(100-120°C).
		3. High pressure hot water heating (HPHW) or pressurised hot water heating was required where the space heat demand was of a relatively high output, or to reach high points within the building. Pipework sizes and pump capacities were reduced but pressurisation plant was required.	BS 5588: 1983	(over 120°C). See 'pressurisation plant' section. Fire precautions in the design and construction of buildings.
		Within the research, the most typical piped installations were of the low pressure type serving continuous perimeter convectors in the office areas, radiators in toilet areas and fan convectors in		

COMPONENT	ARC	GENERAL SPECIFICATIONS	REGULATIONS	GUIDANCE NOTES
General		stairwells, lift lobby areas and entrance halls.		
		The heating pipework can be separated into types:		
		1. Single pipe systems, which were unsuitable for convectors. 2. Two piped flow and return systems. 3. Two piped reverse return systems.		
		And, either an open or sealed system. A cold water feed and expansion tank was required unless a sealed system was used, where small pressurised vessels substituted.		
		Feed and expansion takks are used to fill the system, via a ball valve, by the supply of makeup water to accommodate the explansion of the systems warmed water on firing the boiler. They are also a disposal tank for the vent pipe contents. Feed and explansion tanks and hot water primaries are included in the plant or heat source component associated with each installation, including all necessary supports, insulation, vents, cold feed connections and mains water supply pipe connections, fittings, valves, and all fixings.		See 'heat source' general section.
		Non-storage calorifiers, where a separate water circuit passes through a cylinder containing water and transfers heat from one system to the other, may be required for a piped heating system and are included within the heat source component. They allow the heating system or secondary system to operate at a different temperature and pressure to the conditions produced by the plant equipment or boilers. Including thermostats, valves, gauges, cocks, controls, insulation and all associated fittings and fixings.	 BS 417 : 1973 BS 2871: 1972 BS 3274: 1960 BS 3606: 1978	See 'heat source' general section. See 'HWSTORAG' component. Galvanised mild steel cisterns and covers, tanks and cylinders. Tubes for heat exchanges. Tubular heat exchanges for general purposes. Specification for steel tubes for heat exchanges.
		AIR CONDITIONING SYSTEMS		See 'ventilation general' section.
		Air conditioning is a process which completely controls the air supply, simultaneously maintaining the room temperature within prescribed limits (190°C in winter and 240°C in summer ± control tolerances), the room humidity by humidification in winter and dehumidification in summer (45-60%RH), the air quality (sufficient fresh air suitably cleaned) and the direction and velocity of the air distribution, to meet the requirements of the conditioned space.	BS 5141: 1975-1977 BS 2579: 1955 BS 5491: 1977	Air heating and cooling coils. Solid drawn copper alloy tubes for the manufacture of screened ferrules, and copper alloy screwed ferrules for condenser, evaporation, heater and cooler tubes. Specification for rating and testing unit air conditioners of above 7KW cooling capacity.

ELEMENT 4 HEATING

COMPONENT	ARC	GENERAL SPECIFICATIONS	REGULATIONS	GUIDANCE NOTES
General		The costs of the systems depend mainly on the building shape and design, the flexibility of space partitioning required, the amount of glazing and shading provided and the plant system selected. Since air conditioning systems, by the research definition, should provide cooling, the refrigeration plant required should be examined carefully. Water treatment, automatic control, sound attenuation, standby requirements, fire protection and the location of the air conditioning plant all affect the costs which make it difficult to clearly establish a cost per square metre. Watson (1980) showed upon examination that the area alone appeared to have only an indirect effect on the cost of air conditioning systems, and even the selection of the type of installation appeared to have only a limited effect. Air conditioning central plant systems may comprise of all of the following components: outside air intake points, self cleaning air filters, dry fabric or electro-static type air filters, chilled water cooling coils, air washers, eliminators, re-heaters, supply fans, smoke extractors, extract and recirculation ductwork, extract fans, spray water heaters, strainers and pumps, chilled water pumps, evaporators, compressors, condenser and condenser water pumps, cooling towers, boilers, hot water pumps, motorised valves, temperature and humidity controls, energy management controls, insulation and all associated fittings and fixings. It was apparent from the literature that the entire subject of heating, including air conditioning, was a very complex subject and that the types and combinations of equipment were numerous. The quantity surveyor must constantly keep acquainted with the literature from the various manufacturers to stay abreast with the new innovations. The research considered complete heating installations to serve specific spaces, zones or areas. Dual system estimates were also considered, where two types of installations e.g. DPERFAN or DVERSPER, were used in the same zone. These provide a low level of background heating by the central installation and localised room emitters which rapidly heat to the desired temperature when the space is occupied, or as in the case of dual air conditioning and piped	BS 5643: 1984 BS 5720: 1979	Glossary of refrigeration, heating, ventilating and air conditioning terms. Code of practice for mechanical ventilation and air conditioning in buildings See 'heat source' general section. Joyce (1985) Rodgers (1985)

COMPONENT	ARC	GENERAL SPECIFICATIONS	REGULATIONS	GUIDANCE NOTES
General		systems, provide cooling (or heating) in the central core of the building and heating along the perimeter walls to compensate for glazing heat losses. These systems provide both cost advantages and flexibility. Where a variety of heating installations are used within the same building, but in different zones, e.g. radiators in toilets, fan convectors in lobbies and air conditioning in offices, the estimator should apply a separate cost figure to each zone appropriate to each installation. Zoning of installations tends to increase the cost of each type of system so the estimator is advised to select costs from the higher end of the range. This does not mean that the overall cost of the heating element will be increased, because, for example: a cheaper piped heating system in circulation areas may allow the client to select an air conditioning system for office areas. The variety and number of permutations are enormous for any given development. Heating installations excluded from the research, due to no data available: Heat pumps Underfloor heating Radiant panels Solar heating.		

ELEMENT 4 HEATING (PIPED)

COMPONENT	ARC	GENERAL SPECIFICATIONS	REGULATIONS	GUIDANCE NOTES
Fan Convectors	FANCONV	Number of projects: 13 32% Definition: Fan convectors or forced convectors comprise of a battery constructed from gilled tubing, a propeller type electrically driven fan and a casing incorporating adjustable discharge louvres. It can be arranged to fresh air connectors and filters. 92% of the projects used fan convectors in lobbies or in reception entrances, as air curtains. Heated air is blown across the door openings to prevent or reduce ungress of cold atmospheric air into the building. Ceiling mounted. Components: Fan convector unit casing Supports, and liners Connection to piped hot water Air cocks Union valves Air filters Motors and fans plus associated mountings and fittings Controls: Thermostatic Boost Time Sensors Two or three speed fan control.	BS 3528: 1977	Specification for convection type space heaters operating with steam or hot water. NOTE: Sanford (1985) Fan convectors are particularly well suited to small offices because of the fast warm-up time and low surface temperature. The main advantage of fan convectors is controllability, but the option of bringing in fresh air means that the type also has applications in mid-price office projects as down market 'air conditioning'.
Pipework in connection with Fan Convectors	PWKFAN	Number of projects: 13 Definition: Pipework, flow and return, from heat source to fan convectors. Including insulation, valves, cocks, controls and all associated fittings and fixings. Pumps may also be required.		See 'pipework general' section. See 'insulation general' section.
Fan Convector heat source	HTSFAN	Number of projects: 9 Definition: Percentage of heat source associated with fan convectors, based on serviced floor area.	BS 6230: 1982	Specification for installation of gas-fired forced convection air heaters for commercial and industrial space heating of rated input exceeding 60KW. See 'heat source/plant general' section.
			BS 5991: 1982	Specification for indirect gas fired forced convection air heaters for space heating (60KW up to 2MW input): safety and performance requirements (excluding electrical requirements.
			BS 5990: 1981	Specification for direct gas fired forced convection air heaters for space heating.

COMPONENT	ARC	GENERAL SPECIFICATIONS	REGULATIONS	GUIDANCE NOTES
Electrical work in connection with fan convectors	ELCFAN	Number of projects: 8 Definition: Electrical work in connection with fan convectors: Controls (pipework and units) Motors Fans Pumps Plant.		See 'EWIC general' section.
Perimeter Convectors	PERCONV	Number of projects: 7 17% Definition: A perimeter (natural) convector consists of a furred tube heating element located inside a casing. Air is recirculated over the element via an air inlet slot or grating at the bottom of the casing and a discharge grating at the top. Dampers control the direction of air flow. Individually controlled hot water circuits automatically vary the water temperature within the element to maintain the desired internal temperature, compensating for any changes in the external temperature. (Thermostatic control) Valves mix the flow and return water to correct and maintain the temperature. Perimeter convectors in single pipe loops have furred element sections proportional to the temperature drop in each circuit. Perimeter convectors are intended for installation in long lengths along the perimeter of the building. The convector casing is arranged in modular form to suit possible office partitioning. Most were arranged in zones (north and south) for independent control. Components: Casing including mullions and support brackets Fin-tube elements Dampers Isolating and balancing valves, union valves and air cocks Anchors, guides and bellows Valve boxes Dummy sections Sound baffles Compensators. The casing may incorporate compartmented electrical trunking.	BS 3528: 1977	Specification for convection type space heaters operating with steam or hot water. Sanford (1985) NOTE Perimeter convectors may be conventional in design, trench mounted or incorporated in skirting, valences, benches, planters, handrails, safety rails and so on. The conventional form is a modular type vertical strip heater with sliding front plates to give length variations. It can be either naturally convected or fan assisted.

ELEMENT 4 HEATING (PIPED)

COMPONENT	ARC	GENERAL SPECIFICATIONS	REGULATIONS	GUIDANCE NOTES
Pipework in connection with perimeter convectors	PWKPER	Number of projects: 7 Definition: Pipework from heat source to perimeter convectors, including insulation, valves, cocks, controls and associated fittings and fixings. Pumps may also be required.		See 'pipework general' section. See 'insulation general' section.
Perimeter convector heat source	HTSPER	Number of projects: 6 Definition: Percentage of heat source associated with perimeter convectors, based on serviced floor area.		See 'heat source/plant general' section.
Electrical work in connection with perimeter convectors	ELCPER	Number of projects: Definition: Electrical work in connection with perimeter convectors: Controls (pipework and dampers) Pumps Plant.		See 'EWIC general' section.
Radiators	RADS	Number of projects: 10 24% Definition: A radiator is a convector type space heater, which emits heat by natural convection and relatively low temperature radiation. It comprises of a hollow element, usually welded pressed steel or aluminium, through which the heating medium, steam or hot water, passes. The medium is in direct thermal conductive contact with the external heat emitting surfaces of the element.	BS 3528: 1977 CP 341 : 1956	Specification for convection type space heaters operating with steam or hot water. Central heating by low pressure hot water. NOTE There is a general trend away from radiators in the commercial sector except for lower priced jobs where the radiator's undoubted price advantage is very influential. Nevertheless a great many radiators are still sold for office heating, Sanford(1985) very often as background heaters or as condensation eliminators in a VAV air conditioning system.
		Types: Column Sectional Panel - double or single panelled, with or without fins		
		Components: Radiators Fixings - support brackets Union valves Air cocks Thermostatic Radiator Valves (TRVs) Lockshield valves.	BS 2767: 1972 BS 6284: 1983	Valves and unions for hot water radiators. Specification for thermostatic radiator valves.
		Materials: Cast iron(no longer manufactured) Pressed steel welded Die cast or extended aluminium Copper.		

ELEMENT 4 HEATING (PIPED)

COMPONENT	ARC	GENERAL SPECIFICATIONS	REGULATIONS	GUIDANCE NOTES
Pipework in connection with radiators	PWKRAD	Number of projects: 10 Definition: Pipework, flow and return, from heat source to radiators. Including insulation, valves, cocks, unions, controls and all associated fittings and fixings. Pumps may also be required.		See 'pipework general' section. See (insulation general' section.
Radiator heat source	HTSRAD	Number of projects: 8 Definition: Percentage of heat source associated with radiator installation, based on serviced floor area.		See 'heat source/plant general' section.
Electrical work in connection with radiators	ELCRAD	Number of projects: 5 Definition: Electrical work in connection with radiators: Controls (pipework) Pumps Plant.		See 'EWIC general' section.
Dual Perimeter Convector and fan convector installation	DPERFAN	Number of projects: 3 7% Definition: A dual system within the same serviced area, consisting of fan convectors in the centre core zone and perimeter convectors along the outer perimeter zone. This arc represents the data associated with the perimeter convectors.		See 'perimeter convectors'.
Dual Fan Convector and perimeter convector installation	DFANPAR	Number of projects: 3 Definition: This represents the data associated with fan convectors within a dual installation with perimeter convectors.		See 'fan convectors'.
Pipework in connection with perimeter convectors within a dual system	PWKPAR	Number of projects: 3 Definition: Pipework, flow and return, from heat source to perimeter convectors. Including insulation, valves, cocks, unions, controls and all associated fittings and fixings. Pumps may also be required.		See 'pipework in connection with perimeter convectors'.

COMPONENT	ARC	GENERAL SPECIFICATIONS	REGULATIONS	GUIDANCE NOTES
Dual perimeter convector and fan convector heat source	HTSDPF	Number of projects: 2 Definition: Percentage of heat source associated with dual perimeter and fan convector system, based on serviced floor area.		See 'heat source/plant general' section.
Electrical work in connection with dual piped system	ELCDPF	Number of projects: 2 Definition: Electrical work in connection with fan convectors and perimeter convectors dual system: Controls (pipework and units) Motors Fans Pumps Plant.		

COMPONENT	ARC	GENERAL SPECIFICATIONS	REGULATIONS	GUIDANCE NOTES
Central Air Handling Unit	CAHU	Number of projects: 1 3%		
		Definition:		
		The basic packaged central air handling system is an all-air, single zone system that is used as part of most systems. It can be a single or dual duct installation with low, medium or high pressure distribution. Single duct systems provide variable temperatures (plant) as a constant volume air supply whereas dual duct systems mix hot and cold air, using interlinked dampers, to meet local heating demands at a constant volume.	BS 5720: 1979	Code of practice for mechanical ventilation and air conditioning in buildings. NOTE The particular project used had no cooling capacity. Therefore this could be termed a 'ventilation system' not an air conditioning system.
		Components:		The choice of components depends on the:
		Most components are available in subassembled sections ready for bolting together on site, or completely assembled by the manufacturer. Packaged air handling units provide the function of air movement with a choice of facilities as required: Air mixing Filtration Heating Humidification Cooling Dehumidifying Heat recovery Noise/vibration control.		1. Fuel available 2'. Support structure 3. Space available 4. Requirements 5. Economics.
		1. Casing - usually bolted mild steel sheets including access doors and glass fibre insulation (ladders, catwalks and gantries).		
		2. 100% fresh air inlet (optional) including louvres.		
		3. Recirculated/fresh air inlet including louvres.		
		4. Motorised control dampers.		
		5. Used air exhaust outlet.		
		6. Intake filters: panel, cell, automatic, dry/viscous, cleanable/renewable, fire resistant types to remove air-borne debris, moisture and pests.	BS 5295: 1976 BS 6540: 1985	Environmental cleanliness in enclosed spaces. Air filters used in air conditioning and general ventilation.
		7. Heat recovery devices: thermal wheels, heat pipes, run 'round coils and plate type exchanges.	BS 4979: 1973	Methods for testing and rating air control devices for air distribution systems.
		8. Cooling coil (chilled water) including drip tray.	BS 5141: 1977 (1983)	Air heating and cooling coils. See 'refrigeration' section.
		9. Heating coils (see heat source).		
		10. Intake and discharge attenuators.	BS 4718: 1971	Methods of test for silencers for air distribution systems.

COMPONENT	ARC	GENERAL SPECIFICATIONS	REGULATIONS	GUIDANCE NOTES
	CAHU	11. Humidifiers: spray washers, cell or capillary washers, evaporative coolers (drip, spray and rotary types), spray coils, pan humidifiers, steam injection or mechanical.	BS 5821: 1980 CP 3 : 1972	Method for rating sound insulation in buildings and of building elements. Sound insulation and noise reduction. See 'humidification' section.
		12. Fans including motor starters, access doors, drain plugs, bearings, inlet guide valves and flexible connections.	BS 5258: 1983 BS 6583: 1985	Fan powered appliances. Methods for volumetric testing for rating of fan sections in central air handling units (including guidance on rating).
		13. Air filters, bag and pressure gauge.		See 'fans general' section.
Ductwork in connection with central air handling plant	DWKAHU	Number of projects: 1 Definition: Ductwork, to and from, central air handling plant to inlet terminals and from extract terminals. Including regulating, control and fire dampers, insulation, fans, attenuation, bends, branches, offsets and transformations, fittings and fixings.		See 'ductwork general' section.
Central Air Handling Installation terminals	TERAHU	Number of projects: 1 Definition: Inlet and extract terminal units including shutters, grilles, diffusers, equalisers, air handling luminaires, volume control dampers, silencers or attenuating boxes, registers and all associated fittings and fixings.	BS 4773: 19	See 'terminals general' section. Methods for testing and rating air terminal devices for air distribution systems.
Pipework in connection with central air handling plant	PWKAHU	Number of projects: 0 No projects identified pipework in connection with the central air handling plant, the heat source, or the cooling source.		
Central air handling plant heat source	HTSAHU	Number of projects: 1 Definition: Percentage of heat source associated with the central air handling installation, based on serviced area and system. Types of system: 1. The air heater battery is connected to low pressure hot water, high pressure hot water or steam pipe circuits, served by separate boiler plant.		See 'heat source/plant general' section.

ELEMENT 4 HEATING (AIR)

COMPONENT	ARC	GENERAL SPECIFICATIONS	REGULATIONS	GUIDANCE NOTES
	HTSAHU	2. Electric heater elements contained within the unit. 3. A heat exchanger unit, abstracts heat directly from the primary or secondary heating surfaces of a warm air furnace including a combustion chamber and firing equipment. Components: Water treatment plant Boiler plant including flues, controls and fuel installation Refrigeration plant - chillers Pumps Feed and expansion tanks.		McQuistron & Parker (1982)
Electrical work in connection with central air handling unit	ELCAHU	Number of projects: 1 Definition: Electrical work in connection with the central air handling plant installation: Thermostats (Two-stage) fan controllers Pumps Fans, motors and starters Controls: safety, program and time switches Motorized dampers Isolators Sensors.		See 'EWIC general' section.
Variable air volume	VAV	Number of projects: 3 3% Definition: The Variable Air Volume (VAV) system is essentially a single duct system of air supply, with the means for compensating varying heat loads by regulating the rate of flow of air into the conditioned space. It is a refinement on the simple all air central air handling system because changes in local load conditions are catered for not by adjustment of the temperature of the conditioned air delivered, at a constant volume, but by adjustment of the volume at a constant temperature. Special zoning is not required because each space supplied by a controlled VAV unit is a separate zone, varying the air volume to meet fluctuations in sensible heat gains locally.		Knight (1979) Gosling & Williams (1978) Burberry (1977) Love & Smith (1983)
		It may be used primarily as a cooling system, suitable for large internal office spaces, with re-heaters in the VAV terminals for outer zones or in conjunction with perimeter heating. The re-heaters may also compensate for heat losses due to long lengths of ductwork from the central air handling plant.	BS 4857: 1972 (1983)	See 'dual variable air volume and perimeter heating systems' section. Methods for testing and rating terminal re-heat units for air distribution systems.

ELEMENT 4 HEATING (AIR)

COMPONENT	ARC	GENERAL SPECIFICATIONS	REGULATIONS	GUIDANCE NOTES
	VAV	Types of system: 1. Pneumatically controlled fans are used with variable pitch blades. This enables the air flow to the system to be automatically controlled from full flow to zero by pressure sensors in the ductwork. Individual pneumatic thermostats can control the air in and out of rooms by dampers. Large dampers control the pressure in the main ductwork branches whereas pressure in the whole system is regulated by fan adjustment. VAV boxes control the system (flow and temp.). 2. A fan continuously drives air round the ring ductwork circuit from which room supplies can be diverted off, without requiring adjustment of the fan operation. VAV control terminals adjust to air flow to meet localised requirements and temperature if required. Components: Variable Air Volume control terminals including motorised or pneumatic dampers, sensors, thermostats etc. Optional reheat facility provided by VAV units. Types of VAV terminals: 1. Self-powered units with remote control and terminal reheat facilities. 2. Direct acting units with pressure changing bellows. 3. Self actuating units where a bimetallic element changes with temperature to adjust the bellows. 4. A by-pass terminal where unrequired air is dumped into the ceiling void.		
Central air handling unit associated with a VAV system	AHUVAV	Number of projects: 3 Definition: A central air conditioning plant which treats the air so as to simultaneously control its temperature, humidity, cleanliness and output to meet the requirements of the conditioned space controlled by the VAV system. Including filters, heating and cooling coils, supply and return fans, humidifiers and sound attenuation.	BS 5491: 1977	See 'air conditioning general' section. Specification for rating and testing unit air conditioners of above 7KW cooling capacity.

COMPONENT	ARC	GENERAL SPECIFICATIONS	REGULATIONS	GUIDANCE NOTES
Ductwork in connection with a VAV system	DWKVAV	Number of projects: 3 Definition: Ductwork, to and from, the central air handling plant to inlet terminals and from exact terminals. Including regulating, control and fire dampers, insulation, fans, attenuation, bends, branches, offsets and transformations, fittings and fixings. Distribution is usually at medium or high pressure.		See 'ductwork general' section. Allott, Azarro & Vincent (1982)
VAV system terminals	TERVAV	Number of projects: 3 Definition: Inlet and extract terminal units including shutters, grilles, diffusers, equalisers, louvres, air handling luminaires, volume control dampers, silencers or attenuation boxes, registers and all associated fittings and fixings. A VAV diffuser may be linear with a throttling device or single/twin slot diffusers.		See 'VAV' section. See 'terminals general' section. The terminal or diffuser size is based on the outlet velocity, total air throw, drop and terminal velocity. NOTE It is difficult to say whether there is an inlet terminal component as the supply air terminal may be a part of the VAV unit.
Pipework in connection with VAV systems	PWKVAV	Number of projects: 3 Definition: Pipework in connection with a VAV system, including pipework from water treatment plant, fuse installations, condensers and cooling plant (not included within the heat source or plant room component i.e. from the specific plant to the air handling unit).		NOTE VAV terminal reheat units are assumed to be electric not hot water/steam. See 'pipework general' section.
VAV system heat source	HTSVAV	Number of projects: 3 Definition: Percentage of heat source associated with the variable air volume system, based on serviced area. Including boilers in connection, flues, water treatment plant, fuel installation, refrigeration plant, controls, pumps, mountings, fixings and fittings.		See 'heat source/plant general' section.

ELEMENT 4 HEATING (AIR)

COMPONENT	ARC	GENERAL SPECIFICATIONS	REGULATIONS	GUIDANCE NOTES
Electrical work in connection with VAV systems	ELCVAV	Number of projects: 3 Definition: Electrical work in connection with variable air volume systems: Thermostats and sensors Fan controllers Pumps Fans, motors, starters Controls: safety, program and time Motorised dampers and bellows Isolators Terminals - reheaters Plant.		See 'EWIC general' section.
Versatemp Units	VERSA	Number of projects: 2 5% Definition: The 'Versatemp' system provides localised heating, cooling and dehumidification by a number of reverse cycle heat pumps. The system consists of Versatemp units operated in conjunction with a conditional fresh air make-up system from a central air handling plant. Each heat pump unit is a complete air conditioning machine comprising of an hermetically sealed refrigeration circuit with refrigerant to air and refrigerant to water heat exchanges. Thermostatic control indicates whether the heat exchanges act as evaporators or condensers. The air side heat exchanger adds heat to or extracts heat from the room air circulating over it, whilst the water side heat exchanger either extracts heat from the water or adds heat to it. The units are connected to a two-pipe closed water circuit. Technically, full air conditioning is not provided by the system but it does provide heating or cooling for a highly competitive capital cost. The possible disadvantage of the system is that because a large number of individual units are required, higher than normal maintenance costs may be expected. The units may be ceiling (most popular) or wall mounted. Components: Versatemp units including pumps, heat exchanges, controls, connectors, dampers, valves, fittings and fixings.		Broadbent (1983) HVCA RUAG (1980) Guide to good practice - unit air conditioning including heat pumps.

COMPONENT	ARC	GENERAL SPECIFICATIONS	REGULATIONS	GUIDANCE NOTES
Central air handling unit associated with Versatemp system	AHUVER	Number of projects: 2 Definition: A small central air conditioning plant which may treat the air so as to control humidity and cleanliness. The air may be heated and supplied at high velocity to the Versatemp units, where it is mixed with recirculated air from the conditioned space.		See 'air conditioning general' section.
Ductwork in connection with a Versatemp system	DWKVER	Number of projects: 2 Definition: A small amount of ductwork, to and from, the central air handling plant to inlet terminals and from extract terminals. Including regulating, control and fire dampers, insulation, fans, attenuation, bends, branches, offsets and transformations, fittings and fixings.		See 'ductwork general' section.
Versatemp installation terminals	TERVER	Number of projects: 1 Definition: Inlet and extract terminal units including, shutters, grilles, diffusers, equalisers, louvres, registers, silencers, air-handling luminaires, volume control dampers and all associated fittings and fixings.		See 'terminals general' section.
Pipework in connection with Versatemp installation	PWKVER	Number of projects: 2 Definition: Pipework in connection with heat pump units, including pipework from water treatment plant, fuel installations, cooling towers and boiler (calorifier) plant.		See 'pipework general' section.
Versatemp heat source	HTSVER	Number of projects: 2 Definition: Percentage of heat source associated with the Versatemp system, based on serviced area. Including boiler plant, calorifier for non-storage low pressure hot water, pumps, cooling tower (closed circuit industrial cooler), controls, fixings and fittings.		See 'heat source general' section.

ELEMENT 4 HEATING (AIR)

COMPONENT	ARC	GENERAL SPECIFICATIONS	REGULATIONS	GUIDANCE NOTES
Electrical work in connection with Versatemp installation	ELCVER	Number of projects: 2 Definition: Electrical work in connection with Versatemp installation: Thermostatic controls Manual controls Fan controllers Pumps Motors and starters Motorised dampers Isolators Motorised valves Plant (Energy management unit)		See 'EWIC general' section.
Fancoil installation	FANCOIL	Number of projects: 1 Definition: The fancoil system is a wall ceiling mounted packaged unit contained in a cabinet, including a centrifugal recirculatory fan and motor set, heating and/or cooling coils, through which recirculated room air is passed. The air is supplied and extracted at a constant low velocity, to and from the room by a central air handling unit. Two, three or four pipe closed circuit chilled water and low pressure hot water heating circuits may be used. Heat pumps are an optional extra. Individual room temperature is controlled by varying the water flow (heating or cooling) or by regulation of the fan speed or air flow over the coils. Control valves and thermostats regulate the coding and heating output of the units. The system provides essentially the same service as the Versatemp based unit, but according to some sources, is less costly to maintain. The 'Whalen' system is a fan coil system with the units specifically designed to be of floor to slab height, arranged with piping and air ducting connections at the foot and top of each unit, allowing water circulation through a central full-height-of-building service stack.	BS 4856: 1975 (1983)	Day (1975) Methods for testing and rating fan coil units - unit heaters and unit coders.
		Components: Heat source including refrigeration plant, boilers, pumps and pipework Packaged fan coil units Central air handling plant Ductwork and terminals Electrical work in connection		See 'heat source general' section. Including valves, dampers, drainage collection -ray, fittings and fixings. See 'air conditioning general' section. See 'ductwork general' section and 'terminals'. See 'EWIC general' section.

COMPONENT	ARC	GENERAL SPECIFICATIONS	REGULATIONS	GUIDANCE NOTES
Dual VAV system and perimeter convectors	DVAVPER	Number of projects: 2 5% Definition: A dual system within the same serviced area consisting of variable air volume units in the centre zone and perimeter convectors along the outer sectors. This arc represents the data associated with the variable air volume units. This is one of the most popular types of VAV system arrangements, in that it keeps the control as simple as possible. The VAV system is used in conjunction with an independent low pressure hot water perimeter heating system. The VAV system copes with all cooling in all zones with air, on an all-season cooling cycle, while the perimeter heating system offsets the transmission heat losses, caused by variations in the external environment. The VAV system is a high velocity, single cold duct distribution system with ceiling diffusers. The internal temperature is controlled by thermostatically reducing the volume of cold air introduced.		See 'VAV system' section.
Dual perimeter convectors and VAV system	DPERVAV	Number of projects: 2 Definition: This represents the data associated with perimeter convectors within a dual installation with a VAV system.		See 'perimeter convector systems' section.
Pipework in connection with perimeter convectors within a dual system	PWKDPER	Number of projects: 2 Definition: Pipework, flow and return, from heat source to perimeter convectors. Including insulation valves, cocks, unions, controls and all associated fittings and fixings. Pumps may also be required.		See 'pipework in connection with perimeter convectors section and 'insulation general' section.
Central air handling unit in association with a dual VAV system	AHUDVAV	Number of projects: 2 Definition: A central air handling plant which treats the air temperature, humidity, cleanliness and output to meet the requirements of the conditiond space controlled by the VAV system. Including filters, heating and cooling coils, supply and return fans, humidifiers and sound attenuation.		See 'air conditioning general' section.

ELEMENT 4 HEATING (AIR)

COMPONENT	ARC	GENERAL SPECIFICATIONS	REGULATIONS	GUIDANCE NOTES
Ductwork in connection with a dual VAV system	DWKDVAV	Number of projects: 2 Definition: Ductwork, to and from, the central air handling plant to inlet terminals and from extract terminals. Including regulating and fire dampers, controls, insulation, fans, attenuation, bends, branches, offsets and transformations, fittings and fixings.		CIBSE Commissioning Code for Air Systems. See 'ductwork general' section.
VAV system terminal units in dual install-ation with perimeter convectors	TERDVAV	Number of projects: 2 Definition: Inlet and outlet terminals including shutters, grilles, diffusers, equalisers, louvres, air-handling luminaires, control dampers, attenuation, registers and all associated fittings and fixings. The terminal units are with or without minimum air by-passes and are closely linked to the heat gains produced by the lights. Automatic and manual regulating dampers. The control system may be linked to boosters, override temperature detectors and optimiser start controllers. Also, when the zones are highly dispensed or large, terminal heater or 'reheat' batteries may be used to aid the perimeter heating.		See 'terminals general' section.
Pipework in connection with a dual VAV system	PWKDVAV	Number of projects: 1 Definition: Pipework in connection with a dual VAV system, including condense pipework, pipework from water treatment plant, fuel installations, condensers and cooling plant plus insulation, valves, cocks, unions and controls. Fittings and fixings.		See 'pipework general' section. See 'insulation general' section.
Heat source in connection with dual VAV system and perimeter convectors	HTSDVAV	Number of projects: 2 Definition: Percentage of total heat source plant associated with the variable air volume and perimeter convector dual system, based on serviced area. Including boilers in connection, flues, water treatment plant, fuel installation, refrigeration plant, controls, pumps, mountings, fittings and fixings.		See 'heat source/plant general' section.

COMPONENT	ARC	GENERAL SPECIFICATIONS	REGULATIONS	GUIDANCE NOTES
Electrical work in connection with dual VAV system	ELCDVAV	Number of projects: 2 Definition: Electrical work in connection with dual variable air volume and perimeter convector system, as a percentage of total EWIC. Including thermostats, isolators, sensors, fan controllers, pumps, motors, starters, controls, dampers, bellows, terminals and plant.		See 'EWIC general' section.
Dual Versatemp system and perimeter convectors	DVERSPER	Number of projects: 1 2% Definition: A dual system of heatingand cooling within the same serviced area consisting of Versatemp units (centre zone) and perimeter convectors (outer zone). This arc represents the data associated with the Versatemp units.		See 'Versatemp' section.
Dual perimeter convectors and Versatemp system	DPERVER	Number of projects: 1 Definition: This represents the data associated with perimeter convectors within a dual installation with a Versatemp system.		See 'perimeter convector systems' section.
Pipework in connection with perimeter convectors within a dual system	PWKDPC	Number of projects: 1 Definition: Pipework, flow and return, from heat source to perimeter convectors. Including insulation, valves, cocks, unions, controls and all associated fittings and fixings. Pumps may also be required.		See 'pipework in connection with perimeter convectors and insulation' sections.
Central air handling unit in association with dual dual Versatemp system	AHUDVER	Number of projects: 0 No projects detailed the central air handling plant used in conjunction with the Versatemp system.		
Ductwork in connection with a dual Versatemp installation	DWKDVER	Number of projects: 1 Definition: Ductwork, to and from, the central air handling plant to inlet terminals and from extract terminals. Including regulating and fire dampers, controls, insulation, fans, attenuation, bends, branches, offsets and transformations, fittings and fixings.		See 'ductwork general' section.

ELEMENT 4 HEATING (AIR)

COMPONENT	ARC	GENERAL SPECIFICATIONS	REGULATIONS	GUIDANCE NOTES
Versatemp system terminal units in dual installation with perimeter convectors	TERDVER	Number of projects: 0 No projects detailed the terminals used in conjunction with the Versatemp system.		
Pipework in connection with a dual Versatemp system	PWKDVER	Number of projects: 1 Definition: Pipework in connection with dual Versatemp system, including condense pipework, water treatment plant pipework, fuel pipework, insulation, valves, cocks, unions and controls. Fittings and fixings.		See 'pipework general' section. See 'insulation general' section.
Heat source in connection with dual Versatemp system and perimeter convectors	HTSDVER	Number of projects: 1 Definition: Percentage of total heat source plant associated with the Versatemp and perimeter convector dual system, based on serviced area. Including boilers, flues, water treatment plant, fuel installation, regrigeration plant, controls, pumps, mountings, fittings and fixings.		See 'heat source/plant general' section.
Electrical work in connection with dual Versatemp system	ELCDVER	Number of projects: 1 Definition: Electrical work in connection with dual Versatemp and perimeter convector system, as a percentage of total EWIC. Including thermostats, isolators, sensors, fan controllers, pumps, motors, starters, valves, controls, dampers, terminals and plant.		See 'EWIC general' section.

ELEMENT 5 VENTILATION

COMPONENT	ARC	GENERAL SPECIFICATIONS	REGULATIONS	GUIDANCE NOTES
General		Total number of projects: 20 Ventilation implies air movement systems which provide fresh air or artificially purified air, relieve over-heating, regulate the level of contaminants in the air (smoke, bacteria, fumes and smells), combat condensation and control the relative humidity. Except in the case of simple mechanical extract systems and natural ventilation, some treatment of the air is usually required, filtration, heating and spraying. Jones (1979) states that the difference between air conditioning and ventilation was that ventilation systems provide no mechanical regrigeration: this was the basis on which the research differentiated.	The Building Regulations: 1976 The London Building (Constructional) By-Laws: 1972 + AMD: 1974 Offices, Shops and Railway Premises Act: 1963 Section 7	CIBSE Guide Book B (1972) Sections B2 and B3 Ventilation and air conditioning (requirements, systems and equipment).
			BRE Digest No. 170: 1974	Ventilation of internal bathrooms and WCs in dwellings
			BRE Digest No. 206: 1977	Ventilation requirements.
		Types of mechanical ventilation: 1. Simple supply or extract systems or split systems 2. Plenum systems or combined systems.		Burberry (1977) Kut (1968) Porges (1982) Garrett (1975) Wise (1979)
			BS 5643: 1984	Glossary of refrigeration, heating, ventilating and air conditioning terms.
		The split system relies on electrically driven fans to provide air movement at room temperature. There is a lack of fine control and heating is achieved by alternative systems (radiators etc).	BS 5720: 1979	Code of practice for mechanical ventilation and air conditioning in buildings.
		A plenum ventilation system distributes air through a system of ducts from a central air handling unit. The air may be filtered, warmed or sprayed, and recirculation facilities incorporated to recycle exhaust air modulated with fresh air to meet intermediate season supply temperature requirements and to minimise heating demand during the winter. This system incorporates sophisticated control mechanisms. Unlike the split system which provides individual ventilating units in each space/room, the plenum system can provide ventilation from a central system throughout the entire building.	BS 5925: 1980	Code of practice for design of buildings: ventilation principles and designing for natural ventilation.
		Both systems depend on the level of zoning, the internal heating and cooling loads, the external temperature, the mass of air to be circulated, and the shape of the building.		

ELEMENT 5 VENTILATION

COMPONENT	ARC	GENERAL SPECIFICATIONS	REGULATIONS	GUIDANCE NOTES
General		Components:		
		The motive power for the distribution of air in ventilation systems is invariably provided by electrically driven fans. Propeller fans for simple extract systems in wall openings. Centrifugul fans in air treatment units and duct systems. Axial fans in ductwork. Including anti-interation mountings, fittings and fixings.	BS 848 : 1980 BS 3456: 1971 BS 5285: 1975	Fans for general purposes. Ventilating fans. Performance of a.c. electric ventilating fans and regulators for non-industrial use. See 'fans general' section.
		Filtration is required to some extent by both systems, provided by viscous impingement filters, dry paper filters (cotton wool, glass fibre, cotton, charcoal etc) which can be on automatic or manual feed rools or in replaceable frames, wet filters, oil filters, electrostatic filters, absorption units or mechanical collectors.		CIBSE Guide B (1972) Table B.3.12. Classification of air cleaning devices with relative costs.
		Terminals for ventilation systems can be grilles, registers, diffusers, louvres or shutters. Simple toilet extractors are known as wall-type mushroom ventilators. Grilles and registers may be perforated, pressed or stamped lattice metal (aluminium or steel), single or double deflection units with adjustable louvres (plastic) or fixed bar (plaster) types. Including fixings, gaskets (fittings) and insect, bird or vermin screens. Diffusers may be circular, semi-circular, square, rectangular, linear or slot plus adjustable or fixed cone and baffles. These are usually aluminium, steel or plastic.	BS 4773: 1971	Methods for testing and rating air terminal devices for air distribution systems.
		The plenum system requires an air treatment or handling unit with heater batteries (low or high pressure hot water heated coils), humidifiers (spray jets, tank, drain, pumps and pipes), air ducts including control and fire dampers, stiffeners and sound attenuation, thermostatic control valves, standby and duty fans plus an extensive control panel.	BS 4718: 1971	Burberry (1977) Methods of test for silencers for air distribution systems. NOTE Ventilation should be provided in plant and motor rooms to extract equipment generated heat, and in lift shafts to extract smoke. (See CP 407: 1972).
		Exclusions: Specific ventilation for kitchens, localised equipment or basement car parks.		

ELEMENT 5 VENTILATION

COMPONENT	ARC	GENERAL SPECIFICATIONS	REGULATIONS	GUIDANCE NOTES
No mechanical ventilation provided or natural ventilation	NVENT	Number of projects: 10 50% Definition: No mechanical ventilation was provided for half of the projects. Natural openings (or air conditioning systems) can provide sufficient air for ventilation requirements, but are difficult to control, can produce draughts, noise and pollution.	BRE Digest No. 210: 1978	Principles of natural ventilation. A J Environmental Handbook.
		Types: 1. Open sashes in windows 2. Manual ventilators 3. Roof ventilators and automatic fire vents 4. Inlet gratings behind radiators, convectors etc 5. Gratings in doors or gaps provided at the bottom 6. Openable windows 7. Vertical ducts. Infiltration in the gratuitous leakage of air into (and out of) a building due to air paths in the construction.	BS 493: 1970	Specification for air bricks and gratings for wall ventilation. Wise (1979) Design of natural ventilation.
		Natural ventilation exploits wind effects taking advantage of the fact that wind blowing over a structure or neighbouring structure, creates differential pressures over the building fabric. Placing inlet vents in areas of high pressure and outlet vents in areas of lower pressure encourages air to flow through the building. Temperature differentials within buildings create the 'stack effect'. Natural ventilation is, therefore, very dependent on the shape and location of the building.	BRS CP23: 1970	Wind effects.
Mechanical extract ventilation with natural inlet	EXTRACT	Number of projects: 3 15% Definition: A forced mechanical extract fan creates a negative pressure on the inlet side, causing air within the room to move towards the fan, drawing air out to be discharged into the atmosphere. Fresh air flows in by infiltration. Fire dampered openings balance the internal pressures. An extract system may consist of simple wall or window fans in direct contact with the atmosphere. Roof extract units containing centrifugal or propellor fans. Alternatively, it may be connected to a ductwork system, favoured by projects with internal lavatories.		All three projects used extract ventilation to internally positioned lavatories.

COMPONENT	ARC	GENERAL SPECIFICATIONS	REGULATIONS	GUIDANCE NOTES
	EXTRACT	Components: Fan units including motors, drives, casings, bearings, attenuation, fittings and fixings. Duplicate fans and motors or duplicate motors may be required under local byelaws.		See 'fans general' section.
Extract Ductwork	EXDWK	Number of projects: 3 Definition: Distribution ductwork from extract terminals to the exhaust points, including fire, acoustic and volume control dampers, insulation, fans, attenuation, bends, branches, offsets, transformations, supports, sundry metalwork, fittings and fixings.		See 'ductwork general' section.
Extract terminals	EXTER	Number of projects: 3 Definition: Extract terminal units including diffusers, grilles, louvres, control dampers, silencers, registers, bellows and all associated fittings and fixings.		See 'terminals general' section.
Extract electrical work	EXELC	Number of projects: 2 Definition: Electrical work in connection with the extract ventilation including controls for terminals, time delay switches connected to lights, fans, motors, starters, controls, motorised dampers, isolators and sensors.		See 'EWIC general' section.
Mechanical supply and extract ventilation	SUPEXT	Number of projects: 5 25% Definition: Air supply and extraction is completely controlled by a central air handling plant. Supply air may be warmed, cleaned and humidified. It is distributed throughout the building, or to a central core, by a ductwork system and fans. Extract air may be partially recirculated or expelled into the atmosphere via a ductwork system and fans. This type of installation can be used for interior windowless offices, central sanitary accommodation, or the entire building where windows are sealed and doors fitted with closing mechanisms.		Hitchin (1973) See 'Ventilation general' section.

COMPONENT	ARC	GENERAL SPECIFICATIONS	REGULATIONS	GUIDANCE NOTES
	SUPEXT	Components: Central air handling plant including mixing box, (roll) filters, fans, heating coils, humidifiers/washers, pumps, dampers, mountings attenuation, control valves, fittings and fixings. Fan units including motors, starters, casings, attenuation, mountings, fittings and fixings. The heat source (calorifiers, fuel installation, boiler power, pipework, pumps etc) associated with the air handling plant is included within this component definition. Alternatively electric heater batteries may be used, in which case this is included within the electrical work in connection component.		See 'central air handling unit' section. See 'fans general' section. See 'heat source/plant general' section.
Supply and extract system ductwork	SXDWK	Number of projects: 5 Definition: Distribution ductwork from air handling plant to supply terminals, and from extract terminals to exhaust points or returning to the air handling plant. Including fire and volume control dampers, attenuation, insulation, fans, filters, bends, branches, offsets, transformations, supports, sundry metal work, fittings and fixings.		See 'ductwork general' section.
Supply and extract terminals	SXTER	Number of projects: 5 Definition: Supply and extract terminal units including diffusers, grilles, louvres, air-handling luminaires, volume control dampers, silencers, registers, bellows and all associated fittings and fixings.		See 'terminals general' section.
Supply and extract electrical work	SXELC	Number of projects: 4 Definition: Electrical work in connection with supply and extract ventilation system including thermostats, fan controllers, pumps, controls, motorized dampers, isolators and sensors.		See 'EWIC general' section.

COMPONENT	ARC	GENERAL SPECIFICATIONS	REGULATIONS	GUIDANCE NOTES
Mechanical inlet ventilation with natural extract	SUPPLY	Number of projects: 2 10% Definition: Air pressure inside the building is built up by supply fans, so as to exceed the external pressure. Used air is forced out through windows, ventilators and the building fabric due to the pressure head. An air handling unit may provide tempered ventilation air, heated and/or cleaned, before being pumped into the room. A fully ducted system may also make provision for recirculation of room air, cutting the running costs of heating during the winter months. A fan convector may be termed a heated ventilation unit if supplied with a fresh air inlet. Components: Duplicate supply fans, including associated air treatment plant. Fan units include motors, drives, casings, bearings, attenuation, fittings and fixings. Air treatment plant includes heater batteries, humidifiers, sound attenuation, fans, filters, control valves and dampers, mountings, fittings and fixings. The heat source plant (calorifiers fuel installations, pipework in association, pump etc) is included in this component.		See 'fans general' section. See 'heat source/plant general' section.
Supply ductwork	SUPDWK	Number of projects: 2 Definition: Distribution ductwork from air handling plant to supply terminals including, fire and volume control dampers, attenuation, insulation, fans, filters, bends, branches, offsets, transformations, supports, sundry metalwork, fittings and fixings.		See 'ductwork general' section.
Supply terminals	SUPTER	Number of projects: 2 Definition: Supply terminal units including diffusers, grilles, louvres, air-handling luminaires, volume control dampers, silencers, registers, bellows and all associated fittings and fixings.		See 'terminal general' section.

COMPONENT	ARC	GENERAL SPECIFICATIONS	REGULATIONS	GUIDANCE NOTES
Supply electrical work	SUPELC	Number of projects: 1 Definition: Electrical work in connection with supply ventilation system including thermostats, fan controllers, time switches, pumps, controls, motorized dampers, isolators and sensors.		See 'EWIC general' section.

ELEMENT 6 FIRE PROTECTION

COMPONENT	ARC	GENERAL SPECIFICATIONS	REGULATIONS	GUIDANCE NOTES
General		Total Number of projects: 29	London Building Acts: 1939	
		All elements of the structure, including services elements, should have inherent fire resistance, which comply with all the relevant GLC (Greater London Council) requirements.	GLC publication 3868	Means of escape in case of fire.
			Local Fire Authority regulations.	
				CIBSE Technical Memoranda: 1974 Recommendations relating the design of air handling systems to fire and smoke control in buildings.
			Building Regulations (1978) Part FF	
			BS 4066: 1980	Tests on electric cables under fire conditions.
			BS 4422: 1975 : 1976	Glossary of terms associated with fire; fire protection equipment and miscellaneous terms.
			BS 5588 : 1983	Fire precautions in the design and construction of buildings. Code of practice for office buildings.
			BS 5839: 1980	Fire detection and alarm systems in buildings.
			BS 5306: 1976 to 1984	Code of practice for fire extinguishing installations and equipment on premises.
				CIBSE Technical Memoranda: 1982. Notes on non-statutory codes and standards relating to fire and services in buildings.
			The Shops, Offices and Railway Premises Act: 1963	
			The London Building (Construction) Byelaws: 1972-1974	
				Regional Water Authorities.
				Fire Protection Association.
				National Fire Code (NFPA).
				NOTE The provision of a firemans lift and fire detectors or extinguishers in machine rooms.

COMPONENT	ARC	GENERAL SPECIFICATIONS	REGULATIONS	GUIDANCE NOTES
Hosereels	HOSERLS	Number of projects: 27 Definition:	BS 336 : 1980	Specification for fire hose couplings and ancillary equipment.
		A hosereel is a flexible tube, usually rubber, wound onto a fixed or swinging drum. It is used to convey water to put out fires. The hose is connected to a water supply and fitted with a nozzle and control cock. Where the mains pressure is adequate a simple supply arrangement can be provided. Breaktanks may be used if the building is sufficiently tall. If neither can be used, an auto-pressurisation unit may be required.	BS 1906: 1952 BS 3169: 1981 BS 5306: 1976 (1983)	Hose couplings (air and water) 1/8in to 1 1/4in nominal sizes. Specification for first aid reel hoses for fire fighting purposes. Code of practice for fire extinguishing installations and equipment on premises: Hydrant systems, hose reels and foam inlets. The Institute of Plumbing Design Guide (1977).
		The Fire Officers Committee (FOC) recommends that hosereels should be fitted adjacent to fire exit doors. It also requires that hand appliances (hosereels or loose equipment) be provided in all sprinkled buildings.		<u>NOTE</u> Hose reels may be used to deliver carbon dioxide foam or powder, rather than water. No projects specified that these alternative mediums were used.
		Types: Fixed or swinging arm hosereels.	BS 5274: 1985	Specification for fire hose reels (water) for fixed installations.
		Components: Steel drum or reel (may be hinged) Rubber hose Connection to water supply Control valve Nozzle with cock.		
		For gravity-feed systems: Break-tank(s) Valves Connections Pipework (usually copper) Fittings and fixings.		See 'pipework general' section.
		Plus for auto-pressurisation systems or boosted systems: Duplicate direct coupled centrifugal pumps (one acting as standby) A pipeline pressure unit A control panel incorporating starters, selector switches, time delay unit, auto change-over etc. plus general status indication lights or a booster set (pumps).		See 'pumps general' section. Including electrical work in connection.

ELEMENT 6 FIRE PROTECTION

COMPONENT	ARC	GENERAL SPECIFICATIONS	REGULATIONS	GUIDANCE NOTES
Sprinklers	SPNKLR	Number of projects: 4 14% Definition:		Fire Officers Committee (FOC) Rules. Sections: 3100, 3200 and 3400.
		A sprinkler system is an automatic fire fighting installation which sounds the alarm and helpt to contain a fire. A network of piping connected to a water supply, fixed to the ceiling, uses heat sensitive delivery heads which, when broken, release a spray/jet of water onto the fire. The flow of water operates a turbine-operated fire alarm.	BS 5306: 1979	Code of practice for fire extinguishing installations and equipment on premises; sprinkler systems.
			BS 5306: 1982	Halon 1301 total flooding systems.
			BS 5306: 1984	Halon 1211 total flooding systems.
		Types: Wet installations Wet and dry installations Deluge systems Tail end systems.	BS 5445: 1977	Specification for components of automatic fire detection systems.
		A dry system uses delivery pipes filled with air to overcome problems of freezing. When the sprinkler head is opened, the pressure drops and water is then released.		
		Components: Stop valves Alarm motor and bell Central control panel Location plate Test gear.		Including electrical work in connection.
		Connections to water supply - generally two independent trunk mains or if this is not possible, on site storage facilities. High level cisterns may be used in taller buildings. Pressurized cylinders may also be used Supply and delivery pipes Sprinkler heads: Grinnell-type quartzoid sprinklers Side-wall sprinklers Soldered-strut sprinklers 'Duraspeed' soldered sprinklers.		NOTE Sprinklers may be used to deliver carbon dioxide, foam or powder, rather than water. No projects specified that these alternative mediums were used. See 'pipework general' section.
No sprinklers provided	NSPNKLR	Number of projects: 24 86% A large proportion of the projects reviewed did not contain a sprinkler installation.		

COMPONENT	ARC	GENERAL SPECIFICATIONS	REGULATIONS	GUIDANCE NOTES
Loose Equipment	LEQUIP	Number of projects: 15 52%		NOTE
		Definition:		Projects made provision for loose equipment items, but few specified components.
		Loose equipment: hand extinguishers, blankets and buckets, provided as first aid for occupants to use on small fires while awaiting the arrival of the fire brigade.		The Institute of Plumbing Design Guide (1977). Burberry (1977)
			BS 5306: 1980	Code of practice for fire extinguishing installations and equipment on premises; portable fire extinguishers.
		Components:		
		1. Water buckets: red, round-bottomed and fitted with covers.	BS 5306: 1979	Carbon dioxide systems.
		2. Sand buckets.	BS 5423: 1980	Specification for portable fire extinguishers - containing an extinguishing medium of water, foam, powder, carbon dioxide or halon.
		3. Asbestos or glass fibre blankets.		
		4. Carbon-dioxide cartridge gas, pressure type extinguishers.	BS 6535: 1984	Fire extinguishing media - specifications for carbon dioxide and halogenated hydrocarbons.
		5. Soda acid water, striking type extinguishers.		
		6. Stored gas, pressure type extinguishers.		NOTE Simmons (1981)
		7. Soda acid water, inverstion type extinguishers.		Halogenated hydrocarbons have been used for many years to protect electronic equipment and computer rooms;
		8. Foam, gas pressure type extinguishers.		Halon 1211 or BCF (Bromochlorodifluoremethane) is no longer used.
		9. Vaporising liquid type extinguishers.		Halon 1301 or BTM (Bromotrifluoromethane).
		10.Chemical, foam type extinguishers.		
		11.Dry powder type extinguishers.		
No loose equipment	NLEQUIP	Number of projects: 14 48%		
		Forty-eight percent of projects made no provision for loose equipment to be installed, within the estimates.		
Dry risers	DRYRSR	Number of projects: 20 69%		
		Definition:		
		A dry riser is a permanent empty pipe installation to which the fire brigade pumps may be connected, to convey water for fire-fighting, up the building. It is typically, a 100-150mm galvanised heavy weight tube with screwed fittings and flanges, electrically earthed with hydrant connections on each floor level. An inlet and provision for draining without flooding, is provided at ground level, and an automatic vent at roof level.	BS 3251: 1976	Indicator plates for fire hydrants and emergency water supplies.
			BS 5041: --	Fire hydrant systems equipmen
			Part 2 : 1976	Landing valves for dry risers.
			Part 3 : 1975	Boxes for landing valves for dry risers.
			Part 5 : 1974	Boxes for foam inlets and dry risers.
			BS 5306: 1976	Code of practice for fire extinguishing installations and equipment on premises.

COMPONENT	ARC	GENERAL SPECIFICATIONS	REGULATIONS	GUIDANCE NOTES
	DRYRSR	Components: Empty pipe Drain valve Filters (optional) Inlet valve, cap and chain Alarm valve, motor and gong Pressure gauge Non-return valves Stop valves Differential valves Hydrant valve outlets (on each floor and at roof level) or landing valves Vent.		NOTE Dry risers are normally only installed in buildings up to 61 metres in height. Wet risers are required in taller buildings. See (pipework general' section. Including electrical work in connection.
No dry risers	NDRYRSR	Number of projects: 9 31% No provision for a dry riser installation.		
Fire Alarms	ALARMS	Number of projects: 22 76% Definition:		Fire Officers Rules (FOC): 1600. Appendix D - Rules for Automatic Fire Alarms.
		Fire alarms may be automatic heat or smoke sensitive units or manually operated switches. They are positioned in strategic corridors, lobbies, receptions etc and are wired to a central indicator panel which raises the alarm within the building and, if required, at the local fire station. The operation of any one switch will sound alarms on all floors. The control panel can register which alarm has been activated.	BS 3116: 1974	Automatic fire alarm systems in buildings; control and indicating equipment.
			BS 5445: 1977	Specification for components of automatic fire detection systems: heat sensitive detectors - point detectors containing a static element.
			Part 7 : 1984	Specification for point-type smoke detectors using scattered light, transmitted light or ionization.
		Types: 1. Basic break glass or manual system.	Part 8 : 1984	Specification for high temperature heat detectors.
		2. Automatic systems a. Heat detectors b. Smoke detectors.	BS 5839: 1980	Fire detection and alarm systems in buildings: Code of practice for installation and servicing.
			Part 2 : 1983	Specification for manual cell points.
		Projects may contain more than one type of installation depending on the area served. For example: Entrance halls and lift lobbies may have all three, escape stairs may have breakglass units and, plant and lift motor rooms may have heat detectors.	BS 5979: 1981	Specification for direct line signalling systems and for remote centres for intruder alarm systems. See 'EWIC general' section. Nerdle (1982)
		Components: 1. Control panel which is self contained (battery operated) multi-zoned location indicator, monitoring faults, alarms and battery charging. Including a charger, batteries, terminals, timeswitch sounders, auxiliary relay, resistors, alarm circuits and fault indicators.		

COMPONENT	ARC	GENERAL SPECIFICATIONS	REGULATIONS	GUIDANCE NOTES
	ALARMS	2. Fire alarm repeater panels 3. Heavy duty relays 4. Smoke detectors 5. Heat detectors 6. Breakglass call points 7. Bells 8. Electronic sounders 9. Strobe lights 10. Mineral insulated copper sheathed cables, in vertical risers, ceiling voids and multi-terminal junction boxes located in the electrical riser switchrooms. All electrical work in connection is included (connections, fuses, switches etc). Exclusion: intruder alarm systems. NOTE: Trickle charged accumulators ensure that the system will operate during a period of mains failure.		

ELEMENT 7 LIFTS

COMPONENT	ARC	GENERAL SPECIFICATIONS	REGULATIONS	GUIDANCE NOTES
General		Total number of projects: 30		NOTE In all the projects lift manufacturers were appointed as a nominated sub-contractor, providing a complete packaged lift installation.
		A lift is a permanent appliance serving defined landing levels, by which persons and goods are moved vertically or through an inclination to the vertical of less than 15°, from one level to another. It is defined by the design capacity or recommended maximum number of passengers carried.		Turner (1986)[2] Smith & Julian (1976) Bedford & White (1983) Burberry (1977) Talbot (1981) Otis (1984) PSA (1982) CIBSE Guide Book (1972) Volume B15: Vertical Transportation.
		The number and type of passenger lifts to provide a satisfactory service depends upon the characteristics of the project. The most important of these being:	CP 407 : 1972	Electric, hydraulic and hand-powered lifts.
		1. The total building population (calculated from the average area occupied by one person, and the let floor area) and its distribution within the building	BS 2655: 1970 BS 5655: 1979 -1983	Lifts, escalators, passenger conveyors and paternosters. Lifts and service lifts.
		2. The total height travelled by the lift and the number of floors served.	BS 5810: 1979	Code of practice for access for the disabled to buildings
		3. The maximum peak demand or traffic density in peak hours, (calculated from a proportion of the total population to be handled in the peak five minute period.	BS 6100: 1984 Factories Act: 1961	Glossary of building and civil engineering terms; internal transport.
		4. The expected waiting time or quality of service and travelling interval.	Offices, Shops and Railway Premises Regulations; 1968.	
		The ideal performance of an elevator provides minimum waiting time for a car at any floor level, comfortable acceleration, rapid transportation, smooth and rapid retardation, automatic levelling at landings and, rapid loading and unloading at all stops.	Health and Safety at Work Act: 1974 BS 3819: 1975	McGuiness, Stein & Reynolds (1980). Terms used in connection with lifts, lifting platforms and inclined haulage. (Each part illustrates items and principle components).
		The position of the proposed office development in relation to transport services also affects the selection and disposition of lift services. Care should be taken when undertaking a full traffic analysis to consider inter-floor movement, of which there is very little information to give guidance on the influence of this type of traffic on lift performance, and possible changes in the buildings' occupancy. It is claimed that the population can increase by as much as 25% in a period of 2-5 years after first occupation, so lifts are potentially subject to changes in user demand and capacity.		Hammond & Champress (1982). Pinfold (1966).

ELEMENT 7 LIFTS

COMPONENT	ARC	GENERAL SPECIFICATIONS	REGULATIONS	GUIDANCE NOTES
General		Types of enclosed lifts used within the research: 1. Electric or traction drive 2. Hydraulic or oildraulic providing general purpose or intensive traffic passenger lifts.		
		In office developments with floors more than 18m from the ground level, one of the lifts provided was classed as a fireman's lift (with automatic doors and a capacity of not less than 8 persons). It may be used by the occupants at normal times, but can be reserved for use by firemen if the need arises. Such a lift should have its own separate electricity supply and be capable of travelling the full height in not more than 60 seconds. At each floor there should be a glass panel which the fireman can break to uncover a tumbler type fire switch or control buttons which can isolate the buttons used by the public on other floors so as to restrict the use of the lift for fire-fighting.	London Building Act: 19 Local Fire Authority.	PSA (1975) Burberry (1977) McKay (1975
		Exclusions: 1. Escalators 2. Paternosters 3. Panoramic (rear wall of transparent material) lifts 4. Wall-climber (rear wall extension to produce exposed three walled car-transparent) lifts. These can be 1.8 to 5 times the cost of a conventional lift (Wheeler, 1984) 5. Entirely transparent (glass) lift and shaft installations.		Wheeler (1984)
		The installation costs of lifts are affected by: 1. The number of stops or levels served. The removal of landing door openings on every floor and zoning of lifts reduces costs. 2. The lift speed. Two speed or variable voltage motors are more costly. The car speed is a function of the building height. The nigher the car speed the better the service but with an increase in capital and running costs. 3. The controls. The more complex the system, the greater the cost. 4. The lift car finishes, fixings and extras (telephones, mirrors etc)		Cain (1975)

COMPONENT	ARC	GENERAL SPECIFICATIONS	REGULATIONS	GUIDANCE NOTES
General		5. The height of the building: more door openings, landing controls, longer ropes or rams and guide rails, a change in lift motor specification, including gear, pumps and control gear.		
		Capital costs should always be considered in conjunction with operating costs, but this is frequently ignored according to Roberts (1973). On the basis of capital costs alone, when the cost of builders work is taken into account, the electro-hydraulic lift is not much more expensive than the traction lift.		Roberts (1973)
		Factors not included for within the research: 1. Floor to floor heights greater than 3.3m. 2. More than one main floor served (single occupancy) 3. Levels or landings below ground 4. A canteen, dining area or executive suite above ground level 5. Large numbers of visitors 6. A significant amount of goods traffic requiring the installation of a goods lift.		Williams (1974)
No lifts	NLIFT	Number of projects: 10 33% A third of the projects made no provision for a lift installation.		
Hydraulic lifts	HLIFT	Number of projects: 3 11%		NOTE All the hydraulic lifts analysed were 8-person capacity cars, usually in a pair.
		Definition: The oil-hydraulic lift uses the principle of the hydraulic press. Oil, at high pressure - 2 to 7MPa, is pumped through pipework to a cylinder containing a piston. The force acting on the piston in equal to the pressure multiplied by the area of the piston. The car is lifted and supported on the head of the piston (ram or jack) including the passenger load.		Hall (1982) Lickey & Stebbing (1983) Cain (1975)
			BS 2655: 1970	General requirements for electric, hydraulic and hand-powered lifts.
			BS 5655: 1983	Specification for hydraulic lifts.
		Types of hydraulic lift: Direct acting Side-acting Indirect side-acting Machine below underslung	BS 6331: 1983	Mounting dimensions of single rod double acting hydraulic cylinders.
				Otis (1984)

COMPONENT	ARC	GENERAL SPECIFICATIONS	REGULATIONS	GUIDANCE NOTES
	HLIFT	Hydraulic lifts are most effectively used in buildings with a rise of up to 20m and in restricted conditions. They operate at slower speeds than electric lifts, but are very smooth while travelling and are excellent levellers. The machine equipment or power unit is sited at low level and may be located up to 17.5m from the ram, imposing no structural loads on the lift shaft. They are very robust and maintain high safety standards. Generally, they offer low capital and maintenance costs.		NOTE The imposed limitations on speed are due to the high electrical starting currents required.
		Components:		
		1. Power unit: the pumping medium is oil and pressure is applied by an AC motor driven pump. (Speeds: 0.20-1.75m/s)	BS 5630: 1978	Specification for interface dimensions of snap-on connections for use with electrically controlled hydraulic equipment.
		Motor: Short-time rated, single speed, a.c. squirrel cage type or for higher powers, the slip-ring type.	BS 6494: 1984	Hydraulic fluid power valve mounting surfaces.
			BS 6275: 1982	Hydraulic fluid power filter elements.
		Pump, oildraulic valve controller, control and relief valves and oil reservoir.	BS 4062: 1982	Valves for hydraulic fluid power systems.
		2. Jacking system: solid drawn mild steel cylinder, steel ram, packing gland, line strainer, shut-off valve and silencer unit.	BS 4617: 1983	Methods for determining the performance of pumps and motors for hydraulic fluid power transmission.
		3. Steelwork: gate frames, culls, cull supports, toe guards, architraves and guides for the car.	BS 6525: 1984	Specification for design and construction of reservoirs used in hydraulic fluid power reservoirs.
		4. Lift car: metal/timber. Finishes: vinyl, stainless steel, carpet, lino, rubber, hardwood, melamine laminate, painted glass, timber, fabric, steel (cellulosed, plastic coated or primed), ribbed aluminium, plastic laminates, and store enamel.	BS 5671: 1979	Guide for commissioning, operation and maintenance of hydraulic turbines.
		Fixings: Flush telephone cabinets, handrails, mirrors, lifht fittings, load plate, hinged emergency panel, speech synthesizers, information displays, ashtrays, and extract fans.		
		Doors: Centre opening, side opening or two speed side opening; self closing or power operated doors.		
		Controls.		See 'EWIC'.

COMPONENT	ARC	GENERAL SPECIFICATIONS	REGULATIONS	GUIDANCE NOTES
Electrical work in connection with hydraulic lifts	HLFTELC	Number of projects: 2		
		Definition:		
		Electrical work in connection with hydraulic lifts including door operators, control systems, signals, telephones, security, alarms, and fans. Plant room lighting, small power and heating.		See 'EWIC general' section.
		Components:		
		Control systems:		
		1. Single automatic push button controls.		Cain (1975)
		2. Down collective controls. 3. Simplex full collective controls. 4. Duplex collective controls. 5. Triplex collective controls.	BS 5655: 1983	Specification for manual control devices, indicators and additional fittings.
		6. Microcomputer based controls. 7. Auto by-pass.		Wheeler (1983)
		8. Emergency recall switch.		Hammond & Champress (1982)
		Signals:		PSA (1978)
		1. Call registered lights. 2. 'In use' lights. 3. Directional lights plus electronic gongs.		Signalling curcuits should be 4, 6 or 12 core 1/0.85mm (0.6mm²) PVC sheathed cables.
		4. Position indicators. 5. Car position indicators.	BS 2655: 1970	General requirements for electric, hydraulic and hand-powered lifts.
		Others:		
		Passenger detector mechanisms DC or AC motor controlled doors Light-ray devices Telephone cables Speech synthesizers Information displays Security switches Alarms Emergency stop switch	BS 4794: 1979	Specification for control switches (switching devices, including contactor relays, for control and auxiliary circuits, for voltages up to and including 1000a.c. and 1200 V d.c.).
		Extract fan motors and starters Firemans control	BS 587 : 1957 (1984)	Motor starters and controllers.
		Lighting-emergency and concealed fluorescent lights in the car and lift well	BS 5266: 1981	Emergency lighting.
		Machine - power units, pumps etc.		
		Cables: Control cables to call buttons, position indicators and all landing controls. Trailing cables to feed the lift car.		Travelling cables should be multicore, with stranded high conductivity copper conductros, braided, fire resistant and especially designed for lift duty.
		Only cables associated with the lift installation should run in the lift shaft. They should be armoured, mineral insulated and heat, oil and flame retardant sheathed. Cables should be enclosed in a metal conduit, duct or trunking, high impact PVC conduit or otherwise mechanically protected.	BS 6977: 1981 BS 4568: 1970	Specification for insulated flexible cables for lifts and for other flexible connections. Steel conduit and fittings with metric threads of 150 form for electrical installations.
			BS 4678: 1982	Cable trunking
				Express (1976)
			BS 4607: 1984	Non-metallic conduits and fittings for electrical installations.

COMPONENT	ARC	GENERAL SPECIFICATIONS	REGULATIONS	GUIDANCE NOTES
	HLFTELC	Emergency power supplies (batteries) for maintaining the lift service during power failures.	BS 6004: 1984	Specification for PVC-insulated cables (non-armoured) for electric power and lighting.
		Main switch fuse for each lift Local circuit breakers Local wiring Suppression of radio and TV interference Car ventilation fan	BS 613 : 1977	Specification for components and filter units for electromagnetic interference suppression.
		Power points in plant room.	BS 6201: 1982	Specification for fixed capicitors for radio interference suppression. Selection of methods of test and general requirements.
Electric Lifts	ELIFT	Number of projects: 17 56%		NOTE 5% of electric lifts were of a 6 - person capacity, 17% were 8 - person, 55% were 10-12 person and 7% 15+-person capacity. 16% were not specified. Lickley (1983) PSA (1978)
		Definition: A lift, the machine of which is driven by an electric motor. The lift car is suspended from multiple steel wire lifting ropes which pass over a grooved traction sheave overhead to a counterweight travelling in the same lift well. Both the car and the counterweight travel between vertical rigid guide rails. Motion is transmitted by friction between the ropes and the traction sheave which is driven through worm reduction gearing by an electric motor. In high speed lifts the reduction gearing is not used. Mechanical and electrical safety devices and interlocks on the car, in the well and in the machine room are designed and built to ensure safety.	BS 2655: 1970	General requirements for electric, hydraulic and hand-powered lifts.
			BS 5655: 1979	Safety rules for the construction and installation of electric lifts.
			BS 5655: 1981	Specification for dimensions of standard electric lift arrangements.
		Electric lifts have the advantage of higher speeds, good round trip times, higher handling capacities and shorter waiting intervals. They dominate the market for projects, whose building heights are greater or equal to 20 metres. Variable speed and gearless drive electric lifts were developed from the Ward Leonard principle.	PD 6500: 1984	Explanatory supplement to BS 5655 'Lifts and service lifts'.
		Types: 1. Single speed a.c. drive $\leqslant$ 0.63 m/s 2. Two speed a.c. drive $\leqslant$ 1.60 m/s (suitable for small offices) 3. Variable speed a.c. drive $\leqslant$ 2.00 m/s 4. Variable speed geared d.c. drive $\leqslant$ 2.00 m/s 5. High speed gearless drive $>$ 2.50 m/s.		Bowman (1985)
		The general purpose passenger lift (8-10 persons) can be a two speed drive for 0.75- 1.00 m/s, or a variable voltage drive for 1.00-1.50 m/s, geared.		

COMPONENT	ARC	GENERAL SPECIFICATIONS	REGULATIONS	GUIDANCE NOTES
		Intensive traffic passenger lifts normally travel heights of over 30m and use gearless, variable voltage drive for speeds usually between 2.50-4.00 m/s.		
		The electric traction machinery may be positioned above or below the lift car; alternative roping arrangements may produce double wrap or hitch types (overhead, underneath, single wrap, ordinary double wrap, two-to-one double wrap, single counterweight drum and double counterweight drum).		Otis (1984) Miller (1981) Cain (1975)
		The most advantageous position, according to Cain (1975) is to have the motor at the top of the building as it incurs a lower capital cost of installation (due to less equipment being required).	BS 2618: 1975 BS 4362: 1968 (1984)	Electric traction equipment. Rotating electrical machinery.
		Components:	BS 2048: 1961 (1984)	Motors for general use.
		1. Drive plant: high motor, motor generator set and starter. The motors must be capable of continuous duty at 150 starts per hour for two speed control and 180 starts per hour for variable voltage control.	BS 587 : 1957 (1984) BS 775 : 1974 (1984) BS 5000: 1981	Motor starters and controllers. A.C. Contactors for voltages above 1KV and up to and including 12KV. Rotating electrical machines of particular types or for particular applications.
		2. Standby generator supply.	BS 4999: 1977	General requirements for rotating electrical machines.
		3. Winding machinery; bearings worm gear, angles, traction sheave and brakes.	BS 721 : 1963 (1984)	Specification for worm gearing.
		4. Steel wire suspension ropes and anchorage devices.	BS 329 : 1968	Steel wire ropes for electric lifts.
		5. Counterweight.	BS 3530: 1968	Small wire ropes.
		6. Car safety gear; governors, steel cams and clamps.	BS 4018: 1966	Pulley blocks for use with wire ropes for a maximum lift of 25 ton f combination
		7. Guides, supports and tracks for car and counterweight.	BS 4536: 1970	Heavy duty pulley blocks for use with wire ropes.
		8. Car guide shoes and lining material plus lubrication.	BS 235 : 1972	Gears for electric traction.
		9. Buffers: solid helical metal spring, volute spring or hydraulic.		
		10. Steelwork: supports for winding machine and diverter sheaves, gate frames and cills, cill supports and toe guards, architraves and guides.		
		11. Door locks and doors.		
		12. Insulation to lift gear including motor generators and controllers, to limit noise and vibration.		

COMPONENT	ARC	GENERAL SPECIFICATIONS	REGULATIONS	GUIDANCE NOTES
	ELIFT	13. Lift car: metal/timber. Finishes: vinyl, stainless steel, carpet, lino, rubber, hardwood, melamine laminate, painted, glass, timber, fabric, steel (cellulosed, plastic coated or primed), ribbed aluminium, plastic laminates and stove enamel. Fixings: Flush telephone cabinets, handrails, mirrors, light fittings, load plate, hinged emergency panel, speech synthesizers, information displays, ashtrays and extract fans. Doors: Centre opening, side opening or two speed side opening; self closing or power operated doors.		
		Controls:		See 'EWIC'.
		14. Cat ladder (access to pit)		
		15. Hoisting beams.		
Electrical work in connection with electric lifts	ELFTELC	Number of projects: 10 Definition:		
		Electrical work in connection with electric lifts including the main cable from ground switchboard to lift motor room, motor room lighting, small power and heating. Lift shaft lighting, socket outlets, door operators, control systems, signals, telephone conduits, security wiring, alarms and ventilating fans.		See 'EWIC general' section.
		Components: Control system including controllers to protect motors, reverse and single phase preventors, circuits for starting, slowing, levelling and stopping. Safety in the event of supply failure, fuses, switches, contactors, time delay devices and relays. Variable voltage control applied to the lift motor to provide uniformly varying d.c. voltage. Motor overload protection. Isolators.		Bowman (1985) Wheeler (1983) Hammond & Champness (1982) PSA (1978) Cain (1975)
		Control systems:		
		1. Single automatic push button controls 2. Down collective controls 3. Simplex full collective controls 4. Duplex collective controls 5. Triplex collective controls 6. Microcomputer based controls 7. Auto by-pass 8. Emergency recall switch	BS 5655: 1983	Specification for manual control devices, indicators and additional fittings.
		Local wiring, circuit breakers, fuses and conduits.		

COMPONENT	ARC	GENERAL SPECIFICATIONS	REGULATIONS	GUIDANCE NOTES
	ELFTELC	Signals: 1. Call registered lights 2. 'In use' lights		Signalling circuits should be 4, 6 or 12 core 1/0.85mm (0.6mm²) PVC sheathed cables.
		3. Directional lights plus electronic gongs 4. Position indicators 5. Car position indicators.	BS 2655: 1959	Single-speed polyphase induction motors for driving lifts.
		Others: Passenger detector mechanisms DC or AC motor controlled doors Lifht-ray devices Telephone cables Speech synthesizers Information displays Security switches	BS 4794: 1977	Specification for control switches (switching devices, including contractor relays, for control and auxiliary circuits, for voltages up to and including 1000a.c. and 1200 V d.c.).
		Alarms Emergency stop switch Extract fan motors and starters	BS 587 : 1957 (1984)	Motor starters and controllers.
		Firemans control Lighting - emergency and concealed fluorescent lights in the car and lift well/ shaft	BS 5266: 1981	Emergency lighting.
			BS 775 : 1974 (1984)	Contactors.
		Machinery - power units, pumps, motors etc.	BS 4999: 1977	General requirements for rotating electrical machines.
			BS 4999: 1972	Duty and rating.
			BS 4999: 1984	Winding terminations.
		Cables: control cables to call buttons, position indicators and all landing controls. Trailing cables to feed the lift car.	BS 5000: 1981	Rotating electrical machines. Travelling cables should be multicore, with standed high conductivity copper conductros, braided, fire resistant and especially designed for lift duty.
		Only cables associated with the lift installation should run in the lift shaft. They should be armoured, mineral insulated and heat, oil and flame retardant sheathed. Cables should be enclosed in a metal conduit, duct or trunking, high impact PVC conduit or otherwise mechanically protected. They should be supported by retaining straps and individual cable clamps.	BS 6977: 1981	Specification for insulated flexible cables for lifts and other flexible connections.
			BS 6099: 1981	Conduits for electrical installations.
			BS 4568: 1970	Steel conduit and fittings with metric threads of 150 form for electrical installations.
		Emergency power supplies (batteries) for maintaining the lift service during power failures.	BS 4678: 1982	Cable trunking. Express (1976)
			BS 4607: 1984	Non-metallic conduits and fittings for electrical installations.
			BS 6004: 1984	Specification for PVC-insulated cables (non-armoured) for electric power and lighting.
		Main switch fuses for each lift. Suppression of radio and TV interference.	BS 613 : 1977	Specification for components and filter units for electro-magnetic interference suppression.
		Car ventilation fans. Power points in the machine and pulley rooms.	BS 6201: 1982	Specification for fixed capicitors for radio inter-ference suppression. Selection of methods of test and general requirements.

ELEMENT 8 ELECTRICAL

COMPONENT	ARC	GENERAL SPECIFICATIONS	REGULATIONS	GUIDANCE NOTES
General		Total number of projects: 23 Definition: The supply of electricity from the mains via cables, conduits and trunking including meters, distribution boards, busbars, circuit breakers, relays, switches, fuses, and all necessary fittings and fixings to: Emergency supplies Small power points Lighting points Telephones Control panels (EWIC) Hot water points (EWIC) Heating points (EWIC) Air conditioning points (EWIC) Ventilation points (EWIC) Sprinklers (EWIC) Fire alarms (EWIC) Lift shaft lighting (EWIC) Lift motor supply (EWIC) Refrigeration plant (EWIC) Plant rooms (EWIC) Incorporating interference suppression devices in all electrical equipment.		Hughes (1983) Forges (1982) Jay & Hamsley (1968) Lovegrove (1983) Watson (1983) Hutton (1975) Dickens (1970) IEC: International Electrotechnical Commission. CENELEC: The European Committee for Electrotechnical Standardisation. CIBSE Guide B (1976) Section B10 Electrical Power. CIBSE Application Manual (1984) Automatic controls and their implications for systems design. CIBSE Lighting Code (1984) Code for Interior Lighting. IEE 15th Edition (1981) Wiring Regulations.
		Exclusions: Shaver sockets Hand driers Clocks Computer equipment.	BS 9000: 1981	General requirements for a system for electronic components of assessed quality.
		NOTE: Landlord and tenant areas have not been independantly analysed due to the immense number of permutations possible, comparisons would be extremely difficult. Higher mains and cabling costs may indicate the degree of zoning and extra metering requirements. The offices are therefore assumed to be single occupancy; this is known however, to be incorrect.	BS 9430: 1978 (1983)	Rules for the preparation of detail specifications for integrated circuits of assessed quality: voltage regulators.
			BS 4727: 1971-1983	Glossary of electrotechnical, power, telecommunication, electronics, lighting and colour terms.
			BS 4137: 1967	Guide to the selection of electrical equipment for use in Division 2 areas.
			BS 5733: 1979	Specification for general requirements for electrical accessories.
			BS 613 : 1977	Specification for components and filter units for electromagnetic interference suppression.
			BS 800 : 1977	Specification for radio interference limits and measurements for equipment embodying small motors, contacts, control and other devices causing similar intereference.
			BS 5394: 1983	Specification for radio interference limits and measurements for lighting equipment.

COMPONENT	ARC	GENERAL SPECIFICATIONS	REGULATIONS	GUIDANCE NOTES
General			BS 6201: 1982	Specification for fixed capicitors for radio interference suppression.
			BS 3456: 1978	Specification for safety of household and similar electrical appliances.
			BS 6396: 1983	Code of practice for electrical systems in office furniture and office screens.
				Electrical wiring should comply with standard specification (M&E) No. 1.
			Electricity (Factory Acts) Special Regulations 1908 and 1944.	
			Electricity Supply Regulations, 1937.	
Electrical mains supply	EMAINS	Number of projects: 22 Definition: Electrical mains and sub-mains supply including the connection charge and associated switchgear, meters, distribution boards, fuses and circuit-breakers. Components: 1. Connection charge for the electricity supply from the London Electricity Board. Three phase, four wire supply (215 V phase voltage and 415 V line voltage) should be sufficient for small offices, but where installations exceeding 400 KW are required, a supply taken at high voltage (6.6 or 11 KV) is used. The Electricity Board is likely to require a transformer chamber in all but the smallest office development.		NOTE The degree of division and sub-division of the main supply will depend on the degree of control required and the number of tenants. Maver (1971) The Energy Act (1983) Jay (1973) Nerdle (1982)
			BS 37 : 1952-1970	Electricity meters.
			BS 5685: 1979	Electricity meters.
			BS 77 : 1958	Voltages for a.c. transmission and distribution systems.
		The type of supply will depend on the likely maximum demand. This is determined from the expected loadings of all items of equipment and appropriate allowances for lighting, heating, air conditioning and small power. Usage patterns should also be assessed (diversity factors).	BS 3026: 1958	Voltages for high-voltage d.c. transmission systems. NOTE Larger office developments may take their supply directly at 11 KV and provide their own private substations. As the higher the voltage, the cheaper the supply (Nerdle, 1982).
		From the incoming supply the power is metered, transformed in voltage (if necessary) and distributed from the main switchboard.	BS 162 : 1961	Electric power switchgear and associated apparatus.
			BS 5486: 1977	Specification for factory-built assemblies of switch-gear and control gear for voltages up to and including 1000 V A.C. and 1200 V d.c.

COMPONENT	ARC	GENERAL SPECIFICATIONS	REGULATIONS	GUIDANCE NOTES
	EMAINS	2. High Voltage (HV) switchboards (when required) comprising of an assembly of oil or vacuum circuit breakers and oil switches, as appropriate. The circuit breakers should be of the fully interlocked vertical isolation, horizontal withdrawable type with integral earthing facilities. High voltage busbars of solid copper and insulated with shrunk on PVC or moulded non-hygroscopic insulation. Busbar joints, connections and spouts for connections to the circuit breakers should be insulated with epoxy resin or moulded non-hygroscopic insulation. Including busbar supports. Voltage transformers for HV switchgear of the withdrawable unit isolation types plus protection relays. Current transformers, protection devices, instrumentation and meters.		NOTE Where LV supply is used service fuses, a neutral link, three phase linked switches and meters are required.
			BS 5227: 1975	A.C. metal-enclosed switchgear and controlgear of rated voltage above 1 KV and up to and including 72.5 KV.
				NOTE The supply of power to submains using cables in the riser positions should only be used where it has been requested. For first approximations busbar trunking installations are much simpler. A busbar is a conductor of a relatively large cross section to which the various incoming and outgoing circuits are connected.
			BS 5486: 1978	Busbar trunking systems.
		3. Transformers (3-phase, 50 HZ double wound) arranged for delta-star connections with the neutral point brought out on the low voltage side. High voltage windings with trappints allow for variations in the primary voltage, controlled by an off-load tapping switch arranged to change the taps on all three phases simultaneously. Transformers should withstand a HV impulse level of 95 KV (peak). Automatic fire protection systems should be provided for oil circuit breakers or oil immersed transformers. A 'packaged' substation may be used incorporating a dry-type transformer and air-break circuit breakers, which alleviate some of the fire hazards.		NOTE Meters should be provided for each tenant, or in single occupancy projects, one meter on the supply intake.
			BS 6581: 1985	Common requirements for high voltage switchgear and control gear standards.
			BS 6553: 1984	Guide for selection of fuse links of high voltage fuses for transformer circuit applications.
			BS 171 : 1970	Power transformers.
			BS 3535: 1962	Safety isolating transformers for industrial and domestic purposes.
			BS 3938: 1973 (1982)	Current transformers.
			BS 3941: 1975 (1982)	Voltage transformers.
			BS 5611: 1978	Application guide for on-load tap-changers.
			BS 5953: 1980	Guide to power transformers.
			BS 6435: 1984	Specification for unfilled enclosures for the dry termination of HV cables for transformers and reactors.
		NOTE Subdistribution board should be located near load centres to reduce wiring costs i.e. lift shafts.	BS 6436: 1984	Specification for ground mounted distribution transformers for cable box or unit substation connection.
			BS 9720: 1983	Specification for custom built transformers and inductors of assessed quality.
			BS 4727: 1973	Transformer terminology.

COMPONENT	ARC	GENERAL SPECIFICATIONS	REGULATIONS	GUIDANCE NOTES
	EMAINS		BS 5419: 1977	Specification for air-break switches, air break disconnectors and fuse combination units for voltages up to and including 1000 V a.c. and 1200 V d.c.
			BS 6423: 1983	Code of practice for maintenance of electrical switchgear and control gear for voltages up to and including 650 V.
		4. Switchboards The switchboards distribution and fuse boards should be of a totally enclosed metal clad type with all interconnections, labels, circuit listings, fixings, fuse links, cable glands and an inbuilt isolator. The boards contain an assembly of main and auxiliary switching apparatus for the operation, regulation, protection or other control of the electrical installations. The switchgear (a general term including switches and equipment) ensures the reliability of the electricity supply, safeguards, localises faults, disconnects and facilitates inspection and maintenance.	BS 4727: 1972	Switchgear and control gear terminology (including fuse terminology).
			BS 5463: 1977	Specification for a.c. switches of rated voltage above 1 KV.
			BS 5253: 1975	A.C. disconnectors (isolators) and earthing switches of rated voltage above 1 KV.
			BS 77 : 1958	Voltages for a.c. transmission and distribution systems.
			BS 5583: 1978	Specification for low voltage switchgear and controlgear for industrial use.
		For LV switchgear, located at transformer positions and large load centres, air circuits breakers or fused switches should be used for the control of the outgoing circuits.	BS 842 : 1965 (1980)	A.C. voltage-operated earth leakage circuit breakers.
			BS 3871: 1965 (1984)	Miniature and moulded case circuit breakers.
			BS 4752: 1977	Circuit-breakers.
		Circuit breakers are automatic switches for making or breaking circuits under normal or fault conditions. They can be reset by a switch and are either oil or air blast types. Isolating switches, used mainly for maintenance purposes, isolate circuit breakers and electrical apparatus from live conductors. Relays are used to protect the electrical apparatus, controlling a circuit according to the changes of current in another circuit. Overload relays are used to disconnect plant and equipment because of current excesses. Reverse power and reverse current relays disconnect if the power flows in the opposite direction. Induction and impedence relays are also used.	BS 4293: 1983	Specification for residual current operated circuit breakers.
			BS 5311: 1976	Specification for a.c. circuit breakers of rated voltage above 1 KV.
			BS 142 : 1982	Electrical protection relays.
			BS 5992: 1980	Electrical relays.
			BS 4727: 1971	Relay terminology.
			BS 9150: 1983	Specification for electrical relays of assessed quality.
			BS 9151: 1972 (1983)	Rules for the preparation of detail specifications for all-or-nothing electro-mechanical relays.
			BS 9152: 1978	Rules for the preparation of detail specifications for reed relays of assessed quality.
		Fuses are also used as a safety device, the fuse wire melts when an excess of current flows through the circuit, disconnecting the power. These need to be replaced. Voltmeters and ammeters are included.	BS 88 : 1975	Cartridge fuses for voltage up to and including 1000 V a.c. and 1500 V d.c.

ELEMENT 8 ELECTRICAL

COMPONENT	ARC	GENERAL SPECIFICATIONS	REGULATIONS	GUIDANCE NOTES
	EMAINS		BS 2692: 1975	Fuses for voltages exceeding 100 V a.c.
			BS 5486: 1979	Fuseboards.
			BS 3036: 1958 (1978)	Semi-enclosed electric fuses (ratings up to 100 amperes and 40 volts to earth).
			BS 4265: 1977 (1984)	Specification for cartridge fuse links for miniature fuses.
			BS 5564: 1978	Specification for high voltage fuses for the external protection of shunt power capacitors.
				Tootill (1985) Feenan (1985)
Electricity cables	ECABLE	Number of projects: 21 Definition: Main distribution cables including saddles, cable trays, connectors, spreaders, seals, glands, locknuts, bushes, junction boxes, sleeves, thermistors and cleats, to switchboards on each floor. Earthing of all non-current metalwork and busbars. Bonding of conduits, exposed metalwork; sinks (stainless steel), water pipes and wastes, for firefighting, cold water, heating, air conditioning and refrigeration, ductwork. Busbars for vertical distribution where used, instead of cabling.		
		Main distribution cables are installed at all voltages in various locations throughout a development in cable ducts, trays, trenches, vertical risers and above corridor false ceilings. The various circuits (lighting, heating, power) are segregated, each enclosed in a conduit, steel trunking or the like, including supports (pin racks and brackets), fittings and fixings.	BS 6220: 1983 BS 6121: 1973	Specification for junction boxes for use in electrical installations with rated voltages not exceeding 250 V. Mechanical cable of glands for elastomer and plastics insulated cables.
		A cable is an insulated conductor or set of conductors, formed of one or more wires or strands and used to carry an electric current. Several cores may be enclosed within a protective sheath. Insulation, in different forms, is used to withstand mechanical damage which may result under particular circumstances. They are usually rigid for permanent wiring installations.	BS 4109: 1970	Copper for electrical purposes. Wire for general electrical purposes and for insulated cables and flexible cords.
			BS 4121: 1967	Mechanical cable glands for rubber and plastics insulated cables.

COMPONENT	ARC	GENERAL SPECIFICATIONS	REGULATIONS	GUIDANCE NOTES
	ECABLE	Types of cable: 1. Conductors: PVC Vulcanised rubber Butyl rubber Silicone rubber Paper Magnesium oxide powder Mineral insulated Copper sheathed (MICS)	BS 4553: 1970	PVC-insulated split concentric cables with copper conductors for electric supply.
			BS 4579: 1970	Performance of mechanical and compression joints in electric cable and wire connectors.
			BS 4662: 1970 (1979)	Boxes for the enclosure of electrical accessories.
		3. Mechanical protection: PVC Vulcanised rubber (VRI) Tough rubber sheathed (TRS) Butyl rubber Ethylene propylene rubber Silicone rubber Chloro-sulphonated polythene Neoprene Terylene Copper Aluminium	BS 5308: 1975	Specification for polyethylene insulated cables.
			BS 5308: 1978	Specification for PVC insulated cables.
			BS 5593: 1978 (1984)	Specification for impregnated paper insulated cables with aluminium sheath/neutral conductor and three shaped solid aluminium phase conductors (CONSAC), 500/1000 V, for electricity supply.
			BS 5467: 1977 (1984)	Specification for armoured cables with thermosetting insulation for electricity supply.
			BS 5468: 1977	Specification for cross-linked polyethylene insulation of electric cables.
		The selection of the type of conductor, insulator and mechanical protection depends on the type of supply and earthing requirements, the ambient air temperatures, the moisture and corrosive atmospheric conditions, the presence of flammable or explosive dust, the continuity of service required and standby supply; provision for modification, extensions and re-wiring access, operating and maintenance costs, the relative costs of alternative wiring installations, the expected life of the installation and whether the system is for an existing or new development. The selection of an appropriate cable size and type from the twenty-three IEE 'Tables of Cable Current Ratings', is no easy matter. Correction factors must be applied with care. The location of the cables within ducts, conduits and the like must allow for heat generation, voltage drops and magnetic affects.		Needle (1982)
			BS 5469: 1977	Specification for hard ethylene propylene rubber insulation of electric cables.
			BS 6141: 1981	Specification for insulated cables and flexible cords for use in high temperature zones.
			BS 6081: 1978 (1984)	Specifications for terminations for mineral insulated cables.
			BS 6004: 1984	Specification for PVC-insulated cables (non-armoured) for electric power and lighting.
			BS 6007: 1983	Specification for rubber-insulated cables for electric power and lighting.
			BS 6746: 1976	PVC insulation and sheath of electrical cables.
			BS 6899: 1976	Specification for rubber insulation and sheath for electric cables.
			BS 6234: 1969	Polythene insulation and sheath of electric cables.
			BS 6480: 1969	Impregnated paper-insulated cables for electricity supply.
			BS 6207: 1969	Mineral insulated cables.

COMPONENT	ARC	GENERAL SPECIFICATIONS	REGULATIONS	GUIDANCE NOTES
	ECABLE	Abbreviations are used for typical cables:	BS 6231: 1981	Specification for PVC-insulated cables for switch-fear and controlgear wiring.
		PVC - PVC insulated and sheathed		
		VRI - Vulcanised rubber insulated and sheathed	BS 6346: 1969 (1977)	PVC-insulated cables for electricity supply.
		TRS - Vulcanised rubber insulated and Tough Rubber sheathed	BS 6360: 1981	Specification for conductors in insulated cables and cords.
		MIMS - Mineral insulated and metal sheathed		NOTE PVC and plastic insulated and sheathed cables are generally used in private housing. PVC armoured cables are used for all indoor applications and are a serious competitor to the paper insulated cables, which are generally used as underground feeders and distributors, carrying high currents and voltage ratings. Mineral insulated cables are most common especially for fire alarm and emergency lighting circuits.
		MICS - Mineral insulated and copper sheathed		
		MIAS - Mineral insulated and aluminium sheathed		
		PILCSWA- Paper insulated lead covered steel wire armoured		
		PILCSTA- Paper insulated lead covered steel tape armoured		
		PVCSWA - PVC insulated, single wire armoured.		
		Flexible cables may also be used where connections are made to appliances which vibrate, for plugs or lighting.	BS 6500: 1984	Specification for insulated flexible cords and cables.
			BS 6622: 1985	Specification for cables with extended cross-linked polyethylene or ethylene propylene rubber insulation.
		An earthing system is the main means of protection against earth-leakage currents, limiting the effects of electric shock and reducing the hazard of fire and explosion. It ensures that there are no potential differences between the various metal parts in the system and between all metal parts other than live conductors and the earth i.e. metal conduits, trunking, ducts or metal sheath of cables, earth continuity conductors of cables and glexible cords, lighting points and switch positions, metal socket outlet boxes, all non-current metalwork of 4V switchgear, distribution transformers and LV switchgear, the alternator, rising busbars, distribution boards and fused switches.		Mackenzie (1985)
			CP 1013: 1965	Earthing.
			BS 4444: 1969 (1980)	Guide to electrical earth monitoring.
			BS 4533: 1971	Luminaires - Provision for earthing and protection against electric shock.
			BS 4944: 1973	Reactors, arc-suppression coils and earthing transformers for electric power systems.
			BS 5253: 1975	A.C. disconnectors (isolators) and earthing switches of rated voltage above 1 KV.
			BS 951 : 1948 (1962)	Earthing clamps.
			BS 842 : 1965 (1980)	A.C. voltage-operated earth-leakage circuit-breakers.
		Earthing and earth leakage protection can be achieved by various methods:		Needle (1982)
		1. The consumers earthing terminal can be connected to the main LEB earth terminal.		

COMPONENT	ARC	GENERAL SPECIFICATIONS	REGULATIONS	GUIDANCE NOTES
	ECABLE	2. Earth electrode (copper rods or strips, lead or copper-clad steel cored rods) connections. 3. Protective multiple earthing on approval of the Department of Energy and the Post Office. 4. Earthing Conductors (tapes and rods) and circuit protective conductors. 5. Voltage-operated earth-leakage circuit-breakers. 6. Residual current circuit-breakers. 7. Monitored earth circuits. Bonding is a low-resistance connection between earthed metalwork and extraneous metalwork to prevent a difference of potential arising between the points to be bonded. It is, therefore, an effective means of preventing the emergence of earth leakage currents. Gas and water systems are bonded on the point of entry into the building; exposed metal pipes, radiators, sinks, tanks, accessible structural steelwork and lifts are all bonded.		
		The RICS (1985) defined a busbar as 'a solid conductor forming a cable distribution point at which one incoming cable is connected to several outgoing cables with purpose made fittings'. The conductors are either copper of aluminium, round or rectangular rods or bars, fixed to ceramic insulators, supported at intervals on insulating spacing panels and enclosed in trunking, chases, channels or shafts provided. Fire resisting barriers and insulation may be required. Cables are connected to the busbars by clamps or connection units and fuseboards, known as tapping points. Plug-in type fuse boxes contain trapped nuts, earthed springs, retaining rods, contacts, bushings, fuse units, neutral terminal blocks, mounting panels, location dowels, plates and supports. Busbars provide a great flexibility and can have a variety of current ratings 60-1500A with fuses ranging from 15-500A.	 BS 159 : 1957 BS 5486: 1978	Termate (1985) Busbar and busbar connections. Particular requirements for busbar trunking systems (busways).

COMPONENT	ARC	GENERAL SPECIFICATIONS	REGULATIONS	GUIDANCE NOTES
Electrical trunking	ETRUNK	Number of projects: 23		
		Definition:		
		Skirting, underfloor and overhead cable trunking, overhead busbar trunking and conduits including fitments, draw-in boxes, box spouts, supports, shocks and dies, loop-in boxes, washers, unions and cou;lings, rubber gaskets, fire stops and condensation compound, and all associated fittings and fixings. Trunking (RICS, 1985) is an accessible enclosure for distributing and protecting electrical conductors in a building. A conduit is a tube for distributing and protecting electrical conductors in a building, usually allowing rewirability.		Fixings include: rod suspension, battens, clamps, hangers, eye bolts, stirrups, bushed suspension sets; Fittings include: caps, junctions, copper bonding strips, end plates, sleeves, cover plates, conterminous lid or special access traps, gussets.
		Trunking provided from electrical riser cupboards on each floor level, through ceilings, floors, or skirting walls, to switch positions where conduits may be installed from the trunking system to the switches. Skirting trunking, was very popular within the research; a hollow, partitioned trunking segregating extra-low voltage cables (telephone) and low-voltage (13A ring circuit) services.	BS 4678: 1971 (1979)	Cable trunking: steel surface trunking. NOTE A compartment may be reserved for data communication cables. Fire alarms and emergency lighting cables may also require compartments.
		Underfloor trunking or ducting found particular application in the larger offices, allowing for immediate access, re-partitioning of the floor space using simple grid formations and accommodating the expanding use of electric business machines. Conduits may be used to feed the lighting of the floor below. The ducting may extend to the walls so that the wiring may continue along the skirting trunking. Bonding was automatic because the ducting was electrically continuous and the complete earthed enclosure acts as a barrier for the prevention of radio and television interference. Overhead busbar trunking was also included within this component including universal, horizontal and vertical cable units. Overhead trunking, for the distribution of wiring, may support the lights in suspended ceilings.	BS 4678: 1973	Steel underfloor (duct) trunking.
		The size, location and type of trunking used was dependent on the number and size of distribution cables, the amount of protection required, resistance, earth continuity, the amount of flexibility, expected life, available and cost.	Appendix 12: IEE Regs.	Sizing of cables, conduits and trunking systems.

COMPONENT	ARC	GENERAL SPECIFICATIONS	REGULATIONS	GUIDANCE NOTES
	ETRUNK	Trunking was normally of sheet steel, in light or heavy gauge, square or rectangular in section, with detractable covers. In prestige installations, a zinc coated mild sheet steel, non-corrodible trunking was used. Skirting trunking was generally more costly than underfloor, especially where pitch-fibre ducts were placed in the floor. Trunking, however, is simpler to install and cheaper than large sized conduits, and appears to be the better solution to complex cabling installations.	BS 4678: 1982	Specification for cable trunking made of insulating material.
			BS 6053: 1981	Specification for outside diameters of conduits for electrical installations and threads for conduits and fittings.
		Conduits including boxes, trees, elbows, couplers, switch boxes, joints, lugs, terminals, tees, intersections and angles, fittings and fixing brackets, plates, saddles, hooks or crampets and covers, where used, generally, when two or more wires were needed to feed various points from the trunking. Heavy gauge screwed steel conduit to BS 4568: 1970 was mainly specified, with black enamel and bituminous paint. Galvanised, sheradised (zinc impregnated) and PVC coated conduits were also used (specified areas). Aluminium and copper conduits were less common because of their tendancy to corrode and difficulty in maintaining continuity. Plastic conduits: Rigid super high impact PVC, heavy and light gauge (lighting), Flexible PVC, heavy and light gauge and corrugated flexible (vibration points); were not widely accepted but seemed to be gaining in popularity. Plastic conduits require continuity conductors and should be fire resistant.	BS 4607: 1970-1984	Non-metallic conduits and fittings for electrical installations.
			BS 6099: 1981	Conduits for electrical installations.
			BS 4568: 1970	Steel conduit and fittings with metric threads of ISO form for electrical installations.
			BS 31 : 1940 (1979)	Steel conduit and fittings for electrical wiring.
				Table B5 of IEE Regs: sizes of conduits.
			BS 731 : 1952 (1980)	Flexible steel conduit for cable protection and flexible steel tubing to enclose flexible drives.
			BS 1813: 1974 (1984)	Dimensions of conduit dies, diestocks and guides.
			BS 4108: 1973	Pitch-impregnated fibre conduit.
Emergency lighting and power supplies	EMGNCY	Number of projects: 22 Definition: Lighting and electricity provided for use when the main current or lighting installation fails, also providing lighting for one means of escape.	The Fire Protection Act, 1971. Health and Safety at Work Act, 1974. Fire Certificates (Special Premises) Regulations, 1976.	
		Types: 1. A central battery system	ICEL 1003: 1982	Emergency lighting applicatio guide.
		The batteries for 10-20% of luminaires are housed in one location. Battery types: flat plate lead acid, high performance planté lead acid and vented nickel cadmium. The total output depends on the level of essential supplies	ICEL 1001: Certification	Industrial standard for the manufacture of emergency lighting equipment, which is monitored by the BSI.
				The Greater London Council (GLC) Byelaws.

COMPONENT	ARC	GENERAL SPECIFICATIONS	REGULATIONS	GUIDANCE NOTES
	EMGNCY	required in case of supply failure: essential lighting and small power, essential electrical services including the firemans lift and panel, fire alarm panel and telephone exchange, chillers, cooling towers, boilers, cold water and fire service pumps, and essential extract ventilation systems. Standby generation supplies may provide 45% of the total high voltage supply. Separate cabling, trunking and conduit systems should be included in accordance with IEE Regs. 15.	BS 764 : 1954 (1974)	Automatic change-over contactors for emergency lighting systems.
			BS 2560: 1978	Specification for exit signs (internally illuminated).
			BS 4218: 1978	Specification for self-luminous exit signs.
			BS 4533: 1981	Specification for luminaires for emergency lighting.
			BS 5266: 1975	Code of practice for the emergency lighting of premises other than cinemas and certain other specified premises used for entertainment.
		Within the research, the central battery system supplied power for emergency lighting (provided for use when the normal lighting, which is part of the emergency lighting (ensures that the means of escape can be safely and effectively used).	BS 5266: 1981	Specification for small power relays (electromagnetic) for emergency lighting applications up to and including 32A.
		Components include cubicles, chargers, fusegear, controls (ammeters, voltmeters, neon indicators, switches, monitors, alarms, time clocks), input and load circuits, contactors and transformers.	BS 6290: 1983	Lead-acid stationary cells and batteries.
			BS 4999: 1972	General requirements for rotating electrical machines.
			BS 5000: 1974 (1984)	Rotating electrical machines of particular types or for particular applications.
		2. Central diesel alternators Diesel engine driven local generation plant providing standby power supplies for computers, mechanical controls (air conditioning, ventilation and compressors), lighting, small power, cold water booster pumps, hosereel pumps, toilet ventilation, firemans lift and lift motor room ventilation. Full standby supplies such as this were not specified within the research, however the EWIC components may contain allowances for this.		NOTE: Wilson (1981) Diesel driven alternators are more efficient, available in a wide range of sizes and are generally cheaper than gas turbine sets of the same rating, which are lighter, operate with less vibration, are more amenable to operating at low load and require less maintenance, but are not widely available below approximately 650 KVA.
		Microprocessor based control and logging systems may be connected to the standby power supplies to sense phase or voltage failure via relays, operate circuit breakers, switch off non-essential loads, open ventilation louvres and sound alarms, start engines, for synchronisation, control frequency, share loads, monitor exhaust gases, radiators, oil pressures, vibration, fuel, and upon restoration of the main supply, close down the emergency supplies and return to normal operation.		IEETE (1980)
		3. Inverter systems Localised packaged battery and inverter sets providing power supplies to one tube of twin-tube fluorescent lights. Cheaper than the centralised system as cabling not required or kept to a minimum.		NOTE A pre-requisite of standby plant is that it is immediately available on normal supply failure. An automatic starter is built into the control system which allows the plant to be brought on line and taking load within 30 seconds.

COMPONENT	ARC	GENERAL SPECIFICATIONS	REGULATIONS	GUIDANCE NOTES
	EMGNCY	4. Self-contained emergency lighting units Small, single point fittings may be used, with integral battery and control equipment to illuminate escape routes, plant rooms and circulation areas. They normally drive power from the distribution board, standby generator or nearest luminaire and may contain test monitoring facilities.		Automatic voltage regulators and electronic governers control engine speeds and frequency. Automatic parallelling and synchronisation equipment may also be installed for stability. Protection systems may be required for long periods of supply. Uninterruptible power supply (UPS) equipment allows for continuity of output.
Small Power	POWER	Number of projects: 22 Definition:		
		Bathurst (1971) defined a small power point as 'a place at which a piece of energy-consuming apparatus may be connected to a supply of electricity'. Socket outlets (RICS, 1983) are devices, provided with female contacts, which are intended to be installed with the fixing wiring, and intended to receive a plug.	BS 1363: 1984 BS 196 : 1961	Specification for 13A fused plugs and switched and unswitched socket outlets and boxes. Protected-type non-reversible plugs, socket-outlets, cable-couplers and appliance-couplers, with earthing contacts for single phase a.c. circuits up to 250 volts.
		13 amp switch type socket outlets are generally installed in offices for cleaning, maintenance and small equipment. They may be wall mounted, in floor ducting with accessible top covers with floor boxes fitted to suit the building module, or installed at regular intervals around the office periphery, on landings and in lobbies, at skirting level.	BS 546 : 1950 (1979)	Two-pole and earthing-pin plugs, socket outlets and socket-outlet adaptors for circuits up to 250 volts.
		Wiring and conduits, taken from the trunking installation, to the power points should be included within this component including all associated fittings and fixings.		
LIGHTING General		General illumination to main office areas by means of luminaires, as opposed to supplementary 'spot-lighting'. A luminaire (RICS, 1985) is 'equipment which distributes, filters or transforms the light from one or more lamps and which includes any parts necessary for supporting, fixing and protecting the lamps, but not the lamps themselves, and, where necessary circuit auxiliaries together with the means for connecting them to the supply'.	Shops, Offices and Railway Premises Act, 1963. CP 3 : 1965 (1982) BS 1853: 1979 BS 1875: 1952	Burberry (1977) Flameproof electric lighting fittings. Tubular fluorescent lamps for general lighting service. Bi-pin lamp-holders for tubular fluorescent lamps for use in circuits, the declared voltage of which does not exceed 250 volts.
		Normal lighting is permanently installed artificial lighting, operating from the supply, in normal use. In the absence of adequate daylight they are intended for use during the whole time the	BS 2818: 1981	Specification for ballasts for tubular fluorescent lamps.

COMPONENT	ARC	GENERAL SPECIFICATIONS	REGULATIONS	GUIDANCE NOTES
Lighting General		premises (offices) are occupied.	BS 3772: 1981	Specification for starters for fluorescent lamps.
		Types of lamp:	BS 4017: 1979	Specification for capacitors for use in tubular fluorescent high pressure mercury and low pressure sodium vapour discharge lamp circuits.
		1. Tubular fluorescent Fluorescent lamps are available in wattages and colours suitable for most commercial interiors and provide up to five times as much light for the same power consumption as ordinary incandescent lamps. The initial cost of the lamp may be higher than tungsten lamps, but the running costs are lower and life expectancy higher. Hot cathode fluorescent tubes were most popular within the research. High pressure mercury fluorescent lamps and circular fluorescent lamps were not specified.		BRE (1979)
			BS 4533: 1971-1982	Luminaires.
			BS 4533: 1981	Specification for fixed general purpose luminaires.
			BS 4727: 1972	Lighting technology terminology.
			BS 5225: 1975 (1980)	Photometric data for luminaires.
		2. Incandescent lamps Tungsten filament and halogen lamps were not specified for general illumination as they were more suitable for highlighting or spot-lighting. It should be noted that the capital costs of tungsten lamps and fittings are relatively low compared to fluorescent lamps, but in the present energy-efficiency environment, the estimator should not be tempted to specify them for overall lighting.		Manning (1965) Love & Smith (1983)
			BS 5394: 1983	Specification for radio interference limits and measurements for luminaires using tubular fluorescent lamps and fitted with starters.
				See 'spot' component.
			BS 5717: 1984	Specification for transistorized ballasts for tubular fluorescent lamps.
		The type of lamp specified, lumen output required, appearance, colour, wattage, running costs, heat emission, maintenance access, resistance to damage, task to be illuminated, location, type and extent of windows, heating, area, shape of building, physical environment and flexibility requirements determine the luminaire or light fitting specified and position.	BS 6345: 1983	Method for measurement of radio interference terminal voltage of lighting equipment.
			BS 4533: 1981	Specifications for recessed luminaires.
			BS 8206: 1985	Lighting for buildings. Code of practice for artificial lighting.
		Types of light fittings: 1. Direct: Dispensive reflectors Deep bowl reflectors Diffusing reflectors Closed end enamel through reflectors. 2. Semi-direct: Translucent or open top shades Enclosed or boxed louvred reflectors Battery or V-channel fittings. 3. General diffusing: Plastic enclosed diffusers Flashed opal glass. 4. Semi-indirect: Translucent inverted bowls.		

COMPONENT	ARC	GENERAL SPECIFICATIONS	REGULATIONS	GUIDANCE NOTES
Lighting General		5. Indirect: Cornices, coffers and other similar 'architectural' treatments.	BS 4533: 1982	Specification for air-handling luminaires (safety requirements).
		6. Luminous ceilings.		
		7. Air handling fittings.		IEETE (1980)
		Controls (photoelectric cells, switches, contactors, day and night controls, circuit-breaker distribution boards, time based switches, daylight sensors, dimmers, occupancy sensors) and all wiring, conduits, fittings and fixings associated with the light fittings from the main cabled supply should be included within the components.	BS 4533: 1971 BS 5518: 1977	BRE Digest 272: Automatic lighting controls. BRE Digest 256: Design. External and internal wiring of luminaires, terminations, provision for earthing and operating temperatures. Specification for electronic variable control switches (dimmer switches) for tungsten filament lighting.
		The lighting level emitted from light fittings, measured in Lux or lumens per square metre, was the determining factor within the research, since recommended illuninance levels for specific areas within the offices could most readily be estimated.		A lumen is the light flux or flow of light emitted within unit solid angle from a point source of 1 candela.
		MDA recommend: 1. 600 Lux output in main office areas, computer rooms and drawing rooms. 2. 500 Lux output in main lobbies, circulation areas and receptions. 3. 300 Lux output in toilets, basements, storage rooms and vaults. Toilets may use vanity spot-lighting. 4. 500 Lux supplemented with task spot-lighting, may be preferable to an overall 600 Lux general office environment.		CIBSE (1984) Lighting Code: Code for interior lighting. CIE (1978) Calculations for interior lighting - basic method. CIE (1982) Calculation of interior lighting-applied method. IES (1977) Code: Recommendations for good interior lighting.
600 Lux	600 LUX	Number of projects: 11 32% Definition: 600 Lux fluorescent light fittings providing general illumination to specified areas, including drop rods, connector blocks, luminaires, controls, wiring, cabling, conduits, switches, contactors, fittings and fixings from main cable distribution.		See 'lighting general' section.

COMPONENT	ARC	GENERAL SPECIFICATIONS	REGULATIONS	GUIDANCE NOTES
500 Lux light fittings	500LUX	Number of projects: 16 50% Definition: 500 Lux fluorescent light fittings providing general illumination to specified areas, including drop rods, connector blocks, liminaires, controls, wiring, cabling, conduits, switches, contactors, fittings and fixings from main cable distributions.		See 'lighting general' section.
300 Lux light fittings	300LUX	Number of projects: 7 18% Definition: 300 Lux fluorescent light fittings providing general illumination to specified areas, including drop rods, connector blocks, luminaires, controls, wiring, cabling, conduits, switches, contactors, fittings and fixings from main cable distributions.		See 'lighting general' section.
Spot-lighting	SPOT	Number of projects: 6 20% Definition: Luminaires employed for decorative or 'highlighting' purposes, task or 'spot-lighting'. Their usage is dependent on the extent and pattern of distribution of tasks around the interior and the frequency with which these change.		See 'lighting general' section. BRE (1979)
			BS 161 : 1976	Specification for tungsten flament lamps for general service.
		Types of lamp: 1. Incandescent lamps (40 to 100 W ratings) 2. Tungsten Halogen lamps (low voltage types) 3. Miniature fluorescent lamps (4, 6 and 8 W ratings).	BS 1075: 1961 BS 5971: 1980	Studio spotlight lamps. Safety and interchangeability of tungsten filament lamps for domestic and similar general lighting purposes.
		Types of light fittings: 1. Industrial enamel reflectors 2. Opal spheres 3. Translucent inverted bowls 4. Open-top diffusing reflectors 5. Recessed fittings: black hole spotlights.	BS 6179: 1982 BS 1075: 1985	Specification for tungsten filament lamps for general service (with lives of 2000 hours). Specification for tungsten halogen lamps (non-vehicle).
		Component includes controls, wiring, conduits, switches, contactors, fittings and fixings from the main cable distribution points.		
No spot-lighting provided		Number of projects: 24 80% Definition: No provision was made for 'spot' lighting within the estimate.		

COMPONENT	ARC	GENERAL SPECIFICATIONS	REGULATIONS	GUIDANCE NOTES
Telephones	GPO	Number of projects: 18 76%		OFTEL (Office of Telecommunications) Telecommunications Wiring in Business Premises and Homes (1984)
		Definition:		British Telecom
		The provision of vertical risers, cable trays, trunking, draw-wires, conduits and outlet plates for the installation of Post Office telephone cables. The installation of telephone equipment and cabling is normally carried out by the Post Office engineers after completion of the building.	CP 1022: 1973	The selection and accommodation of telephone, telegraph and data communication installations.
			BS 2950: 1958	Cartrdige fuse-links for telecommunication and light electrical apparatus.
		Components:	BS 3573: 1972	Polyethylene-insulated copper-conductor telecommunication distribution cables.
		1. Cable tray provided between the GPO equipment room and the incoming GPO puddle flange.	BS 4727: 1971	General telecommunications and electronics terminology.
		2. A vertical riser fitted with cable trays and adjacent to the central core installed from the equipment room tray.	BS 4808: 1972	L.F. cables and wires with PVC insulation and PVC sheath for telecommunication.
		3. Multi-compartment floor or skirting trunking connects to the vertical riser at each floor level.	BS 6450: 1983	Private branch exchanges for connection to the British Telecommunications public switched telephone network.
		4. Where individual telephones are remote from the trunking system, conduits are installed.	BS 9520: 1983	Specification for electrical connectors of assessed quality for d.c. and low frequency application.
		Including all associated fittings and fixings.	BS 9153: 1982	Rules for the preparation of detail specifications for all-or-nothing relays of assessed quality primarily for telecommunication applications.
			BS 6305: 1982	Specification for general requirements for apparatus for connection to the British Telecommunications Public switched telephone network.
			BS 6320: 1982	Specification for modems for connection to BT public switched telephone network.
			BS 5938: 1980	Coves for inductors and transformers for telecommunications.
			BS 6328: 1983	Apparatus for connection to British Telecommunications private circuits.
No telephones	NGPO	Number of projects: 6 24% Definition: No provision made for the installation of telephones within the estimate.		

ELEMENT 8 ELECTRICAL

COMPONENT	ARC	GENERAL SPECIFICATIONS	REGULATIONS	GUIDANCE NOTES
Lightning Protection	LTNG	Number of projects: 9 43% Definition: The provision of a lightning conductor as a path of low resistance to the lightning current, so that the discharge to earth will occur through the conductor rather than the building. Components: 1. Upper terminal - roof perimeter tape bonding all metal work superstructure on the roof. 2. Copper, aluminium coronial or, galvanised steel earth tapes which run down the building in recesses, walls or in voids. PVC sheathed aluminium cables may be used. Including all associated fittings and fixings. 3. Earth electrodes - metal rods or strips through earth electrode seals in the foundation slab or into the soil, including inspection pits with covers at grounding points.	CP 326 : 1965 BS 2914: 1972 (1979) BS 951 : 1986 BS 6651: 1985	Nerdle (1982) The protection of structures against lightning. Surge diverters for alternating current systems. Specification for clamps for earthing and bonding purposes. Code of practice for the protection of structures against lightning.
No lightning protection	NLTNG	Number of projects: 12 57% Definition: No provision made for lightning protection within the estimate.		

ELEMENT PIPEWORK

COMPONENT	ARC	GENERAL SPECIFICATIONS	REGULATIONS	GUIDANCE NOTES
General	SANPTS CWPTS CHWPTS SHWHT IHWPTS ISHWHT PWKFAN HTSFAN PWKPER HTSPER PWKRAD HTSRAD PWKPAR PWKDFAN HTSDPE PWKAHU HTSAHU PWKVAV HTSVAV PWKVER HTSVER FANCOIL PWKDPER PWKDVAV HTSDVAV PWKDPC PWKDVER HTSDVER HOSERLS SPNKLR DRYRSR	Pipework and joints to be suitable for the relative fluid and system, the associated materials to be compatible and protected from atmospheric corrosion where applicable. The pipework should be complete with all brackets and supports (fixings) necessary to carry the pipe, prevent deflection and allow for free movement. The spacing of the fixings are relative to the type and size of pipe, including rollers, anchors and slide guides as necessary. Spring hangers may be required where pipework is connected to motorised or vibrating plant. Supports include: clips, saddles, pipehooks, holderbats, brackets, hangers, chairs, guides and anchors. The pipework should be complete with all necessary fittings associated with the installation including: Valves - gate, globe (stopcocks), needle, regulating, double regulating, diaphragm, plug, non-return and check valves, drain and emptying cocks, control, diverter, safety, relief, pressure reducing, hydrant, isolating (fullway gate, lubricated plug and side pressure tappings), parallel slide, oblique, mixing, packless gland, radiator, gland cocks, and test cocks. Thermostats, pressure gauges, traps, bosses, bends, couplings, elbows, reducers, caps and linings, tees, tank connections, compression, capillary and manipulative fittings, adaptors, connectors, crosses, expansion units, access fittings, roof (air) terminal fittings, bushes, nipples, thimbles, sockets, collars, ends, shoes, necks, tappings, unions branches, flanges and stainers. Materials: Cast iron Mild, black and galvanised steel Copper Aluminium Stainless steel Plastics: PVC, ABS, polyurathane, polythene, polypropylene Copper alloys: brasses, bronzes, aluminium brasses, cupro-nickels, gunmetals, admiralty brass, copper/nickel, copper/nickel/iron alloys, titanium.		Fletcher & Moore (1979) The Institute of Plumbing Guide (1977) Evans (1980)
			CP 312 : 1973	Plastics pipework (Thermoplastics materials).
			CP 331 : 1974	Installation of pipes and meters for town gas.
			BS 10 : 1962	Flages and bolting for pipes, valves and fittings.
			BS 66 & 99 : 1970 (1983)	Cast copper alloy pipe fittings for use with screwed copper tubes.
			BS 78 : 1965	Cast iron spigot and socket pipes (vertically cast) and spigot and socket fittings.
			BS 143 & 1256 : 1968	Malleable cast iron and cast copper alloy screwed pipe fittings for steam, air, water, gas and oil.
				NOTE Jointing and fitting connections may be made by either flanges, welding, soldering/brazing, spigot and sockets, screwed, compression, capillary or manipulative means.
			BS 416 : 1973	Cast iron spigot and socket soil, waste and ventilating pipes and fittings.
			BS 437 : 1978	Specification for cast iron spigot and socket drain pipes and fittings.
			BS 534 : 1981	Specification for steel pipes and specials for water and sewage.
			BS 864 : 1983	Specification for capillary and compression fittings for copper tubes.
			BS 864 : 1975	Compression fittings for polyethylene pipes.
			BS 1010: 1973	Specification for draw-off taps and stopvalves for water services.
			BS 1211: 1958 (1981)	Centrifugally cast (spun) iron pressure pipes for water, gas and sewage.
			BS 1212: 1953-1979	Specification for float operated valves.
				Excluded: asbestos-cement lead pipes.
			BS 1306: 1975 (1983)	Copper and copper alloy pressure piping systems.

ELEMENT PIPEWORK

COMPONENT	ARC	GENERAL SPECIFICATIONS	REGULATIONS	GUIDANCE NOTES
General		Coatings: Galvanised - used mainly on steel pipes. Painting - bituminous paint Cathodic protection. The material and coating used is dependant on: the maximum pressure required, maximum temperature required, the corrosive properties of the contained fluid, the flow rates and velocity, the vertical or horizontal orientation of the pipe, the nature of the environment, the pipe lengths and space available, and whatever insulation is required. NOTE Pipes and tubes for pressure purposes are listed under the 'pressurisation plant' section.	BS 1387: 1967	Steel tubes and tubulars suitable for screwing to BS 21 pipe threads.
			BS 1415: 1976	Mixing valves.
			BS 1494: 1951	Fixing accessories for building purposes.
			BS 1965: 1963 (1983)	Butt-welding pipe fittings for pressure purposes.
			BS 1972: 1967	Polythene pipe (type 32) for cold water services.
			BS 1973: 1975 (1983)	Polythene pipe (type 32) for general purposes including chemical and food industry uses.
			BS 2035: 1966 (1981)	Cast iron flanged pipes and flanged fittings.
			BS 2051: 1984	Specification for olive type copper alloy compression tube fittings.
			BS 2640: 1982	Specification for class 11 oxy-acetylene welding of carbon steel pipework for carrying fluids.
			BS 2760: 1973	Pitch-impregnated fibre pipes and fittings for below and above ground drainage.
			BS 2767: 1972	Valves and unions for hot water radiators.
			BS 2871: 1971-1972	Copper and copper alloys. Tubes.
			BS 2971: 1977 (1982)	Specification for class 11 arc welding of carbon steel pipework for carrying fluids.
			BS 3059: 1978	Specification for steel boiler and superheater tubes.
			BS 3284: 1967	Polythene pipe (type 50) for cold water services.
			BS 3505: 1968 (1982)	Unplasticized PVC pipe for cold water services.
			BS 3601: 1974	Steel pipes and tubes for pressure purposes: carbon steel with specified room temperature properties.
			BS 3602: 1978	Specification for steel pipes and tubes for pressure purposes: carbon and carbon manganese steel with specified elevated temperature properties.
			BS 3603: 1977	Specification for steel pipes and tubes for pressure purposes: carbon and alloy steel with specified low temperature properties.

ELEMENT PIPEWORK

COMPONENT	ARC	GENERAL SPECIFICATIONS	REGULATIONS	GUIDANCE NOTES
General			BS 3604: 1978	Specification for steel pipes and tubes for pressure purposes: ferric alloy steel with specified elevated temperature properties.
			BS 3605: 1973	Seamless and welded austenitic stainless steel pipes and tubes for pressure purposes.
			BS 3974: 1974	Pipe hangers, slider and roller type supports.
			BS 3974: 1978	Pipe clamps, cages, cantilerers and attachments to beams.
			BS 4127: 1972 (1981)	Light gauge stainless steel tubes.
			BS 4346: 1969-1982	Joints and fittings for use with unplasticized PVC pressure pipes.
			BS 4368: 1972-1984	Carbon and stainless steel compression couplings for tubes.
			BS 4504: 1969-1974	Flanges and bolting for pipes, valves and fittings.
			BS 4514: 1983	Specification for unplasticized PVC soil and ventilating pipes, fittings and accessories.
			BS 4515: 1984	Specification for process of welding of steel pipelines on land and offshore.
			BS 4622: 1970 (1983)	Grey iron pipes and fittings.
			BS 4772: 1980	Specification for ductile iron pipes and fittings.
			BS 5114: 1975 (1981)	Performance requirements for joints and compression fittings for use with polyethylene pipes.
			BS 5150: 1974	Cast iron wedge and double disk gate valves.
			BS 5151: 1974 (1983)	Cast iron gate (parallel slide) valves.
			BS 5152: 1974 (1983)	Cast iron globe and globe stop and check valves.
			BS 5153: 1974 (1983)	Cast iron check valves.
			BS 5154: 1983	Copper alloy globe, globe stop and check, check and gate valves for general purposes.
			BS 5155: 1984	Specification for butterfly valves.
			BS 5156: 1974	Screwdown diaphragm valves.

ELEMENT PIPEWORK

COMPONENT	ARC	GENERAL SPECIFICATIONS	REGULATIONS	GUIDANCE NOTES
			BS 5157: 1976	Steel gate (parallel slide) valves.
			BS 5158: 1974	Cast iron and carbon steel plug valves for general purposes.
			BS 5159: 1974	Cast iron and carbon steel ball valves.
			BS 5160: 1977	Specification for flanged steel globe valves, globe stop and check valves.
			BS 5222: 1976	Aluminium piping systems.
			BS 5353: 1980	Specification for plug valves.
			BS 5254: 1976	Polypropylene waste pipe and fittings.
			BS 5255: 1976	Plastics waste pipe and fittings.
			BS 5292: 1980	Specification for jointing materials and compounds for installations using water, low pressure steam or gases.
			BS 5480: 1982	Specification for glass reinforced plastics (GRP) pipes and fittings for use with water supply or sewerage
			BS 5572: 1978	Code of practice for sanitary pipework.
			BS 5955: 1983	Code of practice for plastics pipework (thermoplastics materials).
			BS 6087: 1981	Specification for flexible joints for cast iron drain-pipes and fittings and for cast iron soil, waste and ventilating pipes and fittings.
			BS 6283: 1982	Safety devices for use in hot water systems.
			BS 6437: 1984	Specification for polyethylene pipes (type 50) in metric diameters for general purposes.
			BS 6759: 1984	Safety valves.

ELEMENT INSULATION

COMPONENT	ARC	GENERAL SPECIFICATIONS	REGULATIONS	GUIDANCE NOTES
General	INSULTN HINSULTN IHWPTS PWKFAN HTSFAN PWKPER HTSPER PWKRAD HTSRAD PWKPAR PWKDFAN HTSDPF PWKAHU HTSAHU PWKHAV HTSVAV PWKVER HTSVER PWKDPER PWKDVAV HTSDVAV PWKDPC PWKDVER HTSDVER HWSTORAG ISTORAG DWKAHU DWKVAV DWKVER DWKDVAV DWKDVER EXDWK SADWK SUPDWK SPNKLR FANCOIL TERAHU TERVAV TERVER TERDVAV TERDVER EXTER SXTER SUPTER	Thermal, vibration and sound insulation using odourless, vermin proof, rot proof, immune to organic deterioration, non-hygroscopic materials which comply with the local fire authority regulations. Applied, where necessary, to pipework, flues, plant bases, pumps, boilers, cylinders, cisterns, calorifiers, radient panels, skirting heaters, tanks, ducts, fans and ductwork terminals, grilles and diffusers.	Asbestos Regulations, 1969	The Institute of Plumbing Guide (1977)
				CIBSE Guide Volume B (1972) Section B.12
			CP 99 : 1972	Frost precautions for water services.
			DD 71 : 1981	Guide to sprayed mineral insulation.
		Including all necessary fixings and fittings: tie-wires, staples, bands of non-ferrons metal, plastic fibre or adhesive sheet, cement and gypsum plasters, wire reinforcement, painting, rivets and vapour seals.	BS 5970: 1981	Code of practice for thermal insulation of pipework and equipment (in the temperature range of -100°C to +870°C).
			BS 5422: 1977	Specification for the use of thermal insulating materials.
			BS 5608: 1978	Specification for performed rigid urethane and isocyanurate foam for thermal insulation of pipework and equipment.
		Types:		
		Some types of insulation can be slipped over the pipe and pushed on, others, the majority, are split down the longitudinal centre line either in two halves or hinged and jointed with either adhesive or metal bands. The other sections can be left as bought, vapour sealed, covered with a hard protective coating (cement, sheet steel, aluminium or plastic) or weather proofed (vapour sealed).	BS 3533: 1981	Glossary of thermal insulation terms.
			BS 874 : 1973 (1980)	Methods of determining thermal insulating properties, with definitions of thermal insulating terms.
			BS 3958: 1967-1985	Thermal insulating materials; magnesia, calcium silicate, metal mesh faced mineral wool mats and mattresses, bonded preformed man-made mineral fibre pipe sections, bonded mineral wool slabs and finishing materials.
		1. Foam insulants: polyurethane, polyisocyanates, polystyrene, foamflex and phenolics. These are used mainly for cold and hot water services (50-130°C).	BS 5241: 1975	Rigid urethane foam when dispensed or sprayed on a construction site.
		2. Rigid glass silk used for hot and cold water services not below refrigeration point (2-510°C).	BS 5422: 1977	Specification for the use of thermal insulating materials.
		3. Cork sections used for cold water and refrigerant systems, requiring a cement or metal casing (-50°C-88°C).	BS 5821: 1980	Method for rating sound insulation in buildings and of building elements.
			BS 6045: 1981	Ceramic and glass insulating materials.
		4. Polystyrene sections - similar to cork sections (-50°C-77°C).		
			BS 4841: 1975	Rigid urethane foam for building purposes.
		5. Cellular glass used for low temperature applications, but expensive and unpleasant to handle (-196°C-540°C).		Reference: Diamant (1965)
		6. 'Armaflex' used for cold water and some hot water services (sub-zero - 103°C).		
		7. Calcium silicate used on high pressure hot water systems. It is expensive and requires a finishing material. Sometimes combined with a sleeve of		

COMPONENT	ARC	GENERAL SPECIFICATIONS	REGULATIONS	GUIDANCE NOTES
General		ceramic fibre for high insulation (50-650°C). 8. Magnesia sections are used mainly in plant rooms, on all services, usually with a protective finish (50-315°C). 9. Rigid glass silk with aluminium foil finish, used mainly on chilled and condensed water services, where a vapour seal is required (2-510°C). 10. Vermiculite. 11. Kapok insulating quilt. 12. Expanded ebonite. 13. Wood wool slabs. 14. Glass fibre mattresses or preformed sections. 15. Dense PVC mattress. 16. Metal mesh faced mineral wool mats and mattresses. 17. Bonded preformed mineral wool sections and slabs. Valves or flanges may be wrapped in loose insulation, muff boxes, plastic magnesia or covered with a loose mattress and enclosed in a metal or plastic box. Supports may also require insulation. Finishes: Cement and gypsum plaster Scrim cloth (integral) Cotton canvas (integral) Hard setting compounds Galvanised sheet steel Aluminium foil (integral) Plastic (polyisobutylene and PVC). Reinforcement: Galvanised: wire netting, wire spirally wound or wire single strand. Aluminium bands.		85% magnesia and mineral wool.

ELEMENT DUCTWORK

COMPONENT	ARC	GENERAL SPECIFICATIONS	REGULATIONS	GUIDANCE NOTES
General	DWKAHU DWKVAV DWKVER DWKDVAV DWKDVER EXDWK SXDWK SUPDWK	Distributing ductwork including fittings: branches, risers, ends, bends, offsets, pieces, teas, turning valves, splitters, control dampers, access doors, nozzle outlets, connections, cowls, couplings, cones and crosses. Fixings: saddles, unistruts, angles, channels, redheads, rings, rawlbolts, droprods, brackets, bands, bearears, structural steelwork supports for plant and equipment, and specials for example inertia bases for fans, clamps and rollers. Sound attenuation: (ductwork may be lined with absorption materials) fibreglass resin bonded mattress, stillite slabs, expanded polyurethane, fibreboard perforated tiles and Burgess tiles backed with fibreglass. The ductwork usually consists of jointed galvanised mild steel sheets, but glass fibre resin bonded slabs, PVC, aluminium, copper and stainless steel may be used. It is in essence custom built and fabricated from sheet metal. Types: High (over 500 Pa) and low pressure (-500 to 500 Pa) systems. 1. Circular (spiral wound) 2. Flat oval 3. Rectangular or square 4. Double-skinned circular.		Hall (1984) HVCA Specification for sheet metal ductwork DW/142: 1982. The Institute of Plumbing Guide (1977). Standard Method of Measurement (SMM) Section R17-19. Faber & Kell (1979).
			CP 413 : 1973	Ducts for building services.
			BS 1470: 1972	Wrought aluminium and aluminium alloys for general purpose engineering purposes NOTE Jeffries (1982) stated that "it is not unusual for ducting brackets and supports to comprise 10% of the total ductwork value".
			BS 4718: 1971	Methods of test for silencers for air distribution systems.

ELEMENT TERMINALS

COMPONENT	ARC	GENERAL SPECIFICATIONS	REGULATIONS	GUIDANCE NOTES
General	TERAHU TERVAV TERVER TERDVAV TERDVER EXTER SXTER SUPTER	Terminals for ductwork fitted to the air conditioning system often have particular characteristics which give the system its name eg. constant volume boxes, variable air volume (VAV) boxes and fancoil units. They are positioned at terminal air supply, extract and transfer points; and are generally made of sheet metal or extended aluminium. Types: 1. Shutters. 2. Grilles: perforated or stamped lattice, aerofoil vaned with one row of adjustable louvres or two rows of directional louvres, fixed bar and registers (frille and filter). 3. Diffusers: linear (fixed or hinged), fixed or adjustable cones, supply and extract, perforated-face or multi-directional ceiling diffusers (mushrooms), and air handling luminaires (diffuser and light fitting combined). 4. Equalisers. 5. High velocity silencing or attenuating boxes. 6. Plenum boxes. 7. Mechanical volume controllers: variable air volume and variable volume reheat units. Including controls and all associated fittings and fixings.	BS 4857: 1972 (1983)	CIBSE Guide Book B (1972) Section B3. Technical Memoranda CIBSE (1983) Design notes for ductwork. Methods for testing and rating terminal reheat units for air distribution systems.

ELEMENT FANS

COMPONENT	ARC	GENERAL SPECIFICATIONS	REGULATIONS	GUIDANCE NOTES
General	CAHU VAV VERSA FANCOIL DVAVPER DVERSPER EXTRACT SUPEXT SUPPLY FANCONV	Fans are essential to any mechanical ventilation or air conditioning system. Types: Axial flow (with or without guide vanes) Centrifugal or radial flow (forward curved, multivane, straight, paddle-bladed, curved or backwards inclined bladed and aerofoil-bladed) Cross-flow or tangential Mixed flow Propellor.		Faber & Kell (1979) CIBSE Guide Volume B (1972) Section B3.16. Summary of fan types: advantages, disadvantages and applications. RICS (1985)
			BS 848 : 1980	Fans for general purposes.
			BS 5060: 1974 (1984)	Performance of circulating fans and their regulators.
			BS 6583: 1985	Methods for volumetric testing for rating of fan sections in central station air handling units (including guidance on rating).
		The type used in packaged air-handling equipment is almost always of the double-inlet, double width centrifugal type, although high performance axial-type fans may be used in certain installations.	BS 6339: 1983	Specification for dimensions of circular flanges for general purpose industrial fans.
		Small fans using less than 1.1KW motor power require single phase direct drive motors with electric speed regulators. Larger fans require three-phase motors which are vee-belt driven.		See 'motors general' section. See 'EWIC general' section.
			BS 4939: 1973	Safety requirements for electric fans and regulators.
			BS 5285: 1975	Performance of a.c. electric ventilating fans and regulators for non-industrial use.
				Winchester (1985).

ELEMENT HUMIDIFICATION

COMPONENT	ARC	GENERAL SPECIFICATIONS	REGULATIONS	GUIDANCE NOTES
General	CAHU VAV VERSA FANCOIL DVAVPER DVERSPER EXTRACT SUPEXT SUPPLY	Humidifiers are an essential part of mechanical ventilation and air conditioning units. Types: Storage humidifiers: 1. Spray washers including sprays, trays, optional water treatment, bleed and recirculating pumps. 2. Capillary washers are smaller than spray washers but may require a cooling coil. 3. Sprayed cooling coils. 4. Pan humidifiers. 5. Mechanical separators. 6. Steam humidifiers including electrical self-contained heating unit and water treatment plant. Non-storage humidifiers: 1. Mechanical disc. 2. Mechanical pressure. 3. Vapour injection. Absorption humidifiers reduce the humidity by the absorption of moisture by an absorbent material, usually silica gel or activated alumina. Humidification generally requires pumps, eliminators and water treatment.		CIBSE Guide Volume B (1972) Section B3. Eaton-Williams & Fearne (1981) examined the types of systems and commented on their advantages and disadvantages.

ELEMENT HEAT SOURCE

COMPONENT	ARC	GENERAL SPECIFICATIONS	REGULATIONS	GUIDANCE NOTES
General	SHWHT ISHWHT HTSFAN HTSPER HTSRAD HTSDPF HTSAHU HTSVAV HTSVER HTSDVAV FANCOIL HTSDVER	A proportion, related to area served, of the central plant associated with each installation consisting of some or all of the following:		Standard Specification (M&E) No 3. NOTE The location of the plant room affects the costs, Hoyle (1984). Eg. roof top boiler plant - cheaper chimneys/flues and ventilation, more expensive pumping, support, anti-vibration mountings, fire protection etc.
		1. Fuel connection charges and fuel storage.		
		2. Pipework and all associated fittings and fixings.		See 'pipework general' section.
		3. Boilers.		NOTE The amounts of maximum probable heating and cooling load demands are the basis for the selection of plant components i.e. 'heat source' component.
		4. Flues.		
		5. Pumps and motors.		
		6. Pressurisation plant.		
		7. Water treatment plant.		
		8. Cooling plant, condensers, chillers, cooling towers and refrigeration plant.		
		9. Insulation.		See 'insulation general' section.
		10. Controls.		See 'EWIC' section.
		11. Piped heating hot water primaries, feed and expansion tanks, storage and non-storage calorifiers.		See 'heating general' section.
		Fuel Installation.		NIFES (1985)
		Types: Coal Gas (special tariff) Gas (standard tariff) Coke Fuel Oil Electricity (off-peak) Electricity (normal)	Gas Safety (Installation and Use) Regulations, 1984. Building Regulations	Part L and M. Flue requirements.
		The choice of fuel selected for a project will depend on the constraints of capital, running costs, availability and supply. It may affect the choice of plant provided, however, boiler plant may be capable of utilising more than one fuel.	London Building Constriction By-Laws, Part 12. CP 331 : 1974 CP 335 : 1973	Porges (1982) Installation of pipes and meters for town gas. Selection and installation of miscellaneous town gas appliances.
		Coal is the cheapest, and has low running costs, but is inconvenient to use or handle and may incur expensive capital costs.	BS 779 : 1972-1981	Oil burning equipment; burners, storage tanks and safety controls.
		Gas has low capital and running costs, is fairly easy to install but may not be available. Light oil provides an alternative to gas, is competitively priced but has higher capital costs. Electricity is the most expensive in terms of running costs (four times that of	BS 6380: 1983 BS 6380: 1983	Code of practice for oil firing. Guide to low temperature properties and cold weather use of diesel fuels and gas oils.

ELEMENT HEAT SOURCE

COMPONENT	ARC	GENERAL SPECIFICATIONS	REGULATIONS	GUIDANCE NOTES
General		other fuels, Morgan 1985 , unless low cost tariffs are used) but incurs low capital costs. Gas installations appeared to be the most popular within the research. The installations included a gas main, meter, isolation valve or cock, pipework, sleeves, valves to applicances, emergency control valves, fittings and fixings. Gas appliances also require flues, baffles and terminals. Oil fuelled plant requires an oil storage tank, oil feed connection, drain connection, full point cabinet, alarm, vent pipe, filter, pipework, valves, fittings and fixings. Solid fuel and oil fired boilers require cast iron or mild steel flue pipe connections. When considering which fuel installation to use, always consider costs-in-use, future trends, energy conservation and fuel efficiency.		See 'Electrical' section.
			BS 2869: 1983	Specification for fuel oils for oil engines and burners for non-marine use.
			BS 526 : 1961	Definitions of the calorific value of fuels.
			BS 1179: 1980	Glossary of terms used in the gas industry.
			BS 3323: 1978	Glossary of coal terms.
			BS 1016: 1970-1981	Methods for the analysis and testing of coal and coke.
			BS 5440: 1978	Code of practice for flues and air supply for gas appliances of rated input not exceeding 60 KW.
			BS 5376: 1976	Code of practice for selection and installation of gas space heating.
			BS 5871: 1980 (1983)	Code of practice for the installation of gas fires, convectors and fire/back boilers.
			BS 5386: 1976	Specification for gas burning appliances.
			BS 5546: 1979	Code of practice for installation of gas hot water supplies for domestic purposes.
			BS 6332: 1983	Thermal performance of domestic gas appliances.
			BS 4201: 1979 (1984)	Specification for thermostats for gas-burning appliances.
			BS 4161: 1967-1983	Gas meters.
			BS 3636: 1963	Methods for proving the gas tightness of vacuum or pressure plant.
			BS 5963: 1981	Specification for electrically operated automatic gas shut-off valves.
		BOILERS: A boiler is a combustion chamber or heat exchanger in which heat is added to water or a transmission medium, for use within space heating systems or hot water appliances. The size and number of boilers required depends on a proper evaluation of the energy needs for the development, establishing the character of all thermal load sources, the resultant magnitude of each of these specific heat release mechanisms and their effective method of load removal.		Faber & Kell (1979) The Institute of Plumbing Guide (1977) Jaros (1961) Owens (1980) Robertson et al (1969) Day (1976) Garrett (1975, 1981) See 'energy management considerations' chapter. CIBSE Guide Volumes: A Section A9 (1979) B Section B1 (1972) Section B13 (1972)

ELEMENT HEAT SOURCE

COMPONENT	ARC	GENERAL SPECIFICATIONS	REGULATIONS	GUIDANCE NOTES
General		'A thorough analysis of both the total energy balance and the character of the system operating cycle must be made in order to accurately establish the energy requirements for each specific building'. ASHRAE Guide and data book. Highly complicated calculations can be undertaken using degree-day methods, U-Valves, air changes, heat losses, heat loads, lighting loads, occupant loads and building dimensions (area, height, volume etc.). But for estimating purposes, boilers are commonly sized using building volume/boiler power ratios with generous margins concerning standby generation, mains losses and empirical safety percentages.		C Section C5 (1976) CIBSE Practive Notes 1 (1973) and 2 (1975).
			BS 759 : 1984	Specification for valves, gauges, and other safety fittings for application to boilers and to piping installations for and in connection with boilers.
			BS 779 : 1976	Cast iron boilers for central heating and indirect hot water supply.
			BS 855 : 1976	Specification for welded steel boilers for central heating and indirect hot water supply.
		Types:	BS 1894: 1952	Electrode boilers of riveted, seamless, welded and cast iron construction for water heating and steam generating.
		Sectional Pressed steel welded	BS 41 : 1973 (1981)	Cast iron spigot and socket flue or smoke pipes and fittings.
		Vertical multi-tube Shell	BS 715 : 1970	Sheet metal flue pipes and accessories for gas fired appliances.
		Packaged units.	BS 4543: 1976	Factory-trade insulated chimneys.
		Boilers are generally cast iron or steel, and can be fired by:	BS 5854: 1980	Code of practice for flues and flue structures in buildings.
		1. Oil fuel with automatic burners.	BS 5963: 1981	Specification for electrically operated automatic gas shut-off valves.
		2. Solid fuel with mechanical stoker or magazine.	BS 2790: 1982	Specification for shell boilers of welded construction.
		3. Gas with automatic burner, either forced air or atmospheric.	BS 5440: 1978	Flues.
		4. Dual fuel firing.	BS 5978: 1983	Safety and performance of gas-fired hot water boilers.
			BS 6759: 1984	Safety-valves.
		Components: Boilers Fuel burner(s)	BS 3059: 1978	Specification for steel boiler and superheater tubes.
		Safety valve(s)	BS 5410: 1977-1978	Code of practice for oil firing.
		Mains, pilot gas, ignition and shut-down controls Safety, failsafe and limit controls	BS 4433: 1969-	Solid smokeless fuel boilers with rated outputs up to 45KW.
		Vent pipe(s) Pressure gauge(s)	BS 1113: 1969	Water-tube steam generating plant (including superheaters, reheaters and steel tube economizers.
		Thermometer(s), thermostat(s) and terminal boxes	CP 332 : 1970	Boilers of more than 15000 Btu/h (44KW) and up to 2000000 Btu/h (586KW) output.
		Erupting cock(s) or drain valve(s)		

ELEMENT HEAT SOURCE

COMPONENT	ARC	GENERAL SPECIFICATIONS	REGULATIONS	GUIDANCE NOTES
General		[Packaged boiler units come complete with control gears, safety controls, pumps, fans, burners etc.]		
		Flow and return connections		
		Flues, insulation, cleaning doors, drain connections and plug tappings		
		Immersion sensors (where sequence controlled boiler operation used)		
		Energy management controls.		See 'EWIC general' section.
		Including all associated fittings and fixings.		
		PUMPS AND MOTORS		CIBSE Guide Volume B (1976) Section B10: Electrical Power.
		Pumped circulation has the following advantages over natural or gravity circulation:		Nerdle (1982)
		1. Quicker response to heating, cooling or water requirements.	The Electricity (Factory Act) Special Regulations 1908 and 1944.	
		2. Circulation is independent of the temperature difference between the flow and return water.	BS 5316: 1976	Acceptance tests for centrifugal, mixed flow and axial pumps.
		3. Smaller pipes may be used, saving capital and space costs.	CP 310 : 1965	Water supply.
		4. The boiler plant may be sited on the roof.	BS 5257: 1975	Horizontal end-suction centrifugal pumps.
		5. Any type of heat emitter may be used.	BS 4082: 1969	External dimensions for vertical in-line centrifugal pumps.
		Pumps are used for primary and secondary chilled water, primary hot water through boilers, secondary hot water for heating, condenser water, cold and hot water, and fuel oil installations. Standby pump sets may also be required.	BS 1394: 1971	Power driven circulators; gland and glandless pumps.
			BS 4617: 1983	Methods for determining the performance of pumps and motors for hydraulic fluid power transmission.
			BS 3456: 1975	Electrical pumps.
		Types of pump:		BPMA (1986)
		Single stage centrifugal Multi-stage centrifugal In-line, floor or pipeline mounted Coupled: close or direct Glandless Belt-drive Wet rotor Sump		
		Pumps used in air conditioning systems are generally single inlet centrifugal types. Pumps are driven by motors.		

ELEMENT HEAT SOURCE

COMPONENT	ARC	GENERAL SPECIFICATIONS	REGULATIONS	GUIDANCE NOTES
General		Types of motor: 1. Screen protected 2. Drip proof 3. Pipe-ventilated or duct ventilated 4. Totally enclosed 5. Totally enclosed fan cooled 6. Totally enclosed, separately air cooled 7. Flameproof 8. Water proof. Direct currnet (DC) motor, shunt wound, is suitable for pump drives. Polyphase motors (squirrel cage induction (single winding) auto transformer) are suitable for refrigeration compressors. Less than 0.75KW, single phase, totally enclosed frame cooled or fan cooled motors are used. Greater than 0.75KW less than 4KW, three phase, squirrel cage induction type, totally enclosed, frame cooled or fan cooled motors are used. Greater than 4KW, drip-proog enclosures up to and including 55KW, three phase squirrel cage induction types. Above 55KW, three phase, wound motor, slip ring type, totally enclosed and fan cooled. All motors are subject to star-delta starting. For motors less than 30KW, positive temperature coefficient thermistors are required. Above 4KW, surge suppressors are used. For motors less than 75KW a starter with manual reset and adjustable, inverse time delay, ambient temperature compensated thermal overcurrent releases are required. Over 75KW, starters are provided with sensitive discriminating thermal magnetic overcurrent relays having precise time/current characteristics and protection. Components: Pump set(s) Pipe connections (flexible) Strainers Foot valves Discharge non-return valves Relief, check and isolating valves Switchgear Seals Mountings Electric motor(s) and starters (plus indicator lights) Spillage tank Supporting rails, brackets, bolts and associated fixings Thermistors or surge suppressors.	CP 1011: 1961 BS 2757: 1956 (1984) BS 2048: 1961 (1984) BS 587 : 1957 (1984) BS 4941: 1977-1979 BS 5000: 1978 (1984) BS 5000: 1974 (1984) BS 5000: 1981 BS 5856: 1980 BS 5907: 1980	See 'EWIC general' section. Maintenance of electric motor control gear. Classification of insulating materials for electrical machinery and apparatus on the basis of thermal stability in service. Dimensions of fractional horse-power motors. Motor starters and controllers. Specification for motor starters for voltages up to and including 1000 V a.c. and 1200 V d.c. General purpose induction motors. Small-power electric motors and generators. Motors with type of protection 'N'. Direct on-line (full voltage) a.c. starters. Specification for high voltage fuse links for motor circuit applications.

ELEMENT HEAT SOURCE

COMPONENT	ARC	GENERAL SPECIFICATIONS	REGULATIONS	GUIDANCE NOTES
General		PRESSURISATION PLANT:		McLaughlin et al (1981)
		Packaged pressurisation units for heating and chilled water circuits.		See 'pipework general' section.
		Types:	BS 5276: 1977-1984	Specification for pressure vessel details.
		1. A head tank or feed and expansion tank, used to pressurise the system by means of an imposed head of water.	BS 6129: 1981	Code of practice for the selection and application of bellows expansion joints for use in pressure systems.
		2. Vapour pressurisation. A steam boiler is used to place water in a drum under pressure.		See 'heating general' section.
			BS 3600: 1976	Specification for dimensions and masses per unit length of welded and seamless steel pipes and tubes for pressure purposes.
		3. Pressurisation by the expansion vessel uses air above the water as a compressing agent, as the water is warmed from the boiler.	BS 3601: 1974 BS 3602: 1978 BS 3603: 1977 BS 3604: 1978 BS 3605: 1973	Steel pipes and tubes for pressure purposes.
		4. Diaphragm expansion tanks. The separation of air or nitrogen from the water supply by a rubber or rubber composition diaphragm acts as a compression agent as the water is heated and expands.	BS 1501: 1980	Steels for fired and unfired pressure vessels. Plates.
			BS 1502: 1982	Specification for steels for fired and unfired pressure vessels: sections and bars.
		5. Gas pressurisation (normally nitrogen). As the system heats up the gas pressure in the expansion vessel increases. Pressure relief valves adjust the pressure, a compressor, high and low pressure receivers, pressure bottles or spill tanks, pumps, pressure controllers and spill valves may be required.	BS 1504: 1976 (1984)	Specification for steel castings for pressure purposes.
			BS 3463: 1975	Observation and gauge glasses for pressure vessels.
			BS 5500: 1977-1984	Enquiry cases.
		Components:	BS 6144: 1981	Specification for expansion vessels using an internal diaphragm for unvented hot water supply systems.
		Suction tanks, direct coupled centrifugal pumps, sealed pressure vessel(s), pressure switches, gauges and valves, expansion vessel(s), integral controls and the main panel hand/off/auto switches. Pipework connections, all associated fittings and fixings.	BS 1780: 1960	Specification for Bourdon tube pressure and vacuum gauges.
			BS 470 : 1984	Specification for inspection, access and entry openings for pressure vessels.
			BS 4994: 1973	Vessels and tanks in reinforced plastics.
			BS 4814: 1976	Specification for expansion vessels using an internal diaphragm, for sealed hot water heating systems.
			BS 6437: 1969	A review of design methods given in present standards and codes and design proposals for nozzles and openings in pressure vessels.
			PD 6438: 1969	A review of present methods for design of bolted flanges for pressure vessels.
			PD 6480: 1977	Explanatory supplement to BS 4994 'Specification for vessels and tanks in reinforced plastics'.

ELEMENT HEAT SOURCE

COMPONENT	ARC	GENERAL SPECIFICATIONS	REGULATIONS	GUIDANCE NOTES
General		WATER TREATMENT PLANT		Faber & Kell (1979) Burberry (1977)
		Plant for chemically dosing or filtering raw water to reduce hardness by the removal of calcium, magnesium and sodium salts, to reduce the action of corrosive scale in heating and cooling systems, specialised demineralisation and sterilization, and to prevent bacterial and algal growth.	BS 1328: 1969 BS 6068: 1982 BS 2486: 1978	Methods of sampling water used in industry. Water quality. Recommendations for treatment of water for land boilers.
		Demineralisation, deionisation or base exchange techniques percolate the water supply through ion exchange synthetic resins to soften the water. Calcium, magnesium and sodium salts are converted into acids, which are then neutralised by an onion exchange or the addition of an alkaline solution.		
		Chemical additives (lime soda) may be introduced into tanks or through dosing pots, to reduce scale formation, periodically or continuously by specialised treatment plant. Impurity collectors, settling or sludge tanks may be used to remove effluents in large systems.		
		REFRIGERATION PLANT		Barnes (1973) Quick (1985) Smith & Julian (1976) Garrett (1975) Luff (1970) CIBSE Guide (1972) Volume B Sections B2, B3 and B14. Smith (1982) Faber & Kell (1979) Kimura (1977) Strong (1985) HVAC (1984) RUACG (1985) Wilkinson (1984)
		A refrigeration or cooling plant is used to cool water or air for air conditioning systems. Garrett (1975) stated that the degree of accuracy of answers for air conditioning cost and space requirements depends upon the accuracy of the cooling load estimate. The cooling load (Kimura, 1977) is the rate of flow of heat to be extracted from a space in order to maintain the room temperature at the required level. It is dependent on the heat conduction, convection and absorption of solar radiation by the building fabric, the heat emission from occupants, lights and other electrical and mechanical appliances, and the infiltration of warm outdoor air into the building.	BS 1608: 1966 BS 1586: 1982	Electrically-driven refrigerant condensing units. Methods for performance testing and presentation of performance data for refrigerant condensing units.
		Types of refrigeration plant: 1. Compression systems a. Reciprocating or piston direct expansion chillers.		NOTE Direct surface type coolers use a method of heat exchange in an evaporator of a refrigeration system. Indirect coolers chill air by the heat exchange with water which has been cooled by a refrigerant.

ELEMENT HEAT SOURCE

COMPONENT	ARC	GENERAL SPECIFICATIONS	REGULATIONS	GUIDANCE NOTES
General		b. Centrifugal or flooded indirect chillers (most popular).	BS 3122: 1977-1979	Refrigerant compressors.
		c. Hermetic Centrifugal machines which are refrigerant cooled.	BS 4434: 1980	Requirement for refrigeration safety.
		d. Helical screw.	BS 4485: 1969-1977	Water cooling towers.
		2. Absorption Systems.	BS 4788: 1972	Rating and testing of refrigerated dehumidifiers.
		3. Steam-jet, sprayed cooling coils and air spray washers.	BS 5643: 1984	Glossary of refrigeration, heating, ventilating and air conditioning terms.
		4. Reverse heat-pumps. 5. Thermoelectric systems.	BS 4856: 1975 (1983)	Thermal and volumetric performance for cooling duties without additional ducting.
		Refrigeration applications up to 300KW (100 TR) generally utilise reciprocating water chilling sets, from 300-900KW (300 TR) either reciprocating, centrifugal or absorption machinery and above 900KW centrifugal or absorption units.	BS 5141: 1975 (1983) BS 1571: 1975	Method of testing for rating of cooling coils. Testing of positive displacement compressors and exhausters.
		Strong (1985) advised that the absorption systems were significantly more expensive to operate than a well-designed vapour compression systems, but were lower in maintenance costs and more silent in operation.	BS 5791: 1979 BS 6244: 1982 BS 3606: 1978	Compressors (glossary of terms). Code of practice for stationary air compressors. Specification for steel tubes for heat exchangers.
		Typical cooling systems: 1. Direct expansion packaged units with air-cooled condensers.	BS 3274: 1960:	Tubular heat exchangers for general purposes. Capazio & Briganti (1986) Bristowe (1985)
		2. Roof mounted packaged chillers with chilled water units. 3. Condenserless chillers with remote air cooled condensers and packaged chilled water units. 4. Packaged chillers with cooling towers and packaged chilled water units. 5. Packaged chillers with cooling towers and central station air handling units. 6. Glycol packaged units with free cooling system.		
		Chillers form a large part of the central air conditioning plant, but there seems to be a lack of statistical or written information on their market size, manufacture, installation or use.		Quick (1985) NOTE In terms of cost per unit of duty the cooling load will normally be more expensive than the heating load plant.
		Components: 1. EVAPORATORS An evaporator may be a f coil for cooling air or a shell and tube type for cooling water.		Faber & Kell (1979)

COMPONENT	ARC	GENERAL SPECIFICATIONS	REGULATIONS	GUIDANCE NOTES
General		The evaporator coils may be filled with a refrigerant (flooded system) or a vapour (dry system) or water with the refrigerant being dripped over the outside (centrifugal machine). 2. COMPRESSORS These may be reciprocating, rotary (screw) or centrifugal depending on the size of the plant. 3. CONDENSERS An evaporative condenser is used where the compressor can be near to the condenser, but more often in air conditioning system, it takes the form of a heat exchanger of the shell and tube multi-pass type. Pipework is required from the condenser to a water cooler. 4. COOLERS To remove heat from water cooled condensers, the water is usually cooled by contact with the atmosphere. Evaporative coolers are divided into two categories: a. Natural draught (single or double entry crossflow) systems: spray ponds, cooling towers and condenser coils. b. Fan draught (induced or forced draught counterflow) systems: air washers, induced draught cooling towers, film cooling towers and closed circuit water coolers. Since the heat to be removed from the condenser cooling water by the cooling tower is equal to the sum of the cooling load plus the heat equivalent of power absorbed by the compressor, the range in temperature of cooling water will determine the size and cost of the plant. Cooler components include: air inlet filters, baffle vanes, water treatment sprays, circuit coils, coolers, fans, motors, drain outlets, hose connections, water storage basins, eliminators, inlet and outlet silencers, valves, pumps, strainers, fan guards, covers, thermostats, starters, all associated fittings, fixings and electrical work in connection.		NOTE An evaporator adds heat to a low pressure liquid, thus causing evaporation to a low pressure gas. A compressor pressurises a low pressure gas into a high pressure gas. A condenser in conjunction with a cooler, is a device for removing heat from a high pressure gas, thus causing it to condense to a high pressure liquid. An expansion valve is used to lower the pressure of a high pressure liquid (for its return to the evaporator) as a low pressure liquid. NOTE 'Evaporative cooling is a physical process in which conditions for evaporation are encouraged by increased air movement resulting in the removal of the latent heat of evaporation from the surroundings with a consequent drop in temperature'. RICS (1985) NOTE Cooling towers are commonly supplied as packaged units.

ELEMENT HEAT SOURCE

COMPONENT	ARC	GENERAL SPECIFICATIONS	REGULATIONS	GUIDANCE NOTES
General		5. REFRIGERATION CONTROL VALVES a. Hand expansion valves b. Constant pressure expansion valves c. Thermostatic expansion valves d. Capillary tube e. Evaporator pressure regulators f. Suction pressure regulators f. Liquid line solenoid valves.		
		6. PUMPS for both the chilled and condenser water.		See 'pumps general' section.
		7. STANDBY GENERATORS.		See 'EWIC general' section.
		8. MOTORS, FANS AND STARTERS.		
		9. PIPEWORK including sight glasses, controls and electrical work in connection.		See 'pipework general' section.
		10. INSULATION		See 'insulation general' section.

ELEMENT EWIC

COMPONENT	ARC	GENERAL SPECIFICATIONS	REGULATIONS	GUIDANCE NOTES
General	SHWELC ISHWELC IHWELC ELCFAN ELCPER ELCRAD ELCDPF ELCAHU ELCVAV ELCVER ELCDVAV ELCDVER EXELC SXELC SUPELC HLFTELC ELFTELC	Electrical work in connection (EWIC) with mechanical systems generally means the supply and fixing of all motors, starters, remote indicator lights, control switches and all associated equipment and wiring necessary to provide complete mechanical systems. A means of local isolation may also be required where starters are remote from motors.		See 'heat source general' section: pumps and motors. Clwyd County Council (1985) Faber & Kell (1979) Leigh (1983) Armstrong (1983) Fisk (1979) Butler & Jackson (1985) Fisk & Salvidge (1983) CIBSE Application Manual (1984) Automatic controls and their implications for systems design.
		Wiring to fans, pumps, stokers and burners, immersion heaters, boilers, thermostatic radiator valves, room thermostats, time-switches, proportional room temperature controllers with three way valves, flow detectors, outside temperature detectors, a central controller (variable optimum start controllers, programmable controllers, step, simple single point on/off controllers, two or three on/off controllers, time proportioning option controls, one and three mode proportional controllers, and energy management systems), fuel monitors, flue gas temperature monitors, boiler lockout alarms, constant air supply controls, storage calorifier controls, dampers, wind detectors, compensators, automatic two or three way valves, zone controls, solar sensors, boiler low limit return water sensors, mixers, humidistats, contactors, impulse relays, changeover relays/switches, light sensitive switches, timers, push buttons, bell transformers, buzzers, under-voltage protection, reset overload devices, panels, and sound sensing controls.	BS 4794: 1979 BS 6134: 1981 BS 775 : 1974 (1984)	Specification for control switches (switching devices, including contactor relays, for control and auxiliary circuits, for voltages up to and including 1000 a.c. and 1200 V d.c.). Specification for pressure and vacuum switches. Contactors.
		With continuing technological developments, sophisticated information systems and controls continue to improve and integrated building management systems may offer: Energy management of heating, air conditioning and lighting Security Fire protection Centralised data processing.		IEETE (1980) Systems may relay alarms to a central position, remote switching of plant, indicate the operational status of plant, provide 'analogue' information, record and log events, provide preprogrammed control, provide operational control and take actions automatically in response to events.
		Common control and wiring systems can network with one another, benefitting from the shared intelligence. Local micro-processors can adjust fans and dampers to maintain the required temperatures in each zone. The fire and security systems can control, pinpoint and evacuate specific zones, locking doors, pressurising certain areas and ventilating smoke. Security monitors can observe and protect personnel and property. All these systems require some electrical work in connection.		

APPENDIX 9.4

M & E STANDARD COST ANALYSIS REPORT

UNIT : Unit quantity per component

eg. Number (Nr.)
Kilowatt (KW)
Litres (Ltrs)
Kilogram (Kg).

M : Material costs in £s.

LF : Labour factors in manhours.

I.LF : Indexed labour factor.

LR : Labour rate : wages per hour in £s.

TC : Total cost = material costs + (indexed labour factor x labour rate).

I.TC : Indexed total cost.

SA : Served area in m^2.

M&E Standard Cost Analysis Forms

SANITARY FITTINGS

Date of Project

Date of Indices

Project
Code
Number

Indices

	WCs	WHBs	Urinals	Drinking Fountains	Cleaners Sinks	Macerators	Overflows	Sanitary Points
Unit								
M								
LF								
I.LF								
LR								
TC								
I.TC								
SA								
£/m2								
Hrs/m2								
Nr/m2								

Comments ;

COLD WATER INSTALLATIONS

Date of Project

Date of Indices

Project
Code
Number

Indices	Mains	Cold Water Points	Cold Water Storage	Insulation to Pipework
Unit				
M				
LF				
I.LF				
LR				
TC				
I.TC				
SA				
£/m2				
Hrs/m2				
Nr/m2				
Ltrs/m2				
KW/m2				

Comments :

HOT WATER INSTALLATIONS

Date of Project

Date of Indices

Project Code Number

Indices	Hot Water Points	Hot Water Storage	Insulation to Pipework	Pumps	Heat Source	EWIC
Unit						
M						
LF						
I.LF						
LR						
TC						
I.TC						
SA						
£/m2						
Hrs/m2						
Nr/m2						
Ltrs/m2						
KW/m2						

Comments ;

PIPED HEATING SYSTEM : RADIATORS

Date of Project

Date of Indices

Project Code Number

Indices	Radiators	Distribution	Heat Source	EWIC
Unit				
M				
LF				
I.LF				
LR				
TC				
I.TC				
SA				
£/m2				
Hrs/m2				
Nr/m2				

Comments :

PIPED HEATING SYSTEM : PERIMETER CONVECTORS

Date of Project

Date of Indices

Project Code Number

Indices	Perimeter Convectors	Distribution	Heat Source	EWIC
Unit				
M				
LF				
I.LF				
LR				
TC				
I.TC				
SA				
£/m2				
Hrs/m2				
Nr/m2				

Comments :

PIPED HEATING SYSTEM : FAN CONVECTORS

Date of Project

Date of Indices

Project Code Number

Indices	Fan Convectors	Distribution	Heat Source	EWIC
Unit				
M				
LF				
I.LF				
LR				
TC				
I.TC				
SA				
£/m2				
Hrs/m2				
Nr/m2				

Comments :

DUAL PIPED HEATING SYSTEM : FAN CONVECTORS
PERIMETER CONVECTORS

Date of Project

Date of Indices

Project
Code
Number

Indices	Fan Convectors	Distribution	Perimeter Convectors	Distribution	Heat Source	EWIC
Unit						
M						
LF						
I.LF						
LR						
TC						
I.TC						
SA						
£/m2						
Hrs/m2						
Nr/m2						

Comments ;

AIR CONDITIONING SYSTEM : VERSATEMP

Date of Project

Date of Indices

Project Code Number

Indices	Versatemp Units	Central Air Handling Plant	Ductwork	Grilles & Terminals	Pipework	Heat Source	EWIC
Unit							
M							
LF							
I.LF							
LR							
TC							
I.TC							
SA							
£/m2							
Hrs/m2							
Nr/m2							
Kg/m2							

Comments ;

AIR CONDITIONING SYSTEM : VARIABLE AIR VOLUME

Date of Project

Date of Indices

Project Code Number

Indices

	Variable Air Volume Units	Central Air Handling Plant	Ductwork	Grilles & Terminals	Pipework	Heat Source	EWIC
Unit							
M							
LF							
I.LF							
LR							
TC							
I.TC							
SA							
£/m2							
Hrs/m2							
Nr/m2							
Kg/m2							

Comments:

AIR CONDITIONING SYSTEM : C A H U

Date of Project

Date of Indices

Project Code Number Indices		Central Air Handling Plant	Ductwork	Grilles & Terminals	Pipework	Heat Source	EWIC
Unit							
M							
LF							
I.LF							
LR							
TC							
I.TC							
SA							
£/m2							
Hrs/m2							
Nr/m2							
Kg/m2							

Comments:

DUAL AIR CONDITIONING AND PIPED HEATING SYSTEM : PERIMETER CONVECTORS
VAV

Date of Project

Date of Indices

Project Code Number	Indices	Perimeter Convectors	Distrib-ution	Variable Air Volume Units	Central Air Handling Plant	Ductwork	Grilles & Terminals	Pipework	Heat Source	EWIC
	Unit									
	M									
	LF									
	I.LF									
	LR									
	TC									
	I.TC									
	SA									
	£/m2									
	Hrs/m2									
	Nr/m2									
	Kg/m2									

Comments :

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DUAL AIR CONDITIONING AND PIPED HEATING SYSTEM : PERIMETER CONVECTORS VERSATEMP

Date of Project

Date of Indices

Project
Code
Number

Indices

	Perimeter Convectors	Distrib-ution	Versatemp Units	Central Air Handling Plant	Ductwork	Grilles & Terminals	Pipework	Heat Source	EWIC
Unit									
M									
LF									
I.LF									
LR									
TC									
I.TC									
SA									
£/m2									
Hrs/m2									
Nr/m2									
Kg/m2									

Comments:

UNTREATED VENTILATION : EXTRACT

Date of Project

Date of Indices

Project Code Number

Indices

	Extract Plant	Ductwork	Terminals	EWIC
Unit				
M				
LF				
I.LF				
LR				
TC				
I.TC				
SA				
£/m2				
Hrs/m2				
Nr/m2				
Kg/m2				

Comments:

UNTREATED VENTILATION : SUPPLY

Date of Project

Date of Indices

Project
Code
Number

Indices	Supply Plant	Ductwork	Terminals	EWIC
Unit				
M				
LF				
I.LF				
LR				
TC				
I.TC				
SA				
£/m2				
Hrs/m2				
Nr/m2				
Kg/m2				

Comments:

UNTREATED VENTILATION : SUPPLY AND EXTRACT

Date of Project

Date of Indices

Project Code Number

Indices	Supply & Extract Plant	Ductwork	Terminals	EWIC
Unit				
M				
LF				
I.LF				
LR				
TC				
I.TC				
SA				
£/m2				
Hrs/m2				
Nr/m2				
Kg/m2				

Comments:

FIRE PROTECTION

Date of Project

Date of Indices

Project
Code
Number Indices

	Sprinklers	Hosereels	Loose Equipment	Dry Risers	EWIC Fire Alarms
Unit					
M					
LF					
I.LF					
LR					
TC					
I.TC					
SA					
£/m2					
Hrs/m2					
Nr/m2					

Comments:

LIFTS

Date of Project
Date of Indices

Project
Code
Number

Indices

	ELECTRIC LIFT	EWIC		HYDRAULIC LIFT	EWIC
M					
LF					
I.LF					
LR					
TC					
I.TC					
SA					
£/m²					
Hrs/m²					
Nr/m²					

Comments:

ELECTRICAL

Date of Project

Date of Indices

Project
Code
Number Indices

	Mains & Switch-gear	Earthing & Cable Distrib-ution	Trunking Conduits	Lighting Fittings		
				600 Lux	500 Lux	300 Lux
Unit						
M						
LF						
I.LF						
LR						
TC						
I.TC						
SA						
£/m2						
Hrs/m2						
Nr/m2						

Comments:

ELECTRICAL

Date of Project

Date of Indices

Project Code Number Indices

	Emergency Lighting	Small Power & Trunking	GPO Tele-phones	Lightning Protection	Computer Trunking
Unit					
M					
LF					
I.LF					
LR					
TC					
I.TC					
SA					
£/m2					
Hrs/m2					
Nr/m2					

Comments:

APPENDIX 9.5

RAW DATA FREQUENCY POLYGONS

Raw data frequency polygons reproduced for the thesis using MASTERGRAPH III by A.Upton, presented by MICHTRON/MOLIMERX on a Sanyo home computer MBC 555, 256K and EPSON FX-80 printer.

APPENDIX 9.6

The formulation and statistics of the Beta distribution

i) THE FORMULATION OF THE BETA DISTRIBUTION

ii) THE STATISTICS OF THE BETA DISTRIBUTION

6. i) Formulation of the Beta Distribution from the Bernoulli Distribution

The probability that an event will happen X_0 times in N trials:

$$p(X_0) = \frac{N!}{X_0!\,(N - X_0)!}\, p^x\, q^{N-x}$$

$$= \binom{N}{X} p^X q^{N-X}$$

where p = probability of success ie. the event will happen
q = probability of failure = 1 - p .

This discrete probability distribution is known as the Bernoulli Distribution or binomial.

The probability of the event being X_0 or more is denoted by $R(X_0)$.

$$R(X_0) = P(X \geqslant X_0)$$

$$R(X_0) = \sum_{X}^{N} \binom{N}{X} p^x (1 - p)^{N-X}$$

Ullman (1976)
Derman (1978)

For a continuous distribution, the cumulative distribution function is:

$$F(X_0) = 1 - R(X_0)$$

$$= P(X \leqslant X_0)$$

$$= 1 - \sum_{X}^{N} \binom{N}{X} p^X (1 - p)^{N-X}$$

$$= \sum_{0}^{X} \binom{N}{x} p^{X} (1 - p)^{N-X}$$

Ullman (1976)

$$= \binom{N}{X} p^{X} (1 - p)^{N-X} + \binom{N}{X + 1} p^{X+1} (1 - p)^{N-X-1}$$

$$+ \ldots\ldots + Np^{N-1} (1 - p) + p^{N}$$

The probability density function (p.d.f.) or frequency function is:

$$f(X) = \frac{d}{dX} F(X_o)$$

$$= \binom{N}{X} X_p{}^{X-1} (1 - p)^{N-X} -$$

$$\binom{N}{X} (N-X) p^{X} (1 - p)^{N-X-1} + \binom{N}{X + 1}(X + 1) p^{X} (1 - p)^{N-X-1}$$

$$- \binom{N}{X + 1} (N - X - 1) p^{X} (1 - p)^{N-X-2} + \ldots\ldots +$$

$$N(N-1) p^{N-2} (1 - p) - Np^{N-1} + Np^{N-1}$$

$$= \binom{N}{X} Xp^{X-1} (1 - p)^{N-X}$$

$$= \frac{N!}{(X - 1)!\,(N - X)!} p^{X-1} (1 - p)^{N-X}$$

$$0 < p < 1$$

$$= \frac{\Gamma(N + 1)}{\Gamma(X)\Gamma(N - X + 1)} p^{X-1} (1 - p)^{n-X}$$

Larson (1982)

The beta distribution can then be formulated from the binomial since:

$N = p + q - 1$

$X = p$

$p = X = \frac{X_o}{r} = \frac{\text{observed variable}}{\text{range}}$

The beta density function: $0 < x < 1$

$$f(x) = \frac{(q + p - 1)!}{(p - 1)!\,(q - 1)!} X^{p-1} (1 - X)^{q-1}$$

$$= \frac{\Gamma(p + q)}{\Gamma(p)\Gamma(q)} X^{p-1} (1 - X)^{q-1}$$

p and q are parameters greater than zero. It is to be noted that the range of X is finite $0 \leqslant x \leqslant 1$.

The p.d.f. is not a probability but can be conveniently regarded as being proportional to a probability, Lloyd (1980), when

$$\int_0^1 f(x)\,dx = 1$$

This is called the normalisation condition. The normalising constant B(p, q) is the beta function:

$$B(p, q) = \frac{\Gamma(p)\Gamma(q)}{\Gamma(p + q)}$$

which is related to the gamma function $\Gamma(n)$.

6.ii Statistics of the Beta distribution

i) The mean for the beta distribution is:

$$\overline{X}_\beta = \frac{p}{p + q}$$

ii) The standard deviation is:

$$S_\beta = \sqrt{\frac{pq}{(p + q)^2 (p + q + 1)}}$$

Phillips (1973)

$$\text{Variance} = S_\beta^2$$

iii) The mode is:

$$\hat{X}_\beta = \frac{p - 1}{p + q - 2}$$

Lloyd (1980)

iv) Skeweness is:

$$\text{Skew}_\beta = \frac{2 (q - p) (q + p + 1)^{\frac{1}{2}}}{\sqrt{(pq (p + q))}}$$

From this equation it can be seen that when

$p < q$: skewness is positive

$p > q$: skewness is negative

$p = q$: skewness zero ie. normal.

v) Credible intervals for the Beta distribution can be found from the tables (Phillips, 1973) for 95% credible intervals or 99% credible intervals. An inference can therefore be made from a prior distribution that, for example, I am 95% sure that the true cost of sanitary fittings lies between £x_1/m^2 and £x_2/m^2.

When the Beta distribution approaches the mode 0.5 and the parameters (p and q) are too large to use the tables (p or q > 10). Using the statistics computed from the beta parameters, credible intervals can be calculated as a normal density function.

vi) It is not possible, according to Phillips (1973) to find the median directly from p and q; a table of the cumulative distribution would need to be consulted.

vi) No simple moment generating function (m.g.f.) for the beta distribution exists (Lloyd, 1980) neither is it useful according to Larson (1982).

APPENDIX 9.7

EXAMPLES OF MECHANICAL AND ELECTRICAL COST ANALYSES BASED ON THE TRACE VALIDATION SHEETS

COST ANALYSES Iteration No. 80 Total Cost: £68 64·16/m²

Components	Prestige H	M	L	Components	Prestige H	M	L	Components	Prestige H	M	L	Comments:
ELEMENT 1												
SANWCS 0·54		/		Urinals 0·24		/						SANITARY INSTALLATION
SANWHBS 0·23			/	Orkgftns 0·73			/					3·53
SANOFS 0·16		/		Clnrsaks 0·09		/						
SANPTS 1·55		/		~~Maos~~								
ELEMENT 2												COLD WATER INSTALLATION
CWMAINS 0·29		/		Insultn 0·21		/						3·47
CWPTS 1·37	/											
CWSTORAG 1·10		/										
ELEMENT 3												HOT WATER INSTALLATION
CHWPTS 0·71			/	Hwstorag 0·97		/						
				Shwht 0·45			/					2·36
				Shwelc 0·09		/						
				Hinsultn 0·09			/					
				Pumps 0·05			/					
~~IHWPTS~~				~~ISTORAG~~				~~Tohwht~~				
								~~Ishwelc~~				
								~~Ihwht~~				
								~~Ihwelc~~				
ELEMENT 4												HEATING
~~FANCONV~~				~~Pukfan~~								19·11
				~~Htefan~~								
				~~Elefan~~								
~~PERCONV~~				~~Pukper~~								
				~~Hteper~~								
				~~Eleper~~								
RADS 5·06		/		Pukrad 13·41		/						
				Htsrad 0·57		/						
				Elcrad 0·08			/					
~~SPERFAN~~				~~Sfanper~~								
				~~Pukper~~								
				~~Pukdfan~~								
				~~Htedpf~~								
				~~Elodpf~~								
~~SAHU~~				~~Sukahu~~								~~AIR CONDITIONING~~
				~~Tosahu~~								
				~~Pukahu~~								
				~~Htsahu~~								
				~~Elcahu~~								
~~VAV~~				~~Ahuvav~~								
				~~Bukvav~~								
				~~Tosvav~~								
				~~Pukvav~~								
				~~Htevav~~								
				~~Elevav~~								
~~VERSA~~				~~Ahuver~~								
				~~Bukver~~								
				~~Tapver~~								
				~~Pukver~~								
				~~Htever~~								
				~~Elever~~								
~~FANCOIL~~												
~~DUAVPER~~				~~Opesvav~~								
				~~Pukdper~~								
				~~Ahudvav~~								
				~~Dukdvav~~								
				~~Tordvav~~								
				~~Pukdvav~~								
				~~Htedvav~~								
				~~Eledvav~~								
~~DVERSPER~~				~~Desrvar~~								
				~~Pukdpa~~								
				~~Ahudvar~~								
				~~Bukdvar~~								
				~~Tosdvar~~								
				~~Pukdvar~~								
				~~Htedvar~~								
				~~Eledvar~~								
ELEMENT 5												~~VENTILATION~~
				~~EXTRACT~~				~~Exduk~~				
								~~Exbox~~				
								~~Exelc~~				
				~~SUPEXT~~				~~Sxduk~~				
								~~Sxbox~~				
								~~Sxelc~~				
				~~SUPPLY~~				~~Suduk~~				
								~~Supbox~~				
								~~Supelc~~				
ELEMENT 6												FIRE PROTECTION
HOSERLS 2·75	/			~~Sprinkle~~								6·7
				~~Loquis~~								
				Dryrsr 0·70			/					
				Alarms 2·33		/						
ELEMENT 7												~~LIFTS~~
				~~HLIFT~~				~~Hliftelc~~				
				~~ELIFT~~				~~Eliftelc~~				
ELEMENT 8												ELECTRICAL INSTALLATIONS
EMAINS 6·01	/			~~600LUX~~				~~Spot~~				32·88
ECABLE 1·63		/		500LUX 12·25		/		Goo 0·17			/	
ETRUNK 4·96		/		~~300LUX~~				~~Ltng~~				
EMGNCY 2·47	/											
POWER 5·49		/										

COST ANALYSES

Iteration No. 83

Total Cost: £37·039/m^2

Components	Prestige H	M	L	Components	Prestige H	M	L	Components	Prestige H	M	L	Comments:
ELEMENT 1												SANITARY INSTALLATION
SANWCS 0·56		✓		Urinals 0·16		✓						3·00
SANWHBS 0·34			✓	~~Dskgftns~~								
SANOFS 0·30	✓			Clnrseks 0·19	✓							
SANPTS 1·25			✓	Macs 0·20		✓						
ELEMENT 2												COLD WATER INSTALLATION
CWMAINS 0·46		✓		~~Insultn~~								4·08
CWPTS 2·36	✓											
CWSTORAG 1·25		✓										
ELEMENT 3												HOT WATER INSTALLATION
~~SINPTS~~				~~Hwstorag~~								1·12
				~~Shwht~~								
				~~Shwelc~~								
				~~Winsultn~~								
				~~Pumps~~								
IHWPTS 0·61	✓			~~ISTORAG~~				~~Iohwht~~				
								~~Iohwelc~~				
								~~Ihwht~~				
								Ihwelc 0·51		✓		
ELEMENT 4												HEATING
FANCONV 17·00	✓			Pwkfan 5·40		✓						25·62
				Htsfan 0·15		✓						
				Elcfan 0·03			✓					
~~PERGONV~~				~~Pwkper~~								
				~~Hbsper~~								
				~~Elsper~~								
~~RADS~~				~~Pwkrad~~								
				~~Hbsrad~~								
				~~Elsrad~~								
~~OPERFAN~~				~~Ofanpar~~								
				~~Pwkpar~~								
				~~Pwkdfan~~								
				~~Hbsdpf~~								
				~~Elsdpf~~								
~~SAHU~~				~~Bwkahu~~								~~AIR CONDITIONING~~
				~~Terahu~~								
				~~Pwkahu~~								
				~~Htsahu~~								
				~~Elsahu~~								
~~VAV~~				~~Ahuvav~~								
				~~Dwkvav~~								
				~~Tervav~~								
				~~Pwkvav~~								
				~~Htsvav~~								
				~~Elcvav~~								
~~VERSA~~				~~Ahuvas~~								
				~~Dwkvas~~								
				~~Tervas~~								
				~~Pwkvas~~								
				~~Htsvas~~								
				~~Elcvas~~								
~~FANCOIL~~												
~~DUAVPER~~				~~Opaduav~~								
				~~Pwkdper~~								
				~~Ahuduav~~								
				~~Dwkduav~~								
				~~Terdvav~~								
				~~Pwkdvav~~								
				~~Hbsdvav~~								
				~~Elsdvav~~								
~~OVERSPER~~				~~Opaduar~~								
				~~Pwkdpa~~								
				~~Ahuduar~~								
				~~Dwkduar~~								
				~~Tasduar~~								
				~~Pwkduar~~								
				~~Htsduar~~								
				~~Elcduar~~								
ELEMENT 5												~~VENTILATION~~
				~~EXTRACT~~				~~Exduk~~				
								~~Exter~~				
								~~Exelc~~				
				~~SUPEXT~~				~~Sxduk~~				
								~~Sxter~~				
								~~Sxelc~~				
				~~SUPPLY~~				~~Supduk~~				
								~~Supter~~				
								~~Supelc~~				
ELEMENT 6												FIRE PROTECTION
HOSERLS 1·03			✓	~~Sprnkle~~								2·12
				Lequip 0·30	✓							
				Dryrsr 0·79			✓					
				~~Alarms~~								
ELEMENT 7												LIFTS
				~~HLIFT~~				~~Hliftelc~~				20·12
				ELIFT 19·52		✓		Elftelc 0·30		✓		
ELEMENT 8												ELECTRICAL INSTALLATIONS
EMAINS 1·28			✓	600LUX 14·55	✓			~~Gpos~~				31·04
ECABLE 2·79	✓			~~500LUX~~				Gpo 0·40		✓		
ETRUNK 6·97	✓			~~300LUX~~				Ltng 0·59		✓		
EMGNCY 1·79	✓											
POWER 2·68			✓									

COST ANALYSES

Iteration No. 90

Total Cost: £135·054/m^2

Components	Prestige			Components	Prestige			Components	Prestige			Comments:
	H	M	L		H	M	L		H	M	L	
ELEMENT 1												SANITARY INSTALLATION
SANWCS 0·32			✓	Urinals 0·22		✓						2·71
SANWHBS 0·32			✓	Drkgftns 0·36		✓						
SANOFS 0·19		✓		Clnrsaks 0·09		✓						
SANPTS 1·03			✓	Mecs 0·17		✓						
ELEMENT 2												COLD WATER INSTALLATION
CWMAINS 0·60		✓		Insultn 0·21		✓						3·75
CWPTS 2·14	✓											
CWSTORAG 0·90			✓									
ELEMENT 3												HOT WATER INSTALLATION
CHWPTS 0·96		✓		Hwstorag 0·86		✓						3·39
				Shwht 1·08	✓							
				Shwelc 0·13		✓						
				Hinsultn 0·22	✓							
				Pumps 0·15	✓							
~~IHWPTS~~				~~ISTORAG~~				~~Iehwht~~				
								~~Iehwelc~~				
								~~Ihwht~~				
								~~Ihwelc~~				
ELEMENT 4												HEATING
~~FANCONV~~				~~Pwkfan~~								31·20
				~~Htefan~~								
				~~Elcfan~~								
PERCONV 13·05		✓		Pwkper 6·68		✓						
				Htaper 9·75		✓						
				Elcper 1·71		✓						
~~RADS~~				~~Pwkrad~~								
				~~Htsrad~~								
				~~Elcrad~~								
~~DPERFAN~~				~~Dfanper~~								
				~~Pwkper~~								
				~~Pwkdfan~~								
				~~Htsdpf~~								
				~~Elcdpf~~								
~~SAHU~~				~~Dwkahu~~								~~AIR CONDITIONING~~
				~~Tsrahu~~								
				~~Pwkahu~~								
				~~Htsahu~~								
				~~Elcahu~~								
~~VAV~~				~~Ahuvav~~								
				~~Dwkvav~~								
				~~Tsrvav~~								
				~~Pwkvav~~								
				~~Htsvav~~								
				~~Elcvav~~								
~~VERSA~~				~~Ahuver~~								
				~~Dwkver~~								
				~~Tsrver~~								
				~~Pwkver~~								
				~~Htsver~~								
				~~Elcver~~								
~~FANCOIL~~												
~~DUAVPER~~				~~Dpervav~~								
				~~Pwkdper~~								
				~~Ahudvav~~								
				~~Dwkdvav~~								
				~~Tsrdvav~~								
				~~Pwkdvav~~								
				~~Htsdvav~~								
				~~Elcdvav~~								
~~DUERSPER~~				~~Dperver~~								
				~~Pwkdpe~~								
				~~Ahudver~~								
				~~Dwkdver~~								
				~~Tsrdver~~								
				~~Pwkdver~~								
				~~Htsdver~~								
				~~Elcdver~~								
ELEMENT 5												VENTILATION
				EXTRACT 7·57		✓		Exdwk 28·43		✓		42·06
								Exter 6·01		✓		
								Exelc 0·05			✓	
				~~SUPEXT~~				~~Sxdwk~~				
								~~Sxter~~				
								~~Sxelc~~				
				~~SUPPLY~~				~~Supdwk~~				
								~~Supter~~				
								~~Supelc~~				
ELEMENT 6												FIRE PROTECTION
HOSERLS 1·99	✓			~~Sprklr~~								6·11
				Lequip 0·31	✓							
				Dryrer 0·60			✓					
				Alarms 2·32		✓						
ELEMENT 7												LIFTS
				~~HLIFT~~				~~Hlftelc~~				16·03
				ELIFT 15·66		✓		Elftelc 0·37		✓		
ELEMENT 8												ELECTRICAL INSTALLATIONS
EMAINS 6·34	✓			~~600LUX~~				~~Spot~~				29·85
ECABLE 1·23		✓		500LUX 11·15			✓	Spd 1·03	✓			
ETRUNK 3·26			✓	~~300LUX~~				Ltng 0·64		✓		
EMGNCY 1·31		✓										
POWER 4·99			✓									

COST ANALYSES

Iteration No. 52

Total Cost: £ 31 ·34 /m²

Components	Prestige H	M	L	Components	Prestige H	M	L	Components	Prestige H	M	L	Comments:
ELEMENT 1												SANITARY INSTALLATION 3.19
SANWCS 0.43			/	~~Urinals~~								
SANWHBS 0.44	/			Orkgftns 0.27		/						
SANOFS 0.32	/			Clnrseks 0.13	/							
SANPTS 1.40		/		~~Macs~~								
ELEMENT 2												COLD WATER INSTALLATION 1.74
CWMAINS 0.12		/		Insultn 0.09			/					
CWPTS 0.71			/									
CWSTORAG 0.72			/									
ELEMENT 3												HOT WATER INSTALLATION 2.51
CHWPTS 0.65			/	Hwstorag 0.35		/						
				Shunt 0.62		/						
				Shwelc 0.15	/							
				Hinsultn 0.10			/					
				Pumps 0.13		/						
~~IHWPTS~~				~~ISTORAG~~				~~Ishunt~~				
								~~Ishwelc~~				
								~~Ihunt~~				
								~~Ihwelc~~				
ELEMENT 4												HEATING
~~FANCONV~~				~~Owkfan~~								
				~~Htsfan~~								
				~~Elefan~~								
~~PERCONV~~				~~Owkper~~								
				~~Htsper~~								
				~~Elsper~~								
~~RADS~~				~~Owkrad~~								
				~~Htsrad~~								
				~~Elsrad~~								
~~OPERFAN~~				~~Ofanper~~								
				~~Pwkper~~								
				~~Pwkdfan~~								
				~~Htsdaf~~								
				~~Elsdaf~~								
~~SAHU~~				~~Owkahu~~								AIR-CONDITIONING 116.70
				~~Tesahu~~								
				~~Pwkahu~~								
				~~Htsahu~~								
				~~Elsahu~~								
VAV 9.61	/			Ahuvav 7.92		/						
				Owkvav 32.54		/						
				Tervav 18.42		/						
				Pwkvav 7.12		/						
				Htsvav 29.39		/						
				Elcvav 1.70			/					
~~VERSA~~				~~Ahuver~~								
				~~Owkver~~								
				~~Terver~~								
				~~Pwkver~~								
				~~Htsver~~								
				~~Elsver~~								
~~FANCOIL~~												
~~DUAVDER~~				~~Gesrvav~~								
				~~Pwkdoar~~								
				~~Ahuduav~~								
				~~Owkduav~~								
				~~Tesdvav~~								
				~~Pwkdvav~~								
				~~Htsduav~~								
				~~Elsdvav~~								
~~DVERSPER~~				~~Desvar~~								
				~~Pwkdes~~								
				~~Ahuduar~~								
				~~Owkdvar~~								
				~~Tesdvar~~								
				~~Pwkdvar~~								
				~~Htsdvar~~								
				~~Elsdvar~~								
ELEMENT 5												~~VENTILATION~~
				~~EXTRACT~~				~~Exdwk~~				
								~~Exter~~				
								~~Exelc~~				
				~~SUPEXT~~				~~Sxdwk~~				
								~~Sxtes~~				
								~~Sxelc~~				
				~~SUPPLY~~				~~Supdwk~~				
								~~Suptar~~				
								~~Supelc~~				
ELEMENT 6												FIRE PROTECTION 3.45
HOSERLS 1.19			/	~~Sprkls~~								
				~~Lequip~~								
				Dryrsr 1.75	/							
				Alarms 0.51			/					
ELEMENT 7												LIFTS 22.57
				~~HLIFT~~				~~Hlftelc~~				
				ELIFT 22.45		/		Elftslc 0.42		/		
ELEMENT 8												ELECTRICAL INSTALLATIONS 31.18
EMAINS 2.49		/		600LUX 10.91	/			~~Spec~~				
ECABLE 2.38		/		~~500LUX~~				Gpo 1.00	/			
ETRUNK 6.51		/		~~300LUX~~				Ltng 0.70	/			
EMGICY 1.40		/										
POWER 5.98		/										

APPENDIX 9.8

Path Costs for SANFTG, SANWCS and SANWHBS

9.8.1 PATH COST FOR NODE SANFTG
(100 iterations)

9.8.2 PATH COST FOR ARC SANWCS
(100 iterations and sample data)

9.8.3 PATH COST FOR ARC SANWHBS
(100 iterations)

9.8.1 Path Cost for Node Sanitary Fittings (SANFTG) iterations

	X	f		$\bar{X}=3.4106$						
Class interval	Midpoint	Frequency	fx	$(X-\bar{X})^2$	$f(X-\bar{X})^2$	u	fu	fu^2	fu^3	fu^4
2.2293 - 2.3680	2.2987	0.022	0.0506	1.2363	0.0272	-8	-0.176	1.408	-11.264	90.112
2.3680 - 2.5067	2.4374	0.018	0.0439	0.9471	0.0170	-7	-0.126	0.882	-6.174	43.218
2.5067 - 2.6455	2.5761	0.042	0.1082	0.6964	0.0292	-6	-0.252	1.512	-9.072	54.432
2.6455 - 2.7842	2.7149	0.054	0.1466	0.4840	0.0261	-5	-0.270	1.350	-6.750	33.750
2.7842 - 2.9229	2.8536	0.062	0.1769	0.3102	0.0192	-4	-0.248	0.992	-3.968	15.872
2.9229 - 3.0616	2.9923	0.066	0.1975	0.1750	0.0115	-3	-0.198	0.594	-1.782	5.346
3.0616 - 3.2003	3.1310	0.088	0.2755	0.0782	0.0069	-2	-0.176	0.352	-0.704	1.408
3.2003 - 3.3390	3.2697	0.090	0.2943	0.0199	0.0018	-1	-0.090	0.090	-0.090	0.090
3.3390 - 3.4778	3.4084	0.104	0.3545	0	0	0	0	0	0	0
3.4778 - 3.6165	3.5472	0.102	0.3618	0.0187	0.0019	1	0.102	0.102	0.102	0.102
3.6165 - 3.7552	3.6859	0.112	0.4128	0.0758	0.0085	2	0.224	0.448	0.896	1.792
3.7552 - 3.8939	3.8246	0.078	0.2983	0.1714	0.0134	3	0.234	0.702	2.106	6.318
3.8939 - 4.0326	3.9633	0.036	0.1427	0.3055	0.0110	4	0.144	0.576	2.304	9.216
4.0326 - 4.1713	4.1020	0.046	0.1887	0.4780	0.0220	5	0.230	1.150	5.750	28.750
4.1713 - 4.3101	4.2407	0.022	0.0933	0.6891	0.0152	6	0.132	0.792	4.752	28.512
4.3101 - 4.4488	4.3795	0.026	0.1139	0.9388	0.0244	7	0.182	1.274	8.918	62.426
4.4488 - 4.5875	4.5182	0.012	0.0542	1.2268	0.0147	8	0.096	0.768	6.144	49.152
4.5875 - 4.7262	4.6569	0.006	0.0279	1.5533	0.0093	9	0.054	0.486	4.374	39.366
4.7262 - 4.8649	4.7956	0.006	0.0288	1.9182	0.0115	10	0.060	0.600	6.000	60.000
4.8649 - 5.0036	4.9343	0.004	0.0197	2.3217	0.0093	11	0.044	0.484	5.324	58.564
5.0036 - 5.1424	5.0731	0.002	0.0101	2.7639	0.0055	12	0.024	0.288	3.456	41.472
5.1424 - 5.2811	5.2118	0.002	0.0104	3.2443	0.0065	13	0.026	0.338	4.394	57.122
		$\Sigma f = 1.000$ $= N$	3.4106	19.6526	0.2921 $\surd$ 0.5405		0.016	15.188	14.716	687.020

9.8.2 Path Cost for Arc Water Closets (SANWCS)

100 iterations: Observed frequencies:

	X	f		$\overline{X}$=0.62		f		$\overline{X}$=0.63	
Class interval	Midpoint	Frequency	fx	$(X-\overline{X})^2$	$f(X-\overline{X})^2$	Frequency	fx	$(X-\overline{X})^2$	$f(X-\overline{X})^2$
0.15 - 0.24	0.20	0	0	0.18	0	3	0.60	0.18	0.54
0.25 - 0.34	0.30	4	1.20	0.10	0.40	2	0.60	0.11	0.22
0.35 - 0.44	0.40	12	4.80	0.05	0.60	2	0.80	0.05	0.10
0.45 - 0.54	0.50	20	10.00	0.01	0.20	3	1.50	0.02	0.06
0.55 - 0.64	0.60	27	16.20	0	0	5	3.00	0	0
0.65 - 0.74	0.70	16	11.20	0.01	0.16	2	1.40	0	0
0.75 - 0.84	0.80	11	8.80	0.03	0.33	1	0.80	0.03	0.03
0.85 - 0.94	0.90	6	5.40	0.08	0.48	2	1.80	0.07	0.14
0.95 - 1.04	1.00	3	3.00	0.14	0.42	2	2.00	0.14	0.28
1.05 - 1.14	1.10	0	0	0.23	0	0	0	0.22	0
1.15 - 1.24	1.20	1	1.20	0.34	0.34	1	1.20	0.32	0.32
1.25 - 1.34	1.30	0	0	0.46	0	1	1.30	0.45	0.45
		100	61.80		2.93	24	15.00		2.14
			$\overline{X}$=0.62		σ =0.17		$\overline{X}$=0.63		σ =0.30

9.8.3 Path Cost for Arc Wash Hand Basins (SANWHBS)

100 iterations

Range	X Midpoint	X' Normalised	Y_o Observed $f(X_o)$	Y_E Expected $f(X_e)$	Y'_E Normalised Expected	$\frac{(O-E)^2}{E}$ or χ^2
0.05 - 0.14	0.10	0	1	0	0	
0.15 - 0.24	0.20	0.07	12	1.36	9.05	1.72
0.25 - 0.34	0.30	0.13	13	2.75	18.30	1.53
0.35 - 0.44	0.40	0.20	28	3.32	22.09	1.58
0.45 - 0.54	0.50	0.27	18	2.91	19.36	0.10
0.55 - 0.64	0.60	0.33	15	2.19	14.57	0.01
0.65 - 0.74	0.70	0.40	5	1.33	8.85	1.67
0.75 - 0.84	0.80	0.47	3	0.68	4.52	
0.85 - 0.94	0.90	0.53	3	0.33	2.20	
0.95 - 1.04	1.00	0.60	2	0.12	0.80	
1.05 - 1.14	1.10	0.67	0	0.03	0.20	
1.15 - 1.24	1.20	0.73	0	0.01	0.06	0.01
1.25 - 1.34	1.30	0.80	0	0	0	
1.35 - 1.44	1.40	0.87	0	0	0	
1.45 - 1.54	1.50	0.93	0	0	0	
1.55 - 1.64	1.60	1.00	0	0	0	
			$\Sigma 100$	$\Sigma 15.03$	$\Sigma 100$	$\chi^2=6.62$

where:

a) Normalisation of $:X' = \frac{X_o - X_1}{r} = \frac{X_o - 0.10}{1.50}$

$$:Y' = \frac{Y_E}{15.03} \times 100$$

b) Y_E or $f(X_E) = \frac{(q + p - 1)!}{(p - 1)!\,(q - 1)!} X^{p-1} (1 - X)^{q-1}$

(Refer to Appendix 9.6 : The Beta density function.)

$f(X_E) = 495\, x^2 (1 - X)^8$ when $p = 3$, $q = 9$.

APPENDIX 9.9

RESULTANT COST MODELS

```
NETWORK TIME FOR NODE SAMFTG

    CFD    0.1  0.2  0.3  0.4  0.5  0.6  0.7  0.8  0.9  1.0                  RFD    0.05 0.10 0.15 0.20 0.25
0.0602 I----I----I----I----I----I----I----I----I----I----I MIN       0.0602 I----I----I----I----I----I MIN
       I                                                  0.000              I                         0.000
0.0602 I                                                             0.0602 I
       I                                                  0.008              I                         0.008
0.0708 I                                                             0.0708 I
       I*                                                 0.018              I*                        0.010
0.0814 I                                                             0.0814 I
       I***                                               0.066              I****                     0.048
0.0920 I                                                             0.0920 I
       I******                                            0.116              I*****                    0.050
0.1026 I                                                             0.1026 I
       I*********                                         0.174              I*****                    0.058
0.1132 I                                                             0.1132 I
       I*************                                     0.262              I********                 0.088
0.1238 I                                                             0.1238 I
       I****************                                  0.318              I*****                    0.056
0.1344 I                                                             0.1344 I
       I********************                              0.398              I********                 0.080
0.1450 I                                                             0.1450 I
       I************************                          0.480              I********                 0.082
0.1556 I                                                             0.1556 I
       I***************************                       0.540              I******                   0.060
0.1662 I                                                             0.1662 I
       I*******************************                   0.614              I*******                  0.074
0.1768 I                                                             0.1768 I
       I***********************************               0.692              I*******                  0.078
0.1874 I                                                             0.1874 I
       I**************************************            0.760              I******                   0.068
0.1980 I                                                             0.1980 I
       I****************************************          0.808              I****                     0.048
0.2086 I                                                             0.2086 I
       I*******************************************       0.850              I****                     0.042
0.2192 I                                                             0.2192 I
       I********************************************      0.888              I***                      0.038
0.2298 I                                                             0.2298 I
       I***********************************************   0.930              I*****                    0.050
0.2404 I                                                             0.2404 I
       I************************************************  0.958              I**                       0.020
0.2510 I                                                             0.2510 I
       I************************************************* 0.974              I*                        0.016
0.2616 I                                                             0.2616 I
       I************************************************* 0.986              I*                        0.012
0.2722 I                                                             0.2722 I
       I**************************************************0.996              I*                        0.010
0.2828 I                                                             0.2828 I
       I**************************************************1.000              I                         0.004
0.2934 I                                                             0.2934 I
       I**************************************************1.000              I                         0.000
0.2934 I----I----I----I----I----I----I----I----I----I----I MAX       0.2934 I----I----I----I----I----I MAX

       NO OBS------ ------     500  STD ERROR-               0.0409
       COEF OF VARIATION-     0.30  MEAN-------              0.1626
       KURTOSIS (BETA 2)-     2.34  MEDIAN----               0.1592
       PEARSONIAN SKEW---     0.91  MODE------               0.1183
```

```
PATH COST FOR NODE SANFTG

    CFD  0.1  0.2  0.3  0.4  0.5  0.6  0.7  0.8  0.9  1.0                 RFD  0.05 0.10 0.15 0.20 0.25
2.2293 I----I----I----I----I----I----I----I----I----I----I MIN      2.2293 I----I----I----I----I----I MIN
       I                                                  0.000            I                         0.000
2.2293 I                                                            2.2293 I
       I*                                                 0.022            I**                       0.022
2.3680 I                                                            2.3680 I
       I**                                                0.040            I*                        0.018
2.5067 I                                                            2.5067 I
       I****                                              0.082            I****                     0.042
2.6455 I                                                            2.6455 I
       I*******                                           0.136            I*****                    0.054
2.7842 I                                                            2.7842 I
       I**********                                        0.198            I******                   0.062
2.9229 I                                                            2.9229 I
       I*************                                     0.264            I******                   0.066
3.0616 I                                                            3.0616 I
       I******************                                0.352            I********                 0.088
3.2003 I                                                            3.2003 I
       I**********************                            0.442            I*********                0.090
3.3390 I                                                            3.3390 I
       I***************************                       0.546            I**********               0.104
3.4778 I                                                            3.4778 I
       I********************************                  0.648            I**********               0.102
3.6165 I                                                            3.6165 I
       I**************************************            0.760            I***********              0.112
3.7552 I                                                            3.7552 I
       I******************************************        0.838            I*******                  0.078
3.8939 I                                                            3.8939 I
       I********************************************      0.874            I***                      0.036
4.0326 I                                                            4.0326 I
       I**********************************************    0.920            I****                     0.046
4.1713 I                                                            4.1713 I
       I***********************************************   0.942            I**                       0.022
4.3101 I                                                            4.3101 I
       I************************************************  0.968            I**                       0.026
4.4488 I                                                            4.4488 I
       I************************************************* 0.980            I*                        0.012
4.5875 I                                                            4.5875 I
       I************************************************* 0.986            I                         0.006
4.7262 I                                                            4.7262 I
       I**************************************************0.992            I                         0.006
4.8649 I                                                            4.8649 I
       I**************************************************0.996            I                         0.004
5.0036 I                                                            5.0036 I
       I**************************************************0.998            I                         0.002
5.1424 I                                                            5.1424 I
       I**************************************************1.000            I                         0.002
5.2811 I                                                            5.2811 I
       I**************************************************1.000            I                         0.000
5.2811 I----I----I----I----I----I----I----I----I----I----I MAX      5.2811 I----I----I----I----I----I MAX

       NO OBS-------------    500  STD ERROR-          0.5393
       COEF OF VARIATION-    0.16  MEAN------          3.4106
       KURTOSIS (BETA 2)-    2.95  MEDIAN- --          3.4287
       PEARSONIAN SKEW---    0.44  MODE------          3.6400
```

```
NETWORK TIME FOR NODE COLOWT

           CFD  0.1  0.2  0.3  0.4  0.5  0.6  0.7  0.8  0.9  1.0
    0.0421 I----I----I----I----I----I----I----I----I----I----I MIN
           I                                                    0.000
    0.0421 I
           I*                                                   0.016
    0.0545 I
           I**                                                  0.046
    0.0670 I
           I****                                                0.078
    0.0794 I
           I*******                                             0.132
    0.0919 I
           I**********                                          0.194
    0.1043 I
           I**************                                      0.280
    0.1168 I
           I******************                                  0.366
    0.1292 I
           I**********************                              0.436
    0.1417 I
           I**************************                          0.512
    0.1541 I
           I*****************************                       0.590
    0.1666 I
           I*********************************                   0.670
    0.1790 I
           I*************************************               0.736
    0.1915 I
           I****************************************            0.792
    0.2039 I
           I*****************************************           0.818
    0.2164 I
           I*******************************************         0.854
    0.2288 I
           I*********************************************       0.896
    0.2413 I
           I***********************************************     0.936
    0.2537 I
           I************************************************    0.970
    0.2662 I
           I************************************************* 0.982
    0.2786 I
           I**************************************************0.992
    0.2911 I
           I**************************************************0.996
    0.3035 I
           I**************************************************1.000
    0.3160 I
           I**************************************************1.000
    0.3160 I----I----I----I----I----I----I----I----I----I----I MAX

           NO OBS-------------      500  STD ERROR-           0.0578
           COEF OF VARIATION-      0.37  MEAN------           0.1565
           KURTOSIS (BETA 2)-      2.43  MEDIAN----           0.1518
           MULTIMODAL DISTRIBUTION
```

```
           RFD  0.05 0.10 0.15 0.20 0.25
    0.0421 I----I----I----I----I----I MIN
           I                          0.000
    0.0421 I
           I*                         0.016
    0.0545 I
           I***                       0.030
    0.0670 I
           I***                       0.032
    0.0794 I
           I*****                     0.054
    0.0919 I
           I******                    0.062
    0.1043 I
           I********                  0.086
    0.1168 I
           I********                  0.086
    0.1292 I
           I*******                   0.070
    0.1417 I
           I*******                   0.076
    0.1541 I
           I*******                   0.078
    0.1666 I
           I********                  0.080
    0.1790 I
           I******                    0.066
    0.1915 I
           I*****                     0.056
    0.2039 I
           I**                        0.026
    0.2164 I
           I***                       0.036
    0.2288 I
           I****                      0.042
    0.2413 I
           I****                      0.040
    0.2537 I
           I***                       0.031
    0.2662 I
           I*                         0.012
    0.2786 I
           I*                         0.010
    0.2911 I
           I                          0.004
    0.3035 I
           I                          0.004
    0.3160 I
           I                          0.000
    0.3160 I----I----I----I----I----I MAX
```

PATH COST FOR NODE COLDWT

```
      CFD  0.1  0.2  0.3  0.4  0.5  0.6  0.7  0.8  0.9  1.0                  RFD  0.05 0.10 0.15 0.20 0.25
1.5808 I----I----I----I----I----I----I----I----I----I----I MIN        1.5808 I----I----I----I----I----I MIN
       I                                                  0.000              I                         0.000
1.5808 I                                                              1.5808 I
       I*                                                 0.022              I**                       0.022
1.7575 I                                                              1.7575 I
       I**                                                0.042              I**                       0.020
1.9343 I                                                              1.9343 I
       I***                                               0.060              I*                        0.018
2.1110 I                                                              2.1110 I
       I*****                                             0.102              I****                     0.042
2.2878 I                                                              2.2878 I
       I**********                                        0.190              I********                 0.088
2.4646 I                                                              2.4646 I
       I**************                                    0.272              I********                 0.082
2.6413 I                                                              2.6413 I
       I******************                                0.362              I*********                0.090
2.8181 I                                                              2.8181 I
       I************************                          0.470              I**********               0.108
2.9948 I                                                              2.9948 I
       I****************************                      0.552              I********                 0.082
3.1716 I                                                              3.1716 I
       I********************************                  0.634              I********                 0.082
3.3483 I                                                              3.3483 I
       I************************************              0.712              I*******                  0.078
3.5251 I                                                              3.5251 I
       I***************************************           0.772              I******                   0.060
3.7019 I                                                              3.7019 I
       I*****************************************         0.828              I*****                    0.056
3.8786 I                                                              3.8786 I
       I*******************************************       0.868              I****                     0.040
4.0554 I                                                              4.0554 I
       I**********************************************    0.912              I****                     0.044
4.2321 I                                                              4.2321 I
       I***********************************************   0.940              I**                       0.028
4.4089 I                                                              4.4089 I
       I************************************************  0.952              I*                        0.012
4.5856 I                                                              4.5856 I
       I************************************************* 0.970              I*                        0.010
4.7624 I                                                              4.7624 I
       I************************************************* 0.976              I                         0.006
4.9392 I                                                              4.9392 I
       I**************************************************0.992              I*                        0.016
5.1159 I                                                              5.1159 I
       I**************************************************0.996              I                         0.004
5.2927 I                                                              5.2927 I
       I**************************************************1.000              I                         0.004
5.4694 I                                                              5.4694 I
       I**************************************************1.000              I                         0.000
5.4694 I----I----I----I----I----I----I----I----I----I----I MAX        5.4694 I----I----I----I----I----I MAX

       NO OBS-------------       500  STD ERROR-             0.7590
       COEF OF VARIATION-       0.24  MEAN------             3.1484
       KURTOSIS (BETA 2)-       2.95  MEDIAN----             3.0701
       PEARSONIAN SKEW---       0.34  MODE------             2.8984
```

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PATH PERFORMANCE FOR NODE COLDWT

```
     CFD  0.1  0.2  0.3  0.4  0.5  0.6  0.7  0.8  0.9  1.0              RFD  0.05 0.10 0.15 0.20 0.25
2.3963 I----I----I----I----I----I----I----I----I----I----I MIN      2.3963 I----I----I----I----I----I MIN
       I                                                  0.000            I                          0.000
2.3963 I                                                            2.3963 I
       I                                                  0.002            I                          0.002
2.5176 I                                                            2.5176 I
       I*                                                 0.012            I*                         0.010
2.6389 I                                                            2.6389 I
       I*                                                 0.024            I*                         0.012
2.7602 I                                                            2.7602 I
       I**                                                0.040            I*                         0.016
2.8815 I                                                            2.8815 I
       I*****                                             0.092            I*****                     0.052
3.0028 I                                                            3.0028 I
       I*******                                           0.136            I****                      0.044
3.1241 I                                                            3.1241 I
       I*********                                         0.188            I*****                     0.052
3.2454 I                                                            3.2454 I
       I**************                                    0.278            I*********                 0.090
3.3667 I                                                            3.3667 I
       I********************                              0.400            I************              0.122
3.4880 I                                                            3.4880 I
       I*************************                         0.502            I**********                0.102
3.6093 I                                                            3.6093 I
       I******************************                    0.592            I*********                 0.090
3.7306 I                                                            3.7306 I
       I**********************************                0.686            I*********                 0.094
3.8519 I                                                            3.8519 I
       I**************************************            0.762            I*******                   0.076
3.9732 I                                                            3.9732 I
       I*****************************************         0.824            I******                    0.062
4.0945 I                                                            4.0945 I
       I********************************************      0.888            I******                    0.064
4.2158 I                                                            4.2158 I
       I**********************************************    0.922            I***                       0.034
4.3370 I                                                            4.3370 I
       I***********************************************   0.940            I**                        0.026
4.4583 I                                                            4.4583 I
       I************************************************* 0.972            I**                        0.024
4.5796 I                                                            4.5796 I
       I************************************************* 0.988            I*                         0.016
4.7009 I                                                            4.7009 I
       I**************************************************0.994            I                          0.006
4.8222 I                                                            4.8222 I
       I**************************************************0.998            I                          0.004
4.9435 I                                                            4.9435 I
       I**************************************************1.000            I                          0.002
5.0648 I                                                            5.0648 I
       I**************************************************1.000            I                          0.000
5.0648 I----I----I----I----I----I----I----I----I----I----I MAX      5.0648 I----I----I----I----I----I MAX

          NO OBS------------     500   STD ERROR-       0.4647
          COEF OF VARIATION-    0.13   MEAN------       3.6384
          KURTOSIS (BETA 2)-    2.70   MEDIAN----       3.6050
          PEARSONIAN SKEW---    0.42   MODE------       3.4413
```

```
NETWORK TIME FOR NODE HOTWT

   CFD    0.1  0.2  0.3  0.4  0.5  0.6  0.7  0.8  0.9  1.0           RFD   0.05 0.10 0.15 0.20 0.25
0.0069 I----I----I----I----I----I----I----I----I----I----I MIN    0.0069 I----I----I----I----I----I MIN
       I                                                  0.000          I                         0.000
0.0069 I                                                          0.0069 I
       I*****                                             0.094          I*********                0.094
0.0149 I                                                          0.0149 I
       I*************                                     0.258          I****************         0.164
0.0229 I                                                          0.0229 I
       I*******************                               0.382          I************             0.124
0.0309 I                                                          0.0309 I
       I*********************                             0.410          I**                       0.028
0.0390 I                                                          0.0390 I
       I*********************                             0.412          I                         0.002
0.0470 I                                                          0.0470 I
       I*********************                             0.412          I                         0.000
0.0550 I                                                          0.0550 I
       I*********************                             0.426          I*                        0.014
0.0630 I                                                          0.0630 I
       I***********************                           0.456          I***                      0.030
0.0710 I                                                          0.0710 I
       I**************************                        0.514          I*****                    0.058
0.0791 I                                                          0.0791 I
       I******************************                    0.590          I*******                  0.076
0.0871 I                                                          0.0871 I
       I********************************                  0.646          I*****                    0.056
0.0951 I                                                          0.0951 I
       I*************************************             0.738          I*********                0.092
0.1031 I                                                          0.1031 I
       I****************************************          0.796          I*****                    0.058
0.1111 I                                                          0.1111 I
       I*******************************************       0.864          I******                   0.068
0.1192 I                                                          0.1192 I
       I**********************************************    0.912          I****                     0.048
0.1272 I                                                          0.1272 I
       I***********************************************   0.940          I**                       0.028
0.1352 I                                                          0.1352 I
       I************************************************  0.966          I**                       0.026
0.1432 I                                                          0.1432 I
       I************************************************* 0.980          I*                        0.014
0.1512 I                                                          0.1512 I
       I************************************************* 0.986          I                         0.006
0.1593 I                                                          0.1593 I
       I**************************************************0.994          I                         0.008
0.1673 I                                                          0.1673 I
       I**************************************************0.996          I                         0.002
0.1753 I                                                          0.1753 I
       I**************************************************1.000          I                         0.004
0.1833 I                                                          0.1833 I
       I**************************************************1.000          I                         0.000
0.1833 I----I----I----I----I----I----I----I----I----I----I MAX    0.1833 I----I----I----I----I----I MAX

       NO OBS-----------        500  STD ERROR-          0.0446
       COEF OF VARIATION       0.65  MEAN-------         0.0687
       KURTOSIS (BETA 2)-      1.73  MEDIAN-----         0.0776
       PEARSONIAN SKEW---      1.09  MODE ------         0.0200
```

```
PATH COST FOR NODE HOTWT

       CFD 0.1  0.2  0.3  0.4  0.5  0.6  0.7  0.8  0.9  1.0              RFD  0.05 0.10 0.15 0.20 0.25
0.4142 I----I----I----I----I----I----I----I----I----I----I MIN    0.4142 I----I----I----I----I----I MIN
       I                                                  0.000          I                            0.000
0.4142 I                                                          0.4142 I
       I*                                                 0.022          I**                          0.022
0.5860 I                                                          0.5860 I
       I****                                              0.080          I*****                       0.058
0.7577 I                                                          0.7577 I
       I******                                            0.116          I***                         0.036
0.9294 I                                                          0.9294 I
       I********                                          0.150          I***                         0.034
1.1012 I                                                          1.1012 I
       I*********                                         0.186          I***                         0.036
1.2729 I                                                          1.2729 I
       I**************                                    0.284          I*********                   0.098
1.4446 I                                                          1.4446 I
       I******************                                0.350          I******                      0.066
1.6164 I                                                          1.6164 I
       I********************                              0.392          I****                        0.042
1.7881 I                                                          1.7881 I
       I********************                              0.404          I*                           0.012
1.9599 I                                                          1.9599 I
       I*********************                             0.414          I*                           0.010
2.1316 I                                                          2.1316 I
       I*********************                             0.422          I                            0.008
2.3033 I                                                          2.3033 I
       I***********************                           0.458          I***                         0.036
2.4751 I                                                          2.4751 I
       I**************************                        0.516          I*****                       0.058
2.6468 I                                                          2.6468 I
       I*****************************                     0.586          I*******                     0.070
2.8186 I                                                          2.8186 I
       I**********************************                0.680          I*********                   0.094
2.9903 I                                                          2.9903 I
       I**************************************            0.758          I*******                     0.070
3.1620 I                                                          3.1620 I
       I*******************************************       0.854          I*********                   0.096
3.3338 I                                                          3.3338 I
       I**********************************************    0.922          I******                      0.068
3.5055 I                                                          3.5055 I
       I************************************************  0.964          I****                        0.042
3.6772 I                                                          3.6772 I
       I************************************************* 0.980          I*                           0.016
3.8490 I                                                          3.8490 I
       I**************************************************0.990          I*                           0.010
4.0207 I                                                          4.0207 I
       I**************************************************1.000          I*                           0.010
4.1925 I                                                          4.1925 I
       I**************************************************1.000          I                            0.000
4.1925 I----I----I----I----I----I----I----I----I----I----I MAX    4.1925 I----I----I----I----I----I MAX

        NO OBS-------------      500  STD ERROR-           0.9918
        COEF OF VARIATION-      0.43  MEAN-------          2.2986
        KURTOSIS (BETA 2)-      1.71  MEDIAN----           2.6049
        PEARSONIAN SKEW---      0.92  MODE------           1.3862
                                                           ------
```

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```
PATH PERFORMANCE FOR MODE HOTWT

   CFD  0.1  0.2  0.3  0.4  0.5  0.6  0.7  0.8  0.9  1.0                RFD  0.05 0.10 0.15 0.20 0.25
0.0032 I----I----I----I----I----I----I----I----I----I----I MIN    0.0032 I----I----I----I----I----I MIN
       I                                                  0.000          I                         0.000
0.0032 I                                                          0.0032 I
       I*******************                               0.370          I*************************0.370
0.0353 I                                                          0.0353 I
       I*********************                             0.412          I****                     0.042
0.0674 I                                                          0.0674 I
       I*********************                             0.412          I                         0.000
0.0995 I                                                          0.0995 I
       I*********************                             0.412          I                         0.000
0.1316 I                                                          0.1316 I
       I*********************                             0.412          I                         0.000
0.1637 I                                                          0.1637 I
       I*********************                             0.412          I                         0.000
0.1958 I                                                          0.1958 I
       I*********************                             0.412          I                         0.000
0.2279 I                                                          0.2279 I
       I*********************                             0.412          I                         0.000
0.2600 I                                                          0.2600 I
       I*********************                             0.412          I                         0.000
0.2921 I                                                          0.2921 I
       I*********************                             0.412          I                         0.000
0.3242 I                                                          0.3242 I
       I*********************                             0.412          I                         0.000
0.3563 I                                                          0.3563 I
       I*********************                             0.412          I                         0.000
0.3884 I                                                          0.3884 I
       I*********************                             0.418          I                         0.006
0.4205 I                                                          0.4205 I
       I**********************                            0.432          I*                        0.014
0.4526 I                                                          0.4526 I
       I***********************                           0.468          I***                      0.036
0.4847 I                                                          0.4847 I
       I**************************                        0.526          I*****                    0.058
0.5168 I                                                          0.5168 I
       I*****************************                     0.586          I******                   0.060
0.5489 I                                                          0.5489 I
       I**********************************                0.678          I*********                0.092
0.5810 I                                                          0.5810 I
       I***************************************           0.788          I***********              0.110
0.6131 I                                                          0.6131 I
       I********************************************      0.876          I********                 0.088
0.6452 I                                                          0.6452 I
       I************************************************  0.952          I*******                  0.076
0.6773 I                                                          0.6773 I
       I**************************************************1.000          I****                     0.048
0.7094 I                                                          0.7094 I
       I**************************************************1.000          I                         0.000
0.7094 I----I----I----I----I----I----I----I----I----I----I MAX    0.7094 I----I----I----I----I----I MAX

       NO OBS-----------      500  STD ERROR-    -        0.2809
       COEF OF VARIATION-    0.00  MEAN------             0.3522
       KURTOSIS (BETA 2)-    1.17  MEDIAN----             0.5034
       PEARSONIAN SKEW  -    1.18  MODE------             0.0202
```

```
NETWORK TIME FOR NODE HEATING

       CFD  0.1  0.2  0.3  0.4  0.5  0.6  0.7  0.8  0.9  1.0             RFD  0.05 0.10 0.15 0.20 0.25
0.0000 I----I----I----I----I----I----I----I----I----I----I MIN    0.0000 I----I----I----I----I----I MIN
       I                                                  0.000          I                          0.000
0.0000 I                                                          0.0000 I
       I*                                                 0.022          I**                        0.022
0.1229 I                                                          0.1229 I
       I****                                              0.080          I*****                     0.058
0.2459 I                                                          0.2459 I
       I******************                                0.354          I**************************0.274
0.3688 I                                                          0.3688 I
       I***********************                           0.466          I***********               0.112
0.4917 I                                                          0.4917 I
       I*************************                         0.506          I****                      0.040
0.6146 I                                                          0.6146 I
       I***************************                       0.538          I***                       0.032
0.7376 I                                                          0.7376 I
       I*****************************                     0.570          I***                       0.032
0.8605 I                                                          0.8605 I
       I******************************                    0.608          I***                       0.038
0.9834 I                                                          0.9834 I
       I*********************************                 0.650          I****                      0.042
1.1064 I                                                          1.1064 I
       I************************************              0.710          I******                    0.060
1.2293 I                                                          1.2293 I
       I***************************************           0.770          I******                    0.060
1.3522 I                                                          1.3522 I
       I******************************************        0.834          I*****                     0.056
1.4751 I                                                          1.4751 I
       I*********************************************     0.898          I******                    0.054
1.5981 I                                                          1.5981 I
       I***********************************************   0.930          I***                       0.032
1.7210 I                                                          1.7210 I
       I***********************************************   0.938          I                          0.008
1.8439 I                                                          1.8439 I
       I***********************************************   0.940          I                          0.002
1.9669 I                                                          1.9669 I
       I***********************************************   0.940          I                          0.000
2.0698 I                                                          2.0898 I
       I***********************************************   0.942          I                          0.002
2.2127 I                                                          2.2127 I
       I************************************************  0.950          I                          0.008
2.3357 I                                                          2.3357 I
       I************************************************* 0.970          I**                        0.020
2.4586 I                                                          2.4586 I
       I************************************************* 0.986          I*                         0.016
2.5015 I                                                          2.5815 I
       I**************************************************1.000          I*                         0.014
2.7044 I                                                          2.7044 I
       I**************************************************1.000          I                          0.000
2.7044 I----I----I----I----I----I----I----I----I----I----I MAX    2.7044 I----I----I----I----I----I MAX

           NO OBS-------------      500  STD ERROR-          0.6370
           COEF OF VARIATION-      0.76  MEAN------          0.8425
           KURTOSIS (BETA 2)-      3.21  MEDIAN----          0.5967
           PEARSONIAN SKEW---      0.83  MODE------          0.3161
```

```
PATH COST FOR NODE HEATING

      CFD    0.1  0.2  0.3  0.4  0.5  0.6  0.7  0.8  0.9  1.0              RFD   0.05 0.10 0.15 0.20 0.25
  7.8282 I----I----I----I----I----I----I----I----I----I----I MIN       7.8282 I----I----I----I----I----I MIN
         I                                                  0.000             I                         0.000
  7.8282 I                                                             7.8282 I
         I                                                  0.008             I                         0.008
 12.8408 I                                                            12.8408 I
         I****                                              0.074             I******                   0.066
 17.8533 I                                                            17.8533 I
         I****************                                  0.328             I*************************0.254
 22.8658 I                                                            22.8658 I
         I**************************                        0.528             I********************     0.200
 27.8784 I                                                            27.8784 I
         I*************************************             0.748             I**********************   0.220
 32.8909 I                                                            32.8909 I
         I****************************************          0.794             I****                     0.046
 37.9035 I                                                            37.9035 I
         I****************************************          0.800             I                         0.006
 42.9160 I                                                            42.9160 I
         I****************************************          0.802             I                         0.002
 47.9286 I                                                            47.9286 I
         I****************************************          0.802             I                         0.000
 52.9411 I                                                            52.9411 I
         I*******************************************       0.854             I*****                    0.052
 57.9536 I                                                            57.9536 I
         I*******************************************       0.854             I                         0.000
 62.9662 I                                                            62.9662 I
         I*******************************************       0.854             I                         0.000
 67.9787 I                                                            67.9787 I
         I********************************************      0.876             I**                       0.022
 72.9913 I                                                            72.9913 I
         I********************************************      0.878             I                         0.002
 78.0038 I                                                            78.0038 I
         I********************************************      0.884             I                         0.006
 83.0163 I                                                            83.0163 I
         I*********************************************     0.902             I*                        0.018
 88.0289 I                                                            88.0289 I
         I***********************************************   0.934             I***                      0.032
 93.0414 I                                                            93.0414 I
         I************************************************  0.954             I**                       0.020
 98.0540 I                                                            98.0540 I
         I************************************************  0.970             I*                        0.016
103.0665 I                                                           103.0665 I
         I************************************************* 0.974             I                         0.004
108.0791 I                                                           108.0791 I
         I************************************************* 0.974             I                         0.000
113.0916 I                                                           113.0916 I
         I**************************************************1.000             I**                       0.026
118.1041 I                                                           118.1041 I
         I**************************************************1.000             I                         0.000
110.1041 I----I----I----I----I----I----I----I----I----I----I MAX     118.1041 I----I----I----I----I----I MAX

          NO OBS-----------     500  STD ERROR-          25.5386
          COEF OF VARIATION-   0.70  MEAN------          36.3823
          KURTOSIS (BETA 2)-   5.06  MEDIAN----          27.1012
          PEARSONIAN SKEW---   0.57  MODE------          21.7473
```

```
PATH PERFORMANCE FOR NODE HEATING

          CFD  0.1  0.2  0.3  0.4  0.5  0.6  0.7  0.8  0.9  1.0                RFD  0.05 0.10 0.15 0.20 0.25
0.0000 I----I----I----I----I----I----I----I----I----I----I MIN        0.0000 I----I----I----I----I----I MIN
       I                                                   0.000             I                         0.000
0.0000 I                                                              0.0000 I
       I*********************************************      0.898             I*************************0.898
0.3413 I                                                              0.3413 I
       I*********************************************      0.908             I*                        0.010
0.6827 I                                                              0.6827 I
       I*********************************************      0.908             I                         0.000
1.0240 I                                                              1.0240 I
       I*********************************************      0.908             I                         0.000
1.3653 I                                                              1.3653 I
       I*********************************************      0.908             I                         0.000
1.7067 I                                                              1.7067 I
       I************************************************   0.966             I*****                    0.058
2.0480 I                                                              2.0480 I
       I************************************************   0.966             I                         0.000
2.3893 I                                                              2.3893 I
       I************************************************   0.966             I                         0.000
2.7307 I                                                              2.7307 I
       I************************************************   0.966             I                         0.000
3.0720 I                                                              3.0720 I
       I************************************************   0.966             I                         0.000
3.4133 I                                                              3.4133 I
       I************************************************   0.966             I                         0.000
3.7547 I                                                              3.7547 I
       I************************************************   0.966             I                         0.000
4.0960 I                                                              4.0960 I
       I************************************************   0.966             I                         0.000
4.4373 I                                                              4.4373 I
       I************************************************   0.966             I                         0.000
4.7786 I                                                              4.7786 I
       I************************************************   0.966             I                         0.000
5.1200 I                                                              5.1200 I
       I************************************************   0.966             I                         0.000
5.4613 I                                                              5.4613 I
       I************************************************   0.966             I                         0.000
5.8026 I                                                              5.8026 I
       I************************************************   0.966             I                         0.000
6.1440 I                                                              6.1440 I
       I************************************************   0.966             I                         0.000
6.4853 I                                                              6.4853 I
       I************************************************   0.966             I                         0.000
6.8266 I                                                              6.8266 I
       I************************************************   0.966             I                         0.000
7.1680 I                                                              7.1680 I
       I**************************************************1.000             I***                      0.034
7.5093 I                                                              7.5093 I
       I**************************************************1.000             I                         0.000
7.5093 I----I----I----I----I----I----I----I----I----I----I MAX        7.5093 I----I----I----I----I----I MAX

         NO OBS-------------      500  STD ERROR-       1.3856
         COEF OF VARIATION-      3.05  MEAN------       0.4540
         KURTOSIS (BETA 2)-     22.95  MEDIAN----       0.0831
         PEARSONIAN SKEW---      0.20  MODE------       0.1716
```

```
NETWORK TIME FOR NODE VENTN

          CFD  0.1  0.2  0.3  0.4  0.5  0.6  0.7  0.8  0.9  1.0                RFD  0.05 0.10 0.15 0.20 0.25
0.0000 I----I----I----I----I----I----I----I----I----I----I MIN      0.0000 I----I----I----I----I----I MIN
       I                                                  0.000            I                         0.000
0.0000 I                                                            0.0000 I
       I*************************                         0.504            I*************************0.504
0.0337 I                                                            0.0337 I
       I******************************                    0.600            I*********                0.096
0.0675 I                                                            0.0675 I
       I******************************                    0.600            I                         0.000
0.1012 I                                                            0.1012 I
       I******************************                    0.600            I                         0.000
0.1349 I                                                            0.1349 I
       I******************************                    0.600            I                         0.000
0.1686 I                                                            0.1686 I
       I******************************                    0.600            I                         0.000
0.2024 I                                                            0.2024 I
       I******************************                    0.600            I                         0.000
0.2361 I                                                            0.2361 I
       I******************************                    0.600            I                         0.000
0.2698 I                                                            0.2698 I
       I******************************                    0.600            I                         0.000
0.3035 I                                                            0.3035 I
       I******************************                    0.602            I                         0.002
0.3373 I                                                            0.3373 I
       I********************************                  0.650            I****                     0.048
0.3710 I                                                            0.3710 I
       I**********************************                0.688            I***                      0.038
0.4047 I                                                            0.4047 I
       I*************************************             0.740            I*****                    0.052
0.4384 I                                                            0.4384 I
       I***************************************           0.790            I*****                    0.050
0.4722 I                                                            0.4722 I
       I******************************************        0.842            I*****                    0.052
0.5059 I                                                            0.5059 I
       I********************************************      0.872            I***                      0.030
0.5396 I                                                            0.5396 I
       I*********************************************     0.896            I**                       0.024
0.5733 I                                                            0.5733 I
       I**********************************************    0.922            I**                       0.026
0.6071 I                                                            0.6071 I
       I***********************************************   0.938            I*                        0.016
0.6408 I                                                            0.6408 I
       I************************************************  0.960            I**                       0.022
0.6745 I                                                            0.6745 I
       I************************************************* 0.982            I**                       0.022
0.7082 I                                                            0.7082 I
       I**************************************************1.000            I*                        0.010
0.7420 I                                                            0.7420 I
       I**************************************************1.000            I                         0.000
0.7420 I----I----I----I----I----I----I----I----I----I----I MAX      0.7420 I----I----I----I----I----I MAX

       NO OBS------------      500  STD ERROR-          0.2511
       COEF OF VARIATION-     1.23  MEAN------          0.2034
       KURTOSIS (BETA 2)-     1.74  MEDIAN----          0.0000
       PEARSONIAN SKEW  -     0.71  MODE------          0.0106
```

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```
PATH COST FOR NODE VENTN

          CFD  0.1  0.2  0.3  0.4  0.5  0.6  0.7  0.8  0.9  1.0               RFD  0.05 0.10 0.15 0.20 0.25
  0.0000 I----I----I----I----I----I----I----I----I----I----I MIN       0.0000 I----I----I----I----I----I MIN
         I                                                  0.000             I                         0.000
  0.0000 I                                                           0.0000 I
         I*************************                         0.504             I*************************0.504
  4.3288 I                                                           4.3288 I
         I*************************                         0.504             I                         0.000
  8.6576 I                                                           8.6576 I
         I*************************                         0.504             I                         0.000
 12.9864 I                                                          12.9864 I
         I****************************                      0.550             I****                     0.046
 17.3152 I                                                          17.3152 I
         I******************************                    0.600             I*****                    0.050
 21.6440 I                                                          21.6440 I
         I******************************                    0.600             I                         0.000
 25.9728 I                                                          25.9728 I
         I******************************                    0.600             I                         0.000
 30.3016 I                                                          30.3016 I
         I******************************                    0.600             I                         0.000
 34.6304 I                                                          34.6304 I
         I******************************                    0.604             I                         0.004
 38.9592 I                                                          38.9592 I
         I********************************                  0.640             I***                      0.036
 43.2881 I                                                          43.2881 I
         I***********************************               0.692             I*****                    0.052
 47.6169 I                                                          47.6169 I
         I**************************************            0.762             I*******                  0.070
 51.9457 I                                                          51.9457 I
         I****************************************          0.796             I***                      0.034
 56.2745 I                                                          56.2745 I
         I*****************************************         0.810             I*                        0.014
 60.6033 I                                                          60.6033 I
         I******************************************        0.848             I***                      0.038
 64.9321 I                                                          64.9321 I
         I********************************************      0.872             I**                       0.024
 69.2609 I                                                          69.2609 I
         I**********************************************    0.926             I*****                    0.054
 73.5897 I                                                          73.5897 I
         I************************************************  0.954             I**                       0.028
 77.9185 I                                                          77.9185 I
         I************************************************* 0.978             I**                       0.024
 82.2473 I                                                          82.2473 I
         I************************************************* 0.988             I*                        0.010
 86.5761 I                                                          86.5761 I
         I**************************************************0.996             I                         0.008
 90.9049 I                                                          90.9049 I
         I**************************************************1.000             I                         0.004
 95.2337 I                                                          95.2337 I
         I**************************************************1.000             I                         0.000
 95.2337 I----I----I----I----I----I----I----I----I----I----I MAX      95.2337 I----I----I----I----I----I MAX

          NO OBS--------------     500  STD ERROR-           29.7574
          COEF OF VARIATION-      1.16  MEAN-------          25.6189
          KURTOSIS (BETA 2)-      1.70  MEDIAN ---            0.0000
          PEARSONIAN SKEW---      0.79  MODE------            2.1644
```

```
PATH PERFORMANCE FOR MODE VENTN

    CFD    0.1  0.2  0.3  0.4  0.5  0.6  0.7  0.8  0.9  1.0                  RFD  0.05 0.10 0.15 0.20 0.25
0.0000 I----I----I----I----I----I----I----I----I----I----I MIN        0.0000 I----I----I----I----I----I MIN
       I                                                  0.000               I                         0.000
0.0000 I                                                                0.0000 I
       I*************************                         0.504               I*************************0.504
0.3559 I                                                                0.3559 I
       I*************************                         0.504               I                         0.000
0.7118 I                                                                0.7118 I
       I*************************                         0.504               I                         0.000
1.0678 I                                                                1.0678 I
       I******************************                    0.600               I*********                0.096
1.4237 I                                                                1.4237 I
       I******************************                    0.600               I                         0.000
1.7796 I                                                                1.7796 I
       I******************************                    0.600               I                         0.000
2.1355 I                                                                2.1355 I
       I******************************                    0.600               I                         0.000
2.4914 I                                                                2.4914 I
       I******************************                    0.600               I                         0.000
2.8473 I                                                                2.8473 I
       I******************************                    0.600               I                         0.000
3.2033 I                                                                3.2033 I
       I******************************                    0.600               I                         0.000
3.5592 I                                                                3.5592 I
       I******************************                    0.600               I                         0.000
3.9151 I                                                                3.9151 I
       I******************************************        0.846               I************************ 0.246
4.2710 I                                                                4.2710 I
       I******************************************        0.846               I                         0.000
4.6269 I                                                                4.6269 I
       I******************************************        0.846               I                         0.000
4.9828 I                                                                4.9828 I
       I******************************************        0.846               I                         0.000
5.3388 I                                                                5.3388 I
       I******************************************        0.846               I                         0.000
5.6947 I                                                                5.6947 I
       I******************************************        0.846               I                         0.000
6.0506 I                                                                6.0506 I
       I******************************************        0.846               I                         0.000
6.4065 I                                                                6.4065 I
       I******************************************        0.846               I                         0.000
6.7624 I                                                                6.7624 I
       I******************************************        0.846               I                         0.000
7.1184 I                                                                7.1184 I
       I******************************************        0.846               I                         0.000
7.4743 I                                                                7.4743 I
       I**************************************************1.000               I***************          0.154
7.8302 I                                                                7.8302 I
       I**************************************************1.000               I                         0.000
7.8302 I----I----I----I----I----I----I----I----I----I----I MAX        7.8302 I----I----I----I----I----I MAX

        NO OBS ----------     500  STD ERROR-          2.8912
        COEF OF VARIATION-   1.23  MEAN------          2.3486
        KURTOSIS (BETA 2)-   2.25  MEDIAN----          0.0000
        PEARSONIAN SKEW --   0.75  MODE------          0.1780
```

```
PATH COST FOR NODE FIRE

        CFD 0.1  0.2  0.3  0.4  0.5  0.6  0.7  0.8  0.9  1.0
 0.6666 I----I----I----I----I----I----I----I----I----I----I MIN
        I                                                   0.000
 0.6666 I
        I**                                                 0.042
 1.7793 I
        I*******                                            0.138
 2.8920 I
        I***************                                    0.306
 4.0046 I
        I**************************                         0.518
 5.1173 I
        I***********************************                0.704
 6.2299 I
        I****************************************           0.808
 7.3426 I
        I******************************************         0.842
 8.4552 I
        I*******************************************        0.852
 9.5679 I
        I*******************************************        0.854
10.6805 I
        I*******************************************        0.856
11.7932 I
        I*******************************************        0.856
12.9058 I
        I*******************************************        0.858
14.0185 I
        I********************************************       0.884
15.1311 I
        I**********************************************     0.912
16.2438 I
        I**********************************************     0.926
17.3564 I
        I***********************************************    0.944
18.4691 I
        I************************************************   0.958
19.5817 I
        I*************************************************  0.972
20.6944 I
        I************************************************** 0.990
21.8070 I
        I**************************************************0.992
22.9197 I
        I**************************************************0.996
24.0323 I
        I**************************************************1.000
25.1450 I
        I**************************************************1.000
25.1450 I----I----I----I----I----I----I----I----I----I----I MAX

        NO OBS-------------      500  STD ERROR-          5.0014
        COEF OF VARIATION-      0.77  MEAN------          6.5054
        KURTOSIS (BETA 2)-      5.45  MEDIAN----          5.0093
        PEARSONIAN SKEW---      0.36  MODE------          4.7040
```

```
        RFD  0.05 0.10 0.15 0.20 0.25
 0.6666 I----I----I----I----I----I MIN
        I                          0.000
 0.6666 I
        I****                      0.042
 1.7793 I
        I*********                 0.096
 2.8920 I
        I****************          0.168
 4.0046 I
        I*********************     0.212
 5.1173 I
        I******************        0.186
 6.2299 I
        I**********                0.104
 7.3426 I
        I***                       0.034
 8.4552 I
        I*                         0.010
 9.5679 I
        I                          0.002
10.6805 I
        I                          0.002
11.7932 I
        I                          0.000
12.9058 I
        I*                         0.012
14.0185 I
        I*                         0.016
15.1311 I
        I**                        0.028
16.2438 I
        I*                         0.014
17.3564 I
        I*                         0.018
18.4691 I
        I**                        0.024
19.5817 I
        I                          0.004
20.6944 I
        I*                         0.018
21.8070 I
        I                          0.002
22.9197 I
        I                          0.004
24.0323 I
        I                          0.004
25.1450 I
        I                          0.000
25.1450 I----I----I----I----I----I MAX
```

```
PATH PERFORMANCE FOR NODE FIRE

       CFD 0.1  0.2  0.3  0.4  0.5  0.6  0.7  0.8  0.9  1.0          RFD 0.05 0.10 0.15 0.20 0.25
0.0012 I----I----I----I----I----I----I----I----I----I----I MIN   0.0012 I----I----I----I----I----I MIN
       I                                                  0.000          I                          0.000
0.0012 I                                                        0.0012 I
       I*                                                 0.026          I**                        0.026
0.0026 I                                                        0.0026 I
       I****                                              0.074          I****                      0.048
0.0040 I                                                        0.0040 I
       I*******                                           0.138          I******                    0.064
0.0054 I                                                        0.0054 I
       I**********                                        0.196          I*****                     0.058
0.0068 I                                                        0.0068 I
       I***********                                       0.228          I***                       0.032
0.0082 I                                                        0.0082 I
       I************                                      0.246          I*                         0.018
0.0096 I                                                        0.0096 I
       I**************                                    0.288          I****                      0.042
0.0110 I                                                        0.0110 I
       I*****************                                 0.340          I*****                     0.052
0.0125 I                                                        0.0125 I
       I********************                              0.400          I******                    0.060
0.0139 I                                                        0.0139 I
       I***********************                           0.462          I******                    0.064
0.0153 I                                                        0.0153 I
       I**************************                        0.526          I******                    0.064
0.0167 I                                                        0.0167 I
       I******************************                    0.590          I******                    0.064
0.0181 I                                                        0.0181 I
       I*********************************                 0.650          I******                    0.060
0.0195 I                                                        0.0195 I
       I************************************              0.722          I*******                   0.072
0.0209 I                                                        0.0209 I
       I***************************************           0.770          I****                      0.048
0.0223 I                                                        0.0223 I
       I******************************************        0.834          I******                    0.064
0.0238 I                                                        0.0238 I
       I*********************************************     0.908          I*******                   0.074
0.0252 I                                                        0.0252 I
       I************************************************  0.952          I****                      0.044
0.0266 I                                                        0.0266 I
       I************************************************* 0.982          I***                       0.030
0.0280 I                                                        0.0280 I
       I**************************************************0.992          I*                         0.010
0.0294 I                                                        0.0294 I
       I**************************************************0.998          I                          0.006
0.0308 I                                                        0.0308 I
       I**************************************************1.000          I                          0.002
0.0322 I                                                        0.0322 I
       I**************************************************1.000          I                          0.000
0.0322 I----I----I----I----I----I----I----I----I----I----I MAX   0.0322 I   -I---- I ----I---- I ----I MAX

        NO OBS-------------        500  STD ERROR-          0.0075
        COEF OF VARIATION-        0.40  MEAN------          0.0155
        KURTOSIS (BETA 2)-        1.93  MEDIAN----          0.0161
        PEARSONIAN SKEW           1.15  MODE------          0.0241
```

PATH COST FOR NODE LIFTS

```
      CFD  0.1  0.2  0.3  0.4  0.5  0.6  0.7  0.8  0.9  1.0               RFD  0.05 0.10 0.15 0.20 0.25
 0.0000 I----I----I----I----I----I----I----I----I----I----I MIN      0.0000 I----I----I----I----I----I MIN
        I                                                  0.000            I                         0.000
 0.0000 I                                                            0.0000 I
        I***************                                   0.306            I*************************0.306
 1.4585 I                                                            1.4585 I
        I***************                                   0.306            I                         0.000
 2.9170 I                                                            2.9170 I
        I***************                                   0.306            I                         0.000
 4.3755 I                                                            4.3755 I
        I***************                                   0.306            I                         0.000
 5.8340 I                                                            5.8340 I
        I***************                                   0.306            I                         0.000
 7.2925 I                                                            7.2925 I
        I***************                                   0.306            I                         0.000
 8.7510 I                                                            8.7510 I
        I***************                                   0.306            I                         0.000
10.2095 I                                                           10.2095 I
        I****************                                  0.314            I                         0.008
11.6680 I                                                           11.6680 I
        I*****************                                 0.338            I**                       0.024
13.1265 I                                                           13.1265 I
        I*******************                               0.378            I****                     0.040
14.5850 I                                                           14.5850 I
        I**********************                            0.450            I*******                  0.072
16.0436 I                                                           16.0436 I
        I***************************                       0.536            I********                 0.086
17.5021 I                                                           17.5021 I
        I*******************************                   0.616            I********                 0.080
18.9606 I                                                           18.9606 I
        I***********************************               0.702            I********                 0.086
20.4191 I                                                           20.4191 I
        I***************************************           0.770            I******                   0.068
21.8776 I                                                           21.8776 I
        I*****************************************         0.814            I****                     0.044
23.3361 I                                                           23.3361 I
        I********************************************      0.884            I*******                  0.070
24.7946 I                                                           24.7946 I
        I**********************************************    0.928            I****                     0.044
26.2531 I                                                           26.2531 I
        I************************************************  0.960            I***                      0.032
27.7116 I                                                           27.7116 I
        I************************************************* 0.982            I**                       0.022
29.1701 I                                                           29.1701 I
        I**************************************************0.994            I*                        0.012
30.6286 I                                                           30.6286 I
        I**************************************************1.000            I                         0.006
32.0871 I                                                           32.0871 I
        I**************************************************1.000            I                         0.000
32.0871 I----I----I----I----I----I----I----I----I----I----I MAX     32.0871 I----I----I----I----I----I MAX

         NO OBS--------------     500  STD ERROR-          9.9947
         COEF OF VARIATION-      0.72  MEAN -----         13.9374
         KURTOSIS (BETA 2)-      1.70  MEDIAN----         17.0340
         PEARSONIAN SKEW --      1.52  MODE -----          0.7293
```

PATH PERFORMANCE FOR NODE LIFTS

```
       CFD  0.1  0.2  0.3  0.4  0.5  0.6  0.7  0.8  0.9  1.0                RFD  0.05 0.10 0.15 0.20 0.25
0.0000 I----I----I----I----I----I----I----I----I----I----I MIN        0.0000 I----I----I----I----I----I MIN
       I                                                  0.000              I                           0.000
0.0000 I                                                              0.0000 I
       I***************                                   0.306              I***************************0.306
0.0001 I                                                              0.0001 I
       I***************                                   0.306              I                           0.000
0.0001 I                                                              0.0001 I
       I***************                                   0.306              I                           0.000
0.0002 I                                                              0.0002 I
       I***************                                   0.306              I                           0.000
0.0002 I                                                              0.0002 I
       I***************                                   0.306              I                           0.000
0.0003 I                                                              0.0003 I
       I***************                                   0.306              I                           0.000
0.0003 I                                                              0.0003 I
       I****************                                  0.310              I                           0.004
0.0004 I                                                              0.0004 I
       I****************                                  0.325              I*                          0.015
0.0004 I                                                              0.0004 I
       I******************                                0.358              I***                        0.032
0.0005 I                                                              0.0005 I
       I*********************                             0.410              I*****                      0.052
0.0005 I                                                              0.0005 I
       I***********************                           0.460              I*****                      0.050
0.0006 I                                                              0.0006 I
       I***************************                       0.542              I********                   0.082
0.0006 I                                                              0.0006 I
       I*******************************                   0.614              I*******                    0.072
0.0007 I                                                              0.0007 I
       I************************************              0.714              I**********                 0.100
0.0007 I                                                              0.0007 I
       I****************************************          0.796              I********                   0.082
0.0008 I                                                              0.0008 I
       I*******************************************       0.858              I******                     0.052
0.0008 I                                                              0.0008 I
       I*********************************************     0.904              I****                       0.046
0.0009 I                                                              0.0009 I
       I***********************************************   0.946              I****                       0.042
0.0009 I                                                              0.0009 I
       I************************************************* 0.976              I***                        0.030
0.0010 I                                                              0.0010 I
       I**************************************************0.992              I*                          0.016
0.0010 I                                                              0.0010 I
       I**************************************************0.998              I                           0.006
0.0011 I                                                              0.0011 I
       I**************************************************1.000              I                           0.002
0.0011 I                                                              0.0011 I
       I**************************************************1.000              I                           0.000
0.0011 I----I----I----I----I----I----I----I----I----I----I MAX        0.0011 I----I----I----I----I----I MAX

           NO OBS------------     500   STD ERROR-          0.0003
           COEF OF VARIATION-    0.72   MEAN------          0.0005
           KURTOSIS (BETA 2)-    1.67   MEDIAN----          0.0005
           PEARSONIAN SKEW --    1.32   MODE------          0.0006
```

```
NETWORK TIME FOR NODE ELECTRIC

    CFD    0.1  0.2  0.3  0.4  0.5  0.6  0.7  0.8  0.9  1.0             RFD   0.05 0.10 0.15 0.20 0.25
0.2023 I----I----I----I----I----I----I----I----I----I----I MIN      0.2023 I----I----I----I----I----I MIN
       I                                                  0.000            I                          0.000
0.2023 I                                                            0.2023 I
       I                                                  0.006            I                          0.006
0.2072 I                                                            0.2072 I
       I*                                                 0.022            I*                         0.016
0.2122 I                                                            0.2122 I
       I***                                               0.066            I****                      0.044
0.2171 I                                                            0.2171 I
       I*******                                           0.140            I*******                   0.074
0.2221 I                                                            0.2221 I
       I************                                      0.234            I*********                 0.094
0.2270 I                                                            0.2270 I
       I****************                                  0.322            I********                  0.088
0.2319 I                                                            0.2319 I
       I*******************                               0.388            I******                    0.066
0.2369 I                                                            0.2369 I
       I**********************                            0.436            I****                      0.048
0.2418 I                                                            0.2418 I
       I************************                          0.476            I****                      0.040
0.2468 I                                                            0.2468 I
       I**************************                        0.510            I***                       0.034
0.2517 I                                                            0.2517 I
       I****************************                      0.568            I*****                     0.058
0.2567 I                                                            0.2567 I
       I*******************************                   0.614            I****                      0.046
0.2616 I                                                            0.2616 I
       I********************************                  0.646            I***                       0.032
0.2666 I                                                            0.2665 I
       I***********************************               0.694            I****                      0.048
0.2715 I                                                            0.2715 I
       I**************************************            0.754            I******                    0.060
0.2764 I                                                            0.2764 I
       I***************************************           0.784            I***                       0.030
0.2814 I                                                            0.2814 I
       I*****************************************         0.826            I****                      0.042
0.2863 I                                                            0.2863 I
       I******************************************        0.848            I**                        0.022
0.2913 I                                                            0.2913 I
       I*********************************************     0.892            I****                      0.044
0.2962 I                                                            0.2962 I
       I**********************************************    0.918            I**                        0.026
0.3012 I                                                            0.3012 I
       I************************************************* 0.970            I*****                     0.052
0.3061 I                                                            0.3061 I
       I**************************************************1.000            I***                       0.030
0.3111 I                                                            0.3111 I
       I**************************************************1.000            I                          0.000
0.3111 I----I----I----I----I----I----I----I----I----I----I MAX      0.3111 I----I----I----I----I----I MAX

        NO OBS-------------      500   STD ERROR-            0.0290
        COEF OF VARIATION-      0.11   MEAN-------           0.2536
        KURTOSIS (BETA 2)-      1.07   MEDIAN----            0.2510
        PEARSONIAN SKEW---      0.96   MODE------            0.2259
```

```
PATH COST FOR NODE ELECTRIC

          CFD  0.1  0.2  0.3  0.4  0.5  0.6  0.7  0.8  0.9  1.0
17.9459 I----I----I----I----I----I----I----I----I----I----I MIN
        I                                                  0.000
17.9459 I
        I                                                  0.004
19.2242 I
        I*                                                 0.010
20.5025 I
        I*                                                 0.022
21.7809 I
        I**                                                0.044
23.0592 I
        I***                                               0.068
24.3375 I
        I******                                            0.124
25.6158 I
        I********                                          0.168
26.8941 I
        I************                                      0.244
28.1724 I
        I*****************                                 0.340
29.4508 I
        I**********************                            0.446
30.7291 I
        I**************************                        0.516
32.0074 I
        I******************************                    0.594
33.2857 I
        I***********************************               0.696
34.5640 I
        I***************************************           0.780
35.8423 I
        I*******************************************       0.856
37.1207 I
        I*********************************************     0.904
38.3990 I
        I***********************************************   0.942
39.6773 I
        I************************************************  0.968
40.9556 I
        I************************************************* 0.982
42.2339 I
        I**************************************************0.990
43.5122 I
        I**************************************************0.994
44.7906 I
        I**************************************************1.000
46.0689 I
        I**************************************************1.000
46.0689 I----I----I----I----I----I----I----I----I----I----I MAX

         NO OBS-------------     500  STD ERROR-      5.0922
         COEF OF VARIATION-     0.16  MEAN------     31.7884
         KURTOSIS (BETA 2)-     2.71  MEDIAN---      31.6255
         PEARSONIAN SKEW --     0.40  MODE -----     29.7287
```

```
          RFD  0.05 0.10 0.15 0.20 0.25
17.9459 I----I----I----I----I----I MIN
        I                        0.000
17.9459 I
        I                        0.004
19.2242 I
        I                        0.006
20.5025 I
        I*                       0.012
21.7809 I
        I**                      0.022
23.0592 I
        I**                      0.024
24.3375 I
        I*****                   0.056
25.6158 I
        I****                    0.044
26.8941 I
        I*******                 0.076
28.1724 I
        I*********               0.096
29.4508 I
        I**********              0.106
30.7291 I
        I*******                 0.070
32.0074 I
        I*******                 0.078
33.2857 I
        I**********              0.102
34.5640 I
        I********                0.084
35.8423 I
        I*******                 0.076
37.1207 I
        I****                    0.040
38.3990 I
        I***                     0.030
39.6773 I
        I**                      0.026
40.9556 I
        I*                       0.014
42.2339 I
        I                        0.008
43.5122 I
        I                        0.004
44.7906 I
        I                        0.006
46.0689 I
        I                        0.000
46.0689 I----I----I----I----I----I MAX
```

```
PATH PERFORMANCE FOR NODE ELECTRIC

       CFD  0.1  0.2  0.3  0.4  0.5  0.6  0.7  0.8  0.9  1.0             RFD  0.05 0.10 0.15 0.20 0.25
0.4866 I----I----I----I----I----I----I----I----I----I----I MIN    0.4866 I----I----I----I----I----I MIN
       I                                                  0.000          I                           0.000
0.4866 I                                                          0.4866 I
       I                                                  0.004          I                           0.004
0.4891 I                                                          0.4891 I
       I*                                                 0.024          I**                         0.020
0.4917 I                                                          0.4917 I
       I***                                               0.052          I**                         0.028
0.4942 I                                                          0.4942 I
       I****                                              0.082          I***                        0.030
0.4967 I                                                          0.4967 I
       I*******                                           0.136          I*****                      0.054
0.4993 I                                                          0.4993 I
       I*********                                         0.172          I***                        0.036
0.5018 I                                                          0.5018 I
       I***********                                       0.228          I*****                      0.056
0.5043 I                                                          0.5043 I
       I**************                                    0.272          I****                       0.044
0.5068 I                                                          0.5068 I
       I*****************                                 0.330          I*****                      0.050
0.5094 I                                                          0.5094 I
       I********************                              0.396          I******                     0.066
0.5119 I                                                          0.5119 I
       I************************                          0.470          I*******                    0.074
0.5144 I                                                          0.5144 I
       I**************************                        0.526          I*****                      0.056
0.5170 I                                                          0.5170 I
       I*****************************                     0.588          I******                     0.062
0.5195 I                                                          0.5195 I
       I*********************************                 0.654          I******                     0.066
0.5220 I                                                          0.5220 I
       I*************************************             0.740          I********                   0.086
0.5246 I                                                          0.5246 I
       I******************************************        0.830          I*********                  0.090
0.5271 I                                                          0.5271 I
       I*********************************************     0.902          I*******                    0.072
0.5296 I                                                          0.5296 I
       I************************************************  0.956          I*****                      0.054
0.5321 I                                                          0.5321 I
       I************************************************* 0.974          I*                          0.018
0.5347 I                                                          0.5347 I
       I************************************************* 0.980          I                           0.006
0.5372 I                                                          0.5372 I
       I************************************************* 0.988          I                           0.000
0.5397 I                                                          0.5397 I
       I**************************************************1.000          I*                          0.012
0.5423 I                                                          0.5423 I
       I**************************************************1.000          I                           0.000
0.5423 I----I----I----I----I----I----I----I----I----I----I MAX    0.5423 I----I----I----I----I----I MAX

       NO OBS-------------     500  STD ERROR-            0.0121
       COEF OF VARIATION-     0.02  MEAN-------           0.5149
       KURTOSIS (BETA 2)-     2.19  MEDIAN----            0.5159
       PEARSONIAN SKEW ---    0.83  MODE------            0.5250
```

NETWORK TIME FOR NODE SUCCESS

```
       CFD  0.1  0.2  0.3  0.4  0.5  0.6  0.7  0.8  0.9  1.0               RFD  0.05 0.10 0.15 0.20 0.25
0.2248 I----I----I----I----I----I----I----I----I----I----I MIN      0.2248 I----I----I----I----I----I MIN
       I                                                  0.000            I                           0.000
0.2248 I                                                            0.2248 I
       I*********                                         0.172            I*****************          0.172
0.3375 I                                                            0.3375 I
       I****************                                  0.328            I***************            0.156
0.4502 I                                                            0.4502 I
       I*********************                             0.424            I*********                  0.096
0.5630 I                                                            0.5630 I
       I*************************                         0.506            I********                   0.082
0.6757 I                                                            0.6757 I
       I***************************                       0.548            I****                       0.042
0.7884 I                                                            0.7884 I
       I*****************************                     0.580            I***                        0.032
0.9011 I                                                            0.9011 I
       I*******************************                   0.614            I***                        0.034
1.0138 I                                                            1.0138 I
       I*********************************                 0.654            I****                       0.040
1.1265 I                                                            1.1265 I
       I************************************              0.722            I******                     0.060
1.2392 I                                                            1.2392 I
       I***************************************           0.778            I*****                      0.056
1.3519 I                                                            1.3519 I
       I*****************************************         0.828            I*****                      0.050
1.4646 I                                                            1.4646 I
       I*********************************************     0.894            I******                     0.066
1.5773 I                                                            1.5773 I
       I**********************************************    0.924            I***                        0.030
1.6901 I                                                            1.6901 I
       I***********************************************   0.938            I*                          0.014
1.8028 I                                                            1.8028 I
       I***********************************************   0.940            I                           0.002
1.9155 I                                                            1.9155 I
       I***********************************************   0.940            I                           0.000
2.0282 I                                                            2.0282 I
       I***********************************************   0.942            I                           0.002
2.1409 I                                                            2.1409 I
       I***********************************************   0.944            I                           0.002
2.2536 I                                                            2.2536 I
       I************************************************  0.958            I*                          0.014
2.3663 I                                                            2.3663 I
       I************************************************* 0.972            I*                          0.014
2.4790 I                                                            2.4790 I
       I************************************************* 0.988            I*                          0.016
2.5917 I                                                            2.5917 I
       I**************************************************1.000            I*                          0.012
2.7044 I                                                            2.7044 I
       I**************************************************1.000            I                           0.000
2.7044 I----I----I----I----I----I----I----I----I----I----I MAX      2.7044 I----I----I----I----I----I MAX

        NO OBS-------------      500  STD ERROR-           0.5907
        COEF OF VARIATION-      0.67  MEAN------           0.8902
        KURTOSIS (BETA 2)-      3.53  MEDIAN----           0.6651
        PEARSONIAN SKEW---      0.94  MODE------           0.3279
```

PATH COST FOR NODE SUCCESS

```
       CFD   0.1  0.2  0.3  0.4  0.5  0.6  0.7  0.8  0.9  1.0              RFD 0.05 0.10 0.15 0.20 0.25
 51.3816 I----I----I----I----I----I----I----I----I----I----I MIN     51.3816 I----I----I----I----I----I MIN
         I                                                  0.000            I                          0.000
 51.3816 I                                                           51.3816 I
         I*                                                 0.010            I*                         0.010
 61.1258 I                                                           61.1258 I
         I**                                                0.046            I***                       0.036
 70.8700 I                                                           70.8700 I
         I*******                                           0.140            I*********                 0.094
 80.6142 I                                                           80.6142 I
         I*************                                     0.250            I***********               0.110
 90.3584 I                                                           90.3584 I
         I*******************                               0.382            I*************             0.132
100.1026 I                                                          100.1026 I
         I************************                          0.486            I**********                0.104
109.8468 I                                                          109.8468 I
         I***************************                       0.534            I****                      0.048
119.5911 I                                                          119.5911 I
         I*****************************                     0.578            I****                      0.044
129.3353 I                                                          129.3353 I
         I*********************************                 0.656            I*******                   0.078
139.0795 I                                                          139.0795 I
         I*************************************             0.734            I*******                   0.078
148.8237 I                                                          148.8237 I
         I****************************************          0.804            I*******                   0.070
158.5679 I                                                          158.5679 I
         I********************************************      0.870            I******                    0.066
168.3121 I                                                          168.3121 I
         I*********************************************     0.902            I***                       0.032
178.0563 I                                                          178.0563 I
         I***********************************************   0.930            I**                        0.028
187.8005 I                                                          187.8005 I
         I***********************************************   0.946            I*                         0.016
197.5447 I                                                          197.5447 I
         I************************************************  0.952            I                          0.006
207.2889 I                                                          207.2889 I
         I************************************************  0.968            I*                         0.016
217.0331 I                                                          217.0331 I
         I************************************************* 0.982            I*                         0.014
226.7773 I                                                          226.7773 I
         I**************************************************0.992            I*                         0.010
236.5215 I                                                          236.5215 I
         I**************************************************0.994            I                          0.002
246.2657 I                                                          246.2657 I
         I**************************************************0.998            I                          0.004
256.0099 I                                                          256.0099 I
         I**************************************************1.000            I                          0.002
265.7541 I                                                          265.7541 I
         I**************************************************1.000            I                          0.000
265.7541 I----I----I----I----I----I----I----I----I----I----I MAX    265.7541 I----I----I----I----I----I MAX

          NO OBS-------------      500  STD ERROR-              40.0992
          COEF OF VARIATION-      0.33  MEAN -----             123.0900
          KURTOSIS (BETA 2)       3.00  MEDIAN----             112.0860
          PEARSONIAN SKEW         0.70  MODE------              94.6459
```

OVERALL COST FOR NODE SUCCESS

```
     CFD  0.1  0.2  0.3  0.4  0.5  0.6  0.7  0.8  0.9  1.0              RFD  0.05 0.10 0.15 0.20 0.25
 51.3816 I----I----I----I----I----I----I----I----I----I----I MIN       51.3816 I----I----I----I----I----I MIN
         I                                                  0.000              I                          0.000
 51.3816 I                                                             51.3816 I
         I*                                                 0.010              I*                         0.010
 61.1258 I                                                             61.1258 I
         I**                                                0.046              I***                       0.036
 70.8700 I                                                             70.8700 I
         I*******                                           0.140              I*********                 0.094
 80.6142 I                                                             80.6142 I
         I*************                                     0.250              I***********               0.110
 90.3584 I                                                             90.3584 I
         I*******************                               0.382              I*************             0.132
100.1026 I                                                            100.1026 I
         I************************                          0.486              I**********                0.104
109.8468 I                                                            109.8468 I
         I***************************                       0.534              I****                      0.048
119.5910 I                                                            119.5910 I
         I*****************************                     0.578              I****                      0.044
129.3352 I                                                            129.3352 I
         I*********************************                 0.656              I*******                   0.078
139.0794 I                                                            139.0794 I
         I*************************************             0.734              I*******                   0.078
148.8236 I                                                            148.8236 I
         I****************************************          0.804              I*******                   0.070
158.5678 I                                                            158.5678 I
         I********************************************      0.870              I******                    0.066
168.3120 I                                                            168.3120 I
         I*********************************************     0.902              I***                       0.032
178.0562 I                                                            178.0562 I
         I***********************************************   0.930              I**                        0.028
187.8004 I                                                            187.8004 I
         I***********************************************   0.946              I*                         0.016
197.5446 I                                                            197.5446 I
         I************************************************  0.952              I                          0.006
207.2888 I                                                            207.2888 I
         I************************************************  0.968              I*                         0.016
217.0330 I                                                            217.0330 I
         I************************************************* 0.982              I*                         0.014
226.7772 I                                                            226.7772 I
         I**************************************************0.992              I*                         0.010
236.5214 I                                                            236.5214 I
         I**************************************************0.994              I                          0.002
246.2656 I                                                            246.2656 I
         I**************************************************0.998              I                          0.004
256.0099 I                                                            256.0099 I
         I**************************************************1.000              I                          0.002
265.7541 I                                                            265.7541 I
         I**************************************************1.000              I                          0.000
265.7541 I----I----I----I----I----I----I----I----I----I----I MAX      265.7541 I----I----I----I----I----I MAX

         NO OBS--------------     500  STD ERROR-          40.8992
         COEF OF VARIATION-      0.33  MEAN------         123.0900
         KURTOSIS (BETA 2)-      3.08  MEDIAN----         112.0030
         PEARSONIAN SKEW --      0.70  MODE- ----          94.6459
```

```
PATH PERFORMANCE FOR NODE SUCCESS

          CFD  0.1  0.2  0.3  0.4  0.5  0.6  0.7  0.8  0.9 , 1.0
 3.4019 I----I----I----I----I----I----I----I----I----I----I MIN
        I                                                  0.000
 3.4019 I
        I*****                                             0.090
 4.1782 I
        I*****************                                 0.346
 4.9546 I
        I*************************                         0.490
 5.7310 I
        I****************************                      0.556
 6.5073 I
        I*****************************                     0.574
 7.2837 I
        I******************************                    0.596
 8.0601 I
        I***********************************               0.698
 8.8365 I
        I****************************************          0.792
 9.6128 I
        I*****************************************         0.814
10.3892 I
        I*****************************************         0.818
11.1656 I
        I*******************************************       0.852
11.9419 I
        I**********************************************    0.924
12.7183 I
        I************************************************  0.964
13.4947 I
        I************************************************* 0.982
14.2710 I
        I************************************************* 0.988
15.0474 I
        I**************************************************0.990
15.8238 I
        I**************************************************0.992
16.6002 I
        I**************************************************0.992
17.3765 I
        I**************************************************0.992
18.1529 I
        I**************************************************0.992
18.9293 I
        I**************************************************0.996
19.7056 I
        I**************************************************1.000
20.4820 I
        I**************************************************1.000
20.4820 I----I----I----I----I----I----I----I----I----I----I MAX

        NO OBS-------------      500  STD ERROR-            3.2901
        COEF OF VARIATION-      0.45  MEAN------     .      7.3397
        KURTOSIS (BETA 2)-      3.47  MEDIAN----            5.8398
        PEARSONIAN SKEW---      0.82  MODE------     .      4.6418
```

```
        RFD  0.05 0.10 0.15 0.20 0.25
 3.4019 I----I----I----I----I----I MIN
        I                         0.000
 3.4019 I
        I*********                0.070
 4.1782 I
        I*************************0.255
 4.9546 I
        I**************           0.144
 5.7310 I
        I******                   0.066
 6.5073 I
        I*                        0.018
 7.2837 I
        I**                       0.022
 8.0601 I
        I**********               0.102
 8.8365 I
        I*********                0.094
 9.6128 I
        I**                       0.022
10.3892 I
        I                         0.004
11.1656 I
        I***                      0.034
11.9419 I
        I*******                  0.072
12.7183 I
        I****                     0.040
13.4947 I
        I*                        0.018
14.2710 I
        I                         0.006
15.0474 I
        I                         0.002
15.8238 I
        I                         0.002
16.6002 I
        I                         0.000
17.3765 I
        I                         0.000
18.1529 I
        I                         0.000
18.9293 I
        I                         0.004
19.7056 I
        I                         0.004
20.4820 I
        I                         0.000
20.4820 I----I    -I----I----I----I MAX
```

```
NODES CRITICAL PATH INDEX - NO. PATHS =  500
                   0.1  0.2  0.3  0.4  0.5  0.6  0.7  0.8  0.9  1.0
                I----+----+----+----+----+----+----+----+----+----+I
ELEMENT4  0.2820 I**************
                I    +    +    +    +    +    +    +    +    +    +I
FAN/DIS   0.0040 I                                                  I
                I    +    +    +    +    +    +    +    +    +    +I
PER/DIS   0.0400 I**                                                I
                I    +    +    +    +    +    +    +    +    +    +I
RAD/DIS   0.0360 I**                                                I
                I    +    +    +    +    +    +    +    +    +    +I
DFF/DIS   0.0180 I*                                                 I
                I    +    +    +    +    +    +    +    +    +    +I
AHU/DIS   0.0300 I**                                                I
                I    +    +    +    +    +    +    +    +    +    +I
VAV/DIS   0.0260 I*                                                 I
                I    +    +    +    +    +    +    +    +    +    +I
VER/DIS   0.0580 I***                                               I
                I    +    +    +    +    +    +    +    +    +    +I
DAP/DIS   0.0400 I**                                                I
                I    +    +    +    +    +    +    +    +    +    +I
DVP/DIS   0.0100 I*                                                 I
                I    +    +    +    +    +    +    +    +    +    +I
HEATING   0.2820 I**************                                    I
                I    +    +    +    +    +    +    +    +    +    +I
ELEMENT5  0.3240 I****************                                  I
                I    +    +    +    +    +    +    +    +    +    +I
EXT/TER   0.1120 I******                                            I
                I    +    +    +    +    +    +    +    +    +    +I
SX/TER    0.2120 I***********                                       I
                I    +    +    +    +    +    +    +    +    +    +I
VENTN     0.3240 I****************                                  I
                I    +    +    +    +    +    +    +    +    +    +I
ELEMENT7  0.0060 I                                                  I
                I    +    +    +    +    +    +    +    +    +    +I
ELT/EEL   0.0060 I                                                  I
                I    +    +    +    +    +    +    +    +    +    +I
LIFTS     0.0060 I                                                  I
                I    +    +    +    +    +    +    +    +    +    +I
ELEMENT8  0.3880 I*******************                               I
                I    +    +    +    +    +    +    +    +    +    +I
ELC/LTG   0.3880 I*******************                               I
                I    +    +    +    +    +    +    +    +    +    +I
LTG/SPT   0.3880 I*******************                               I
                I    +    +    +    +    +    +    +    +    +    +I
SPT/GPO   0.3880 I*******************                               I
                I    +    +    +    +    +    +    +    +    +    +I
GPO/LTN   0.3880 I*******************                               I
                I    +    +    +    +    +    +    +    +    +    +I
ELECTRIC  0.3880 I*******************                               I
                I    +    +    +    +    +    +    +    +    +    +I
SUCCESS   1.0000 I**************************************************I
                I----+----+----+----+----+----+----+----+----+----+I
                   0.1  0.2  0.3  0.4  0.5  0.6  0.7  0.8  0.9  1.0
```

```
ARCS CRITICAL PATH INDEX - NO. PATHS = 500
                         0.1   0.2   0.3   0.4   0.5   0.6   0.7   0.8   0.9   1.0
                   I-----------------------------------------------------------I
FANCONV   0.0040   I
                   I     +     +     +     +     +     +     +     +     +     +I
PERCONV   0.0400   I**
                   I     +     +     +     +     +     +     +     +     +     +I
RADS      0.0360   I**
                   I     +     +     +     +     +     +     +     +     +     +I
OPERFAN   0.0180   I*
                   I     +     +     +     +     +     +     +     +     +     +I
CAHU      0.0300   I**
                   I     +     +     +     +     +     +     +     +     +     +I
VAV       0.0260   I*
                   I     +     +     +     +     +     +     +     +     +     +I
VERSA     0.0580   I***
                   I     +     +     +     +     +     +     +     +     +     +I
FANCOIL   0.0200   I*
                   I     +     +     +     +     +     +     +     +     +     +I
OVAVPER   0.0400   I**
                   I     +     +     +     +     +     +     +     +     +     +I
OVERSPER  0.0100   I*
                   I     +     +     +     +     +     +     +     +     +     +I
PWKFAN    0.0040   I
                   I     +     +     +     +     +     +     +     +     +     +I
HTSPER    0.0460   I**
                   I     +     +     +     +     +     +     +     +     +     +I
PWKRAD    0.0360   I**
                   I     +     +     +     +     +     +     +     +     +     +I
HTSOPF    0.0180   I*
                   I     +     +     +     +     +     +     +     +     +     +I
OWKAHU    0.0300   I**
                   I     +     +     +     +     +     +     +     +     +     +I
OWKVAV    0.0260   I*
                   I     +     +     +     +     +     +     +     +     +     +I
OWKVER    0.0080   I
                   I     +     +     +     +     +     +     +     +     +     +I
PWKVER    0.0320   I**
                   I     +     +     +     +     +     +     +     +     +     +I
HTSVER    0.0180   I*
                   I     +     +     +     +     +     +     +     +     +     +I
OWKDVAV   0.0360   I**
                   I     +     +     +     +     +     +     +     +     +     +I
HTSDVAV   0.0040   I
                   I     +     +     +     +     +     +     +     +     +     +I
OWKDVER   0.0100   I*
                   I     +     +     +     +     +     +     +     +     +     +I
E4        0.2820   I**************
                   I     +     +     +     +     +     +     +     +     +     +I
EXTRACT   0.1120   I******
                   I     +     +     +     +     +     +     +     +     +     +I
SUPEXT    0.2120   I***********
                   I     +     +     +     +     +     +     +     +     +     +I
EXOWK     0.1120   I******
                   I     +     +     +     +     +     +     +     +     +     +I
SXOWK     0.2120   I***********
                   I     +     +     +     +     +     +     +     +     +     +I
E5        0.3240   I****************
                   I     +     +     +     +     +     +     +     +     +     +I
ELIFT     0.0060   I                                                           I
                   I     +     +     +     +     +     +     +     +     +     +I
ELFTELC   0.0060   I                                                           I
                   I     +     +     +     +     +     +     +     +     +     +I


E7        0.0060   I                                                           I
                   I     +     +     +     +     +     +     +     +     +     +I
EMAINS    0.0300   I**                                                         I
                   I     +     +     +     +     +     +     +     +     +     +I
ETRUNK    0.1660   I********                                                   I
                   I     +     +     +     +     +     +     +     +     +     +I
POWER     0.1920   I**********
                   I     +     +     +     +     +     +     +     +     +     +I
600LUX    0.1420   I*******
                   I     +     +     +     +     +     +     +     +     +     +I
500LUX    0.2100   I***********
                   I     +     +     +     +     +     +     +     +     +     +I
300LUX    0.0360   I**
                   I     +     +     +     +     +     +     +     +     +     +I
SPOT      0.0960   I*****
                   I     +     +     +     +     +     +     +     +     +     +I
NSPOT     0.2920   I***************
                   I     +     +     +     +     +     +     +     +     +     +I
GPO       0.3220   I****************
                   I     +     +     +     +     +     +     +     +     +     +I
NGPO      0.0660   I***
                   I     +     +     +     +     +     +     +     +     +     +I
LTNG      0.1520   I********
                   I     +     +     +     +     +     +     +     +     +     +I
NLTNG     0.2380   I************
                   I     +     +     +     +     +     +     +     +     +     +I
E8        0.3880   I*******************
                   I-----------------------------------------------------------I
                         0.1   0.2   0.3   0.4   0.5   0.6   0.7   0.8   0.9   1.0


     LAST RANDOM NUMBER SEED =    1337608300
```

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