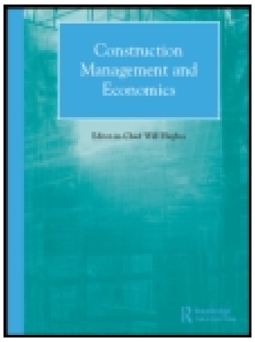

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Simulation applied to construction projects

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The paper describes the uncertain environment in which construction activity occurs, and in particular the variability in productivity and the occurrence of external interferences. The paper then describes a suite of computer programs known as the Construction Project Simulator (CPS) whose features include: a hierarchy of linked bar charts, 'preliminaries schedule', weather data, direct costs, and resources for costing and/or resource restraint. The results of an actual project are presented to demonstrate the type and range of output available, including duration and cost predictions and cash flow curves. The results of four varied construction projects subjected to simulation are presented, with the results demonstrating an improvement in accuracy over the common deterministic estimating procedures of the UK construction industry.

Keywords: Uncertainty, risk, simulation, interference, variability

Introduction

This paper describes the results of a research project supported by the UK Science and Engineering Research Council under the Specially Promoted Programme in Construction Management. The research project culminated in the development of a suite of computer programs for a common business micro-computer known as the *Construction Project Simulator* (CPS). The suite of programs is based upon the theoretical and practical hypothesis that much of construction activity is dominated by the uncertain environment in which it takes place. This general uncertainty is subdivided into two specific elements, namely, productivity variability and external interferences to the construction process on site. Data describing a particular project – bar charts, direct and indirect costs, resources, weather, productivity data – is input and fed to a series of stochastic simulation programs which produce cost and time predictions for the project. The data input is designed to be simple and suitable for computer illiterates.

The simulator was validated against four actual construction projects, drawn from typical market sectors in the UK building market, and the results of one are used to illustrate the type and style of the output available. The results of all the case studies are presented and the simulator is shown to provide better predictions than normal methods.

The construction problem

A construction project presents a unique problem to those involved in managing the construction process. Each project is different from all others, and must be carried out at a

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different location each time. The project must be formulated and executed by integrating the efforts of a large number of different organizations and individuals, all of whom have different and often conflicting priorities and objectives (Feiler, 1972). The manager of the process must consider and assess different technologies and alternative combinations of labour and equipment. While the manager knows what must be done he has considerable latitude in how it is to be executed. Furthermore, he must consider the effects of imponderables such as weather, material shortages, labour problems, unknown subsurface conditions, and inaccurate estimates of duration and cost. All these considerations combine to form a complex, dynamic problem (Riggs, 1979).

The construction manager must assess this dynamic problem in the context of future events and performance. Estimates and predictions must be made which attempt to forecast the future. Inevitably the forecasted value will deviate from the actual outcome, due to a lack of complete information about future events.

Another major effect common in construction projects is that the initial definition of the project is changed in scope due to modifications in the basic plan to incorporate changes. Quite often it is these unknown factors which create surprises for the client who commissions the construction project (Traylor *et al.*, 1978).

All managers face a certain amount of unknown possibilities, which can affect the process they are attempting to control. However, the construction manager is likely to have to confront and resolve problems of a type and magnitude not found in other industries. Every manager engaged in construction, at whatever level, encounters these problems in the course of every working day. The problems are readily identifiable and are accepted in the industry at large – a few typical examples are listed below (Lichtenberg, 1981).

the actions of external agencies (e.g. government)
unknown or unassessed elements of the work to be performed
errors and omissions in working drawings
delays in obtaining management approvals
the effects of the weather on construction operations
late delivery of purchased material and equipment
unknown results of testing and commissioning complex services systems
unknown rates of inflation
variable performance work rates
mechanical breakdown or malfunction of equipment
rejection of poor quality work and re-work

All these factors and the complexity of the construction problem have long been recognized. This recognition led to the establishment of the Project Management discipline and the adoption in recent years of computerized, critical-path-network-based systems to provide assistance in planning, budgeting, scheduling and controlling projects. Yet, the availability of such sophisticated management tools and the establishment of a construction management profession has not generally provided the hoped-for improvement in project performance. Total project cost and time overruns are still commonly reported and clearly the use of sophisticated management techniques has not eliminated project estimating or performance problems. In view of this track record the client, who must use the facility provided by the construction process, has become increasingly critical of the ability of construction managers and has come to view the industry with mistrust – as highlighted by the recent British Property Federation proposals (British Property Federation, 1983).

A major reason for this perception has been the many changes forced on projects by the external, uncontrollable forces described before. However, this perception has been unwittingly nurtured by the tendency to characterize projects by single-value measures – single cost, single duration – which give illusions of certainty. The economist, Ken Boulding, has said, 'an important source of bad decisions are illusions of certainty'. It is clear that uncertainty is endemic in construction and needs to be explicitly recognized by construction managers.

Simulation

As well as an awareness of uncertainty a manager requires a management tool to use in quantifying and assessing the impact this uncertainty may have on the project. The manager must be aware of the effects uncertainty may have so that he may make a rational decision as to what level of risk to accept in the light of the circumstances at the time. A management tool incorporating uncertainty will not make decision-making easier, but it will present more and better information, than currently available, on which to base a decision and therefore arguably improve the possibility of a good decision.

The technique which is employed to form a management tool in an uncertain environment, to augment the decision maker's intuition and experience, is *simulation*. Simulation is also referred to as the Monte Carlo technique – due to the gambling aspect of the process – or a stochastic technique – due to the presence of random processes. Stochastic simulation typically generates durations and costs for each activity in a plan by randomly calculating a feasible value for each from a statistical probability frequency distribution – which represents the range and pattern of possible outcomes for an activity. To ensure that the chosen values are representative of the pattern of possible outcomes, a large number of repetitive deterministic calculations – known as iterations – are made. The result is typically presented as a cumulative distribution plot and a frequency histogram.

Due to the repetitiveness of the process and the handling of large amounts of numerical information it has only been feasible to implement this technique since the advent of computers. The current practices of industry, in using single-value, deterministic methods are a legacy from the era before computing liberated people from laborious calculations. Also it allows a deeper investigation of problems – such as construction – which do not have a single-value solution that can be represented by a set formula, nor operate in a totally random environment which can be represented by statistics, but has a limited random component (i.e. stochastic) which can be investigated most effectively through simulation.

It has been claimed that the introduction of simulation methods for construction management is likely to have as great an impact on the construction industry as did the introduction of network planning and scheduling methods some two decades ago (Nunnally, 1981). Some of the advantages claimed for the technique are summarized below.

1. The major advantage is that the results of such a simulation, given the validity of input assumptions, provide an unbiased estimate of the project completion distribution. This is

particularly important in the light of evidence of inherent bias in deterministic network techniques.

2. Simulation provides an almost unlimited capacity to model construction operations, and they permit the construction manager to quickly evaluate many different combinations of equipment and methods under varying conditions of operation at moderate cost.

3. Simulation can give the manager an insight into which factors are important – and hence where to concentrate his effort – and how they interact.

4. Simulation allows the user to experiment with different strategies without the risk of disturbing the real project and incurring costs. Also simulation enables one to study dynamic systems in much less time than is needed to study the actual system.

5. Additionally if a person can interact with the computer simulation in a gaming environment, experience can be gained under realistic conditions before the work is started. This should lead to better management through a deeper knowledge of the problem.

6. Finally, and most importantly, simulation models often predict things which are not specifically incorporated into the model. Simulation of repetitive processes has shown that when uncertainty exists there are large penalties rather than benefits of scale. There is some evidence that in the construction industry it is the larger projects which go wrong most frequently. Also, most work-study experts talk about the benefits of specialization. Simulation shows that for large projects subject to uncertainty there are penalties of specialization. Further, most models of construction processes assume that the cost of a project is the sum of the costs of the activities. Simulations of repetitive processes show that costs are largely generated by the uncertainties that exist, and that simple additive models like the Bill of Quantities seriously under-estimate cost. Finally, the traditional approach to construction would expect financial benefit to accrue from productivity increases and would direct effort towards increasing the speed of production. Simulations incorporating uncertainty direct attention towards obtaining benefits from reductions in interferences. The benefits to be gained by these reductions in interference can be shown to be very much larger in magnitude than gains made possible by productivity increases (Fine, 1982).

The only disadvantage of simulation techniques is that they are time-consuming and expensive in computer time, due to the requirement to perform many iterations of the same calculation. This has been true in the past when the only computers with the required capacity were large main-frame computers with high operating costs. Presently, however, due to the pace of technological development relatively cheap micro-computers with sufficient capacity are readily available. The objection that the process is time-consuming is also overcome by allowing a fully automatic operation and carrying out the processing at times when the micro-computer would not normally be used (i.e. at lunchtime or at night). Looking into the near future, if even some of the promises of the 'fifth generation' computers are realized then even these drawbacks will be nullified.

The use of computer simulations for construction applications is a recent development dating from the early 1970s. However, in this time nearly 30 different simulation models have been developed. All have their inherent strengths and weaknesses and they were reviewed during the course of the research. The objective in developing a new computer program was to overcome many of the shortcomings of previous techniques. Specifically the CPS includes processes to model the two components of uncertainty: variability and interference, it operates on a relatively cheap, easily available microcomputer, it has an increased capacity over earlier models in being able to accommodate more facilities such as more activities, costs, weather, resources and preliminaries in one package; and above all it is a model which is simple to operate, being designed for use in industry by managers who are not computer literate.

Uncertainty

The many contributing factors to the construction problem – some of which are outlined above – are referred to collectively as *uncertainty*. An underlying hypothesis is that this global uncertainty can be subdivided into two major components, namely, *variability* in the performance of a task, and *interference* from outside the task which frustrates its progress. This categorization is supported by evidence from the direct observation of the construction process and by evidence from other construction academics (Bishop, 1966; Crandall, 1977; Woolery and Crandall, 1983).

When making decisions managers cannot be certain of good outcomes, because they cannot completely control external events or have total foresight. However, management can try to increase the probability of good outcomes by taking into account all the major factors. In particular where there is uncertainty as to which events might occur, the logic of the decision process should include that information.

There is a basic need to be able to quantify and assess the impact that uncertainty can have on a project, and to incorporate this knowledge in the project brief and the management of the project. This expanded awareness of the project gives executive management and the client a more complete view of the project and a basis for decision making. It provides a much higher quality of information on which to base a decision, and allows an assessment of both uncertainty and risk while incorporating the manager's own value judgement into the decision. The inclusion of uncertainty further supports the efforts of management in concentrating on the essential elements of the project. If construction project prediction and performance are to be improved, uncertainty and its sources must be dealt with seriously and specifically. Not as a final rudimentary 'contingency item' (whether explicit or not), but detailed systematically as an integrated part of the management process (Lichtenberg, 1981).

Variability

Introduction and definition

The use in the simulator model of variability as a component of uncertainty is based on the factual observation of the construction process, as the following discussion will illustrate. However, neglect of this variable is still proposed by texts of 'classical' network analysis, with such statements as 'only an occasional construction project will have variances in activity durations' (Harris, 1982). While observation of construction operations leads to the conclusion that it is pervasive and very large (Hall and Stevens, 1982). The importance of its inclusion in any realistic model of construction is illustrated by the fact that when only one activity was allowed to be variable (by $\pm 45\%$) in an otherwise deterministic 28 activity network, the result was an increase in project duration of three days from the deterministic result of 76 days ($+3.9\%$) (Feiler, 1976).

Variability can be defined as the range and frequency distribution of possible durations in the execution of a particular task.

This arises as performances are subject to wide variation since in any given discipline there is a wide range of capabilities. Different skill levels, degrees of motivation and fatigue, and other behavioural factors will affect worker performance and produce the normal variations found in practice. In addition, certain construction tasks are inherently uncertain due to the nature of the material, e.g. excavation with variable ground conditions or the refurbishment of boiler linings (Feiler, 1972). Also in practice an appreciable and uncertain amount of repeat work is carried out due to poor workmanship or design, and substandard materials.

It is important to realize that the variability referred to here is specific to a particular task. Thus in gathering data on variability it is necessary to compare like with like. The quantity and quality of work carried out, and the method of execution should be identical or at least very similar. Thus, comparing the data for the input to two- and three-storey houses with different areas is misleading; while it is proper to compare the variability for the same task for each of these projects. Similarly it would be misleading to compare the same task using different methods of execution, e.g. with placing concrete by tower crane or by hand and barrow. The degree of variability for the same task with different quantities may well be of the same magnitude, but the density function will be about a different mean. The objection to different quantities of work could be overcome by expressing the duration for a unit of work, e.g. square metres of half-brick walling. One further step which would aid the standardization of data and the ease with which data from different sources could be amalgamated, would be to express the data in a unit of time which reflects the resource input. The best measure would be man hours, as this would not require a knowledge of gang sizes. The shape and range of a distribution would be the same whatever units were used, but the adoption of man hours would allow the production of distributions where the data is drawn from more than one source. This will have the effect of increasing the size of the data sample and hence the reliability of the distribution.

It is also important to consider only the effort expended in completing the task at the workplace and not to account for any time when the activity was suspended through inclement weather, lack of information, etc. There is considerable evidence that, in building work typically, many separate visits are needed to complete a task (McLeish, 1981, Roderick, 1977); and so it is important to only account for the time actually spent on the task. The data used should include the following: all work done, setting out and checking, preparation, handling materials, and nonproductive time at the workplace.

Learning and experience effects

It is also worth briefly discussing learning curves, as their effect is often assumed to affect variability. A learning effect is observable while an unfamiliar task is mastered, and an experience effect is present through the gradual improvement of experience gained while repeating the familiar task. The categories are not mutually exclusive and the effects overlap.

The learning effect is apparent in the building industry and studies of site operations note the improvement in productivity during the first few repetitions of a task (Clapp, 1965, McLeish, 1981). Once the task is mastered a further improvement is observable for the same gang under controlled conditions. However, although this effect is theoretically possible it is not common as a number of factors relevant to the construction process negate its effect.

Firstly, in building, the nature of the product imposes certain limits on the learning effect, as the workers and not the product have to be moved from one area to another (Relf, 1974). Also the unfavourable influence of interruptions to work render the problems of coordination and continuity of work more difficult to solve in construction than in other production work (United Nations, 1965). Continuity of work is essential, as any interruption to the process dramatically reduces any improvement. This is illustrated in Fig. 1. From actual observation of construction operations it is apparent that interruptions, for whatever reason, are frequent (Bishop, 1966, McLeish, 1981, Roderick, 1977). Interruptions are mostly caused by external influences and can completely neutralize any advantage gained through repetition (United Nations, 1965).

The series of repetitions in the construction cycle must be large enough to sustain the experience effect (United Nations, 1965). Also the operations carried out have to be identical, as even small differences can seriously affect improvements (United Nations, 1965). Further, any experience effect is lost when members of the gang change. Changing gang members is the rule rather than the exception in construction where the labour turnover is high.

In practice the combined effect of all those factors usually results in a severe limitation of the learning effect. Improvements are seen on the first few repetitions of a project, but there is much evidence to show that due to adverse pressures continuing improvement is not carried through the rest of the work (McLeish, 1981). However, where circumstances are better controlled or more favourable then the learning effect can be experienced throughout the project (United Nations, 1965). Even in these circumstances variations in output are still the norm.

In the context of productivity variability the learning effect is apparent normally for the first few repetitions of a project, and should be accounted for by modelling these earlier activities with an appropriately increased duration. However, it is likely that in all but the most advantageous circumstances this learning curve is not continued into the rest of the project, due to the influence of the factors discussed before. It is for this reason that a further learning effect, after the first few repetitions, can be discounted as contributing to the usual production variation in the construction industry.

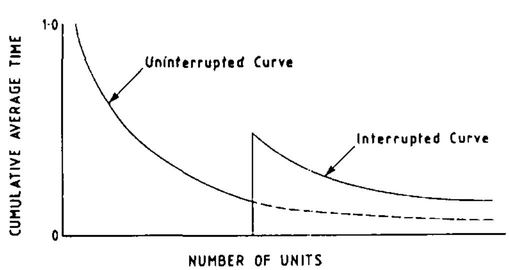


Fig. 1. Cumulative experience curve with interruptions.

Sources of data

Any attempt to quantify variability and differentiate between different activities is plagued by a dearth of information. All the published sources draw on data collected by the Building Research Establishment (BRE) and are for traditional house building only. As well as a lack of information, the accuracy of the data is also questionable. Some studies include time related to interruptions in the variability measure. The source of earlier data is often from site records and its accuracy dubious. The most accurate data was collected by direct observation, with the BRE site activity analysis package (Stevens, 1969) whose accuracy can be calculated (see Table 1) although rarely specified, but is often of the order ± 5 to 35%.

Table 1. Accuracy of activity sampling observations.

Estimated manhours from observations	95% confidence limits
10 000	±2%
1 000	±6%
100	±20%
10	±64%
5	±87%

The size of the sample also has a bearing on the accuracy; and the largest sample used is 52, but is more often in the range 20 to 30. This is exacerbated by the need to compare tasks on identical buildings, which are limited to one site. An improvement in sample size could be achieved by using a common unit of expression for the same task on different sites. It is also necessary to limit the observations to reasonably precise tasks (e.g. secondary work packages), as the variability of an operation (e.g. brickwork superstructure) is greater than that of the whole (e.g. house completions) (Clapp, 1965). Comparison of results is also complicated by different methods of presentation. The best method would be a density function, as this has an influence on which duration is chosen on each iteration in the model, but three methods are used in the literature and are given for all data, where available: the range expressed as a ratio of the largest data value to the smallest; the range expressed as a ± percentage about the centre; and the coefficient of variation, i.e. the standard deviation, expressed as a percentage of the mean.

Several studies have drawn on the data collected by the BRE, but these are limited to traditional house building on three separate sites. Limiting the discussion to those studies which conform with the definition of variability it is possible to draw tentative conclusions, although considerably more research is needed in this area.

A typical histogram representing the variability in output for bricklayers is presented in Fig. 2. From this source and several others relating to brickwork it is apparent that brickwork has a variability in the order of ±30%, with a coefficient of variability of 15%. This is considerably lower than the other trades and is possibly more reliable being based on a larger sample size.

Brickwork superstructure was the only operational activity which exhibited any significant difference from the norm in the pattern of performance when the standard *T*-test was applied.

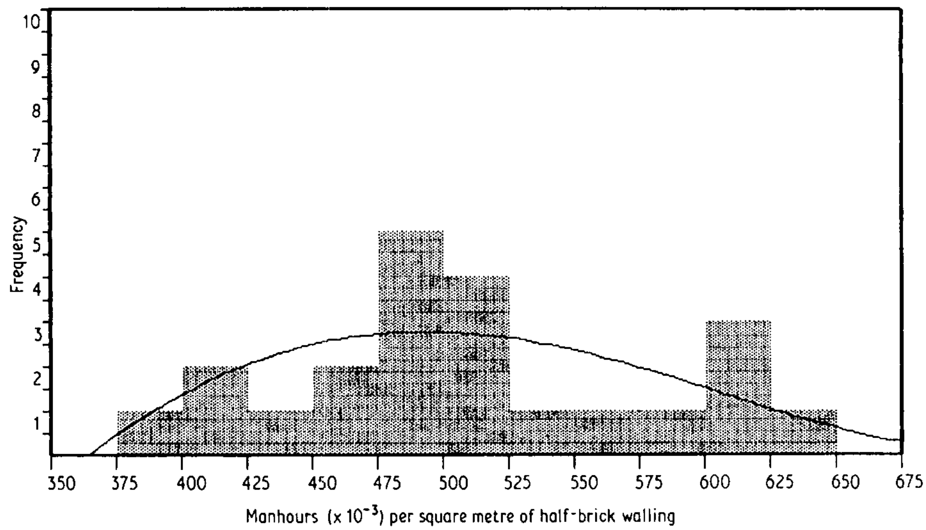


Fig. 2. Brickwork superstructure (half-brick walls only), variability of output for all gangs, one site (McLeish, 1981). Sample size = 22; range = 1.6:1 ($\pm 24\%$); coefficient of variability = 14%.

To explain this difference it has been suggested that historically bricklaying has always been organized into relatively large and relatively independent operations, with lower non-productive times. Support for this view, with particular regard to housing, can be found in the housing project used as a case study. In this case the only operation in the sub-structure primary work package (PWP) which had planned, and actual, continuity of operation was the foundation brickwork to damp proof course (DPC) level. This arrangement prevented the earliest start on subsequent operations of the first few housing blocks, i.e. if the brickwork item had been discontinuous in the early stages then a start on following operations could have been made sooner. In the superstructure PWP the dominance of brickwork required that the sequence of locational areas for work to progress through was changed from those operations before and after the brickwork. This change was necessary to give continuity of work to bricklayers at a constant gang size. For all other building operations it is only possible to state that the range is in the order of ± 50 to 60%, with a coefficient of variability from 30 to 40%.

Data from industry

The previous section describes the currently available best sources of data on variability of building work, but the search for relevant data was extended to organizations with links to industry and to commercial contracting companies.

Many organizations were approached and none within the UK were able to supply data in a relevant format. However, two large progressive contracting organizations were interviewed as to the state of their productivity data base. In both cases the results were similar. Extensive libraries of productivity output rates exist for very detailed tasks. These are used for planning and bonus targetting. Where the source of the data is recorded it is based upon work study exercises carried out when this technique was in favour, in the 1960s and early 1970s. Limited exercises have been carried out since then, but mainly to update data for operations involving increased mechanical aids (e.g. concrete pumping) or on sites where progress was slow as part of other measures to improve productivity.

However, to use the raw data in a deterministic commercial environment, the variability of the data has been reduced by the use of work study relaxation allowances for such things as the conditions of work, and the physical effort expended (i.e. a subjective judgement of individual productivity against some standard). Further treatment of the data, by the exclusion of certain 'non-productive' times which contribute to variability (e.g. idle/inefficient, early tea/lunch, talking to supervisor), by the omission of extreme values, and the averaging of the remaining data values to produce a single figure as an output rate, render the libraries of information unsuitable for use with the simulator. Sufficient raw data was collected during the work study exercises to form the basis of suitable frequency distributions, but this raw data has been lost or dispersed through the company to an extent that any re-analysis is practically frustrated.

The discussions with industry tended to confirm the existence of variability, but did not provide any better data than that described above. The data obtained from published sources was therefore used in subsequent simulations of live projects.

Interference

Introduction and definition

That interference exists in the construction process, as external influences on the progress of site works which cause stops to production, is readily apparent to all practitioners in the building industry. It stems from a wide variety of sources such as: the structure and work of the industry, acts of God, or human and social factors (Lichtenberg, 1981), risks outside the contractor's control (Ahuja, 1982), integrating the effort of a number of different organizations and individuals, many not under direct control (Feiler, 1976), legal (Woolery and Crandall, 1983) and environmental factors exhibiting random, seasonal or periodic behaviour.

These give rise to specific events which prevent work starting or continuing. The most frequently mentioned are: the weather, planning permission and building codes, lack of design details, non-availability of materials, non-attendance by subcontractors, labour strikes and shortages, equipment breakdown, and theft and vandalism. Occurrences of interferences on any one project are to be found in abundance.

The recognition of interferences as a separate category of uncertainty is an important step for practical as well as theoretical application. By focusing attention on the external influences it redefines the strategic and tactical management of a project to encompass the control of external events and the mitigation of their effects. The concentration of management effort on reducing the impact of interferences may have a greater beneficial effect than the control of production variability, which is essentially a site, operational, management task.

Classification of interferences

Previous attention in this area has been limited. However, a few studies have attempted a subdivision of the general interference class.

A classification by source defines: interruptions from those not directly involved in the building process (government departments, planning procedures, the general public, etc.); interruptions from resources (labour, equipment and materials); and interruptions from within the building team (Tavistock Institute, 1966). Another classification has been between interferences due to nature and 'acts of God', and other human and social interferences (Lichtenberg, 1981). Fig. 3 illustrates the effect these interferences have over and above the productivity variability.

A further classification is between those risks within, and those outside, a contractor's control (Ahuja, 1982). This source is from the USA and includes factors such as design which are traditionally outside a contractor's control in the UK.

Previous work in this area has thus been sparse, and a need exists to further refine and classify the components of interference, to gain a wider acceptance of the concept and to enable measurement of the magnitude of each element. It is postulated that the general classification of interference is made up of four major components, each of which affects to some degree the progress and cost of actual construction activities. These components are: interferences originating from the design process, interferences originating from the procurement process, interferences from the weather, and those other external human and social factors remaining.

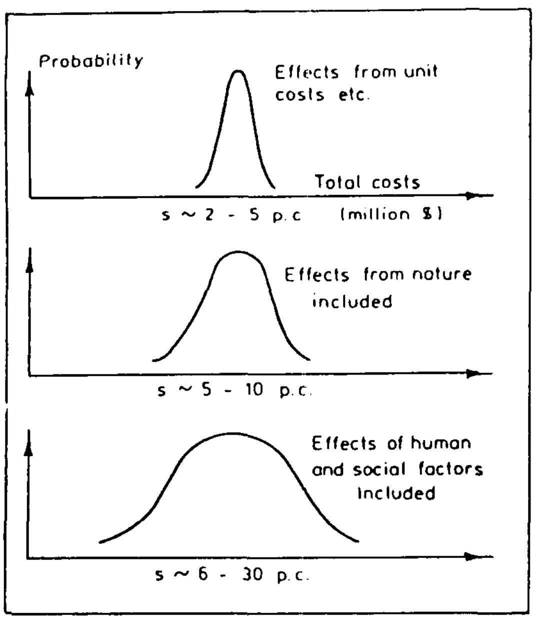


Fig. 3. Illustrating the effect of interferences from various sources on task uncertainty (Lichtenberg, 1981).

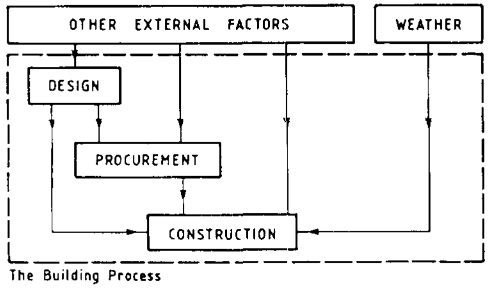


Fig. 4. The components of interference and their interaction.

This classification is illustrated in Fig. 4. One type of interference which is sometimes encountered is termed 'internal interference' and results from a conflict between on-going operations. It can be explained with reference to a line of balance diagram, illustrated in Fig. 5, where due to a difference in productivity one gang prevents another from working through not completing their task and not vacating the locational work area. This is internal interference, as opposed to an external interference where work stops for other reasons. This internal interference in a project is automatically taken into account by the simulation process and it is important, particularly for data collection, not to include any amount for this in values used. Its automatic inclusion is generated through the choice of different durations through the influence of variability and the logical connections between activities – this leads to a different gradient in the line-of-balance for each operation each iteration and produces internal interferences.

Interference data

Though interferences are readily recognized and accepted in industry and academia, the present research project and the previous one (Bennett and Fine, 1980) were the first to identify it as a distinct and separate classification within the general uncertainty of the building industry. For

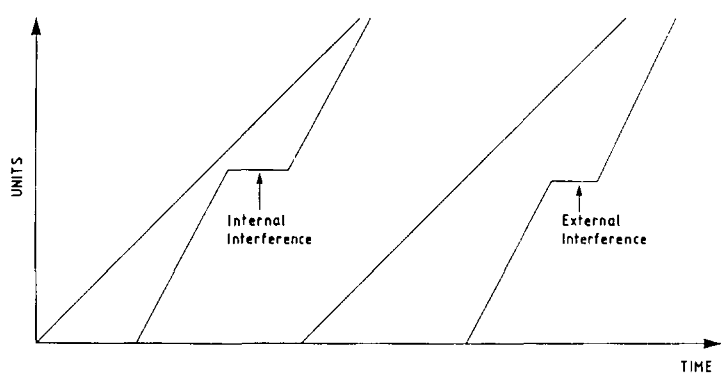


Fig. 5. Internal and external interference illustrated with a line-of-balance diagram.

this reason, and the general lack of data collection practices by industry and research bodies, after an extensive search no data in an entirely suitable form has been identified.

Some information on the frequency with which different interferences occur could easily be recorded. This, however, would not give any indication as to the duration of the interferences. It is anticipated one day that reliable data may become available, and for this reason a facility has been provided in the simulator for the entry of a histogram plotting the relative frequency and duration of interferences experienced by any operation.

Data on the frequency with which different interferences occurred on the projects forming the case studies were collected from formal reports, where available. These, however, may not be comprehensive in that every interference which occurred may not have been recorded. It is also probable that the type of interference recorded has been influenced by the contractual responsibilities of a project. For example, it is clear that the extent of subcontractor non-attendance or labour supply problems has not been accurately recorded for those subcontractors appointed by the contractor, and for whom he has a contractual responsibility. However, the interferences from subcontractors appointed by the professional team, by nomination, and for whom the contractor can contractually claim time and cost extensions to the contract, have been more diligently recorded. With these reservations borne in mind, Table 2 lists the identified sources of interferences and their relative frequency of occurrence for the case studies.

One further technique which is applicable to industry has also been identified. This is the use of Foreman-Delay Surveys (Rogge and Tucker, 1982) which were originated in the USA, but which have been used at least once in the UK. The delay forms are completed by trade foremen at the same time they complete their daily time sheets. Work study exercises carried out in conjunction with the delay surveys indicate that after an initial 'settling down' period there is a good correlation between the results of a formal work study and the results of the delay survey. An important point stressed in the practical application of this technique is the active involvement of the foremen completing the forms. This is achieved by using the results of the surveys as the regular basis of two-way communication between the workforce and management. This brings delays to light, for the action of management, and ensures that foremen are not penalized for the causes of delay thus helping to ensure their accurate reporting. This method of highlighting delays and the focusing of management effort on them consistently resulted in a reduction in time lost due to delays when the method was adopted. Productivity improvement is accomplished primarily through the identification of specific problems causing delay and the resulting corrective action which is taken. This management of interferences, on the two sites studied in the USA, resulted in a general increase in performance as foremen reported a reduction in delays (Rogge and Tucker, 1982).

Some results from this technique are available from eight industrial construction sites in the USA. These are included to give an impression of the type and quality of data which could be expected using this method to quantify interferences, the specific values are not directly applicable as they refer to a diffferent country with a different method of managing building construction. Average and maximum weekly values for each category of delay for all eight sites are presented in Table 3 in order of decreasing severity.

Table 4 presents similar information for six commonly occurring crafts at these sites.

Foreman-delay surveys performed on the above industrial construction projects reported

Table 2. Frequency of formally reported interferences on the case studies as a percentage of the total reported interferences.

Interferences		Case studies			
Source	Description	7[a]	8	9	10
Design	Late or inaccurate design information, from any source		44%	47.8%	58%
	Additional work through design changes or unforeseen work		26%	21.5%	16%
Procurement	Subcontract supply problems of labour and materials		29%	21.5%	20%
Other	Rework through accident or bad workmanship (an element of variability)		NA	9.2%	6%
	Other unspecified		1%	NA	NA

[a] No data available

Table 3. Typical foreman-delay survey values, site averages (Tucker, Rogge and Hendrickson, 1982).

Foreman-delay survey category (1)	Average, as a percentage (2)	Maximum, as a percentage (3)
Design rework	4.4	12.6
Construction rework	1.6	5.4
Pre-fabrication rework	1.2	6.2
Total rework	6.1[a]	17.1
Crew interference	0.8	5.8
Waiting for construction equipment	0.8	2.5
Waiting for materials	0.7	6.8
Moving to new work site	0.6	3.4
Waiting for information	0.3	1.9
Waiting for tools	0.2	1.3
Crowded work areas	0.2	1.6
Other delays	1.4	—
Total delays (non-rework)	4.9	20.5

[a] This average includes all sites, some of which did not subdivide rework categories. Therefore, this value is not equal to the sum of separate rework category averages.

Table 4. Typical foreman-delay survey values for common crafts in the USA, as a percentage of the working week lost (Tucker, Rogge and Hendrickson, 1982).

	Carpenter		Electrician		Ironworker		Labourer		Pipefitter	
Foreman-delay survey category (1)	Average (2)	Maximum (3)	Average (4)	Maximum (5)	Average (6)	Maximum (7)	Average (8)	Maximum (9)	Average (10)	Maximum (11)
Design rework	0.4	3.2	3.3	17.2	3.2	14.8	0.5	7.7	8.3	23.0
Pre-fabrication rework	0.2	3.8	0.0	0.1	0.9	9.2	0.0	0.0	3.2	11.7
Construction rework	0.8	7.8	1.4	10.4	1.7	6.5	—0.1	0.5	2.9	12.6
Total rework	1.9[a]	11.3	4.7[a]	23.8	3.1[a]	14.4	0.5[a]	7.8	13.5[a]	38.5
Waiting for materials	1.4	10.9	0.3	1.1	0.9	4.9	0.0	1.0	1.1	8.7
Waiting for tools	0.1	0.6	0.1	0.4	0.3	9.3	0.1	0.5	0.5	2.9
Waiting for construction equipment	1.4	10.9	0.3	1.1	1.7	6.6	0.4	3.5	1.5	5.3
Waiting for information	0.3	5.9	0.2	3.8	0.1	0.5	0.1	1.0	0.7	6.3
Crew interference	0.1	1.5	0.6	3.8	0.4	1.8	0.0	0.8	1.8	9.9
Crowded work areas	0.1	0.6	0.5	5.4	0.1	0.3	0.0	0.3	0.4	8.8
Move to other work areas	1.0	11.5	0.5	2.3	0.9	2.7	0.3	1.3	1.0	5.1
Other delays	0.7	—	0.5	—	1.7	—	0.3	—	2.2	—
Total delays (non-rework)	5.1	46.1	3.0	11.0	6.1	63.5	1.2	4.4	9.2	26.0

[a] This average includes all sites, some of which did not subdivide rework categories. Therefore, this value is not equal to the sum of separate rework category averages.

delays from near 0% to more than 20% of the working week. Values varied with size of project and craft mix. Reported delays generally increased as the size of the manual work force increased (Tucker, Rogge and Hendrickson, 1982). Given the absence of suitable data part of the research became calculating allowances for interference in the case studies which modelled reality. The way in which this was done and the results are described later in this paper.

Computer program

The development of the computer program known as the *Construction Project Simulator* (CPS) was undertaken with the aid of a research grant from the Science and Engineering Research Council and is based on the ideas and theories outlined above.

The software philosophy has been to make the operation of the programs as easy and simple as possible. This was accomplished by the extensive use of computer graphics, the inclusion of many checks for errors and error messages, through minimizing the use of the keyboard, and the inclusion where practicable of 'help' screens to prompt the user in the correct operating procedure. Also the structure of the programs is based on a hierarchical approach to allow ease of use and present a choice of levels for answers to increasingly complex questions, as schemes and strategies for a project develop.

The suite of programs is driven by a menu where all program operation must return to before another function can be chosen. The suite of programs are basically configured into two different categories; the series of programs allowing the entry of data describing a project, and two programs where this data is used to perform simulations and produce the end result as output.

The programs have been coded in compiled Basic, and operate on a 512 Kbyte ACT Sirius I micro-computer with twin floppy disc drives providing 1.2 Mbyte of data storage.

Data input programs

The following programs and facilities require input from the user and all provide data in one form or another to the simulation programs described later. Some programs can be used only after another program has been successfully completed and saved on disc, as they draw on information produced earlier – program operation automatically checks for these conditions.

Commencing a project

Two floppy discs are required, one containing the CPS suite of programs and one data disc.

The programs are then initiated by entering the three characters 'cps'. This starts an automatic process which loads the graphics software and checks the data disc for existing data. If the data disc is blank a program is entered which allows the entry of the project title, start date, anticipated end date, and a time unit to be used in the primary bar chart. If the data disc already has project data present then the menu program is run – through which the user moves from one program to another.

Bar charts

The bar chart programs represent the heart of the CPS data input routine. The bar charts are arranged as a hierarchy, which is reflected in the structure of most other programs, and also models the way effective managers plan. The first bar chart to be presented is the primary level bar chart, in which the user defines separate activities known as primary work packages (PWPs). Each one of these PWPs may subsequently be 'exploded', or magnified, to define a secondary level bar chart which allows the constituents of the PWP to be planned in detail. Within the secondary level bar chart the user defines separate activities known as secondary work packages (SWPs).

The primary bar chart is presented from the data entered previously – the start and end dates, and the time unit (weeks or months) – and a calendar of dates and time unit numbers are calculated and presented on the screen along with the project title. The time unit and the length of the project defines how large the steps are between cursor movements on the screen – as the cursor moves horizontally in steps or jumps of one time unit. Thus activity durations have to be in whole time unit lengths. All of this process is carried out automatically and the user is presented with a titled, dated and scaled blank bar chart screen, ready for the entry of PWPs.

The maximum number of PWP bars permitted is 39, however, only 15 are displayed at one time on the screen, but the screen 'scrolls' up or down, one bar at a time, so that all bars may be viewed. The user enters a bar by typing its title in the title panel, and by defining the start and end positions, using one function key and two direction keys, the bar is automatically presented. Only one bar per line is permitted. Once a bar has been set up the start and end dates may be changed, and the bar redrawn in the desired position. Changes to bar charts can thus be rapidly executed. Bars may be inserted or deleted from the bar chart, and bar titles may be retyped.

The PWPs are interconnected by the device of logical links, entered by the user and drawn on the screen as thin lines. The maximum number of links is 250. The links act as logical restraints to progress and are entered by setting the cursor at the desired position on one bar, pressing one function key and moving the cursor, by four direction keys (or one day by the use of a mouse!), to the desired position on another bar and pressing the same function key again. Certain strict rules govern link arrangements, as this is the basis of the logic employed during simulation. Basically all links must pass down the screen when drawn, and are sorted by 'rescheduling' so that at least one link between any two bars is vertical and none slope from right to left. Links may be erased by placing the cursor on their origin and pressing one function key on the key board.

The combination of rapid data entry, graphic display, and the ease with which changes can be made provides a powerful tool to investigate the effect of logic or duration changes, as at the throw of a switch the logical effect of any change is made – much as the non-graphical and un-timescaled critical path analysis performs. An example of a primary bar chart is illustrated in Fig. 6.

Holiday periods may be entered and deleted in much the same fashion as bars are entered. The maximum number of holiday periods permitted is nine. As the cursor moves in time unit steps the duration of a holiday period must be a whole number of time units.

After a session of data input to the bar chart, whether initial input or as the result of some change to the plan, the user must press the 'reschedule' function key before he is permitted to save the bar chart details permanently on disc. The reschedule checks, and if necessary rearranges, the logical links to ensure the plan is logically correct. The requirement to always reschedule before the save function key is enabled is to ensure that all plans contained on disc are correct ones.

Once a correct primary bar chart has been created and saved each PWP of this bar chart can be expanded to form the basis for a secondary level bar chart, when the more detailed constituent SWPs can be entered by the user.

The secondary level bar chart program takes the PWP title and calendar (and week number) start and end dates, and the presence of any holiday periods from the primary bar chart program. The user then has to select a time unit, equal to or less than the primary bar chart time unit – in weeks, half-weeks, or days – and the computer presents a titled, dated and scaled blank bar chart screen with any holiday periods in the right place, ready for the entry of SWPs.

The processes used to enter SWPs and logical links are exactly the same as those used in the primary bar chart, and described above. The maximum number of SWP bars permitted is 39,

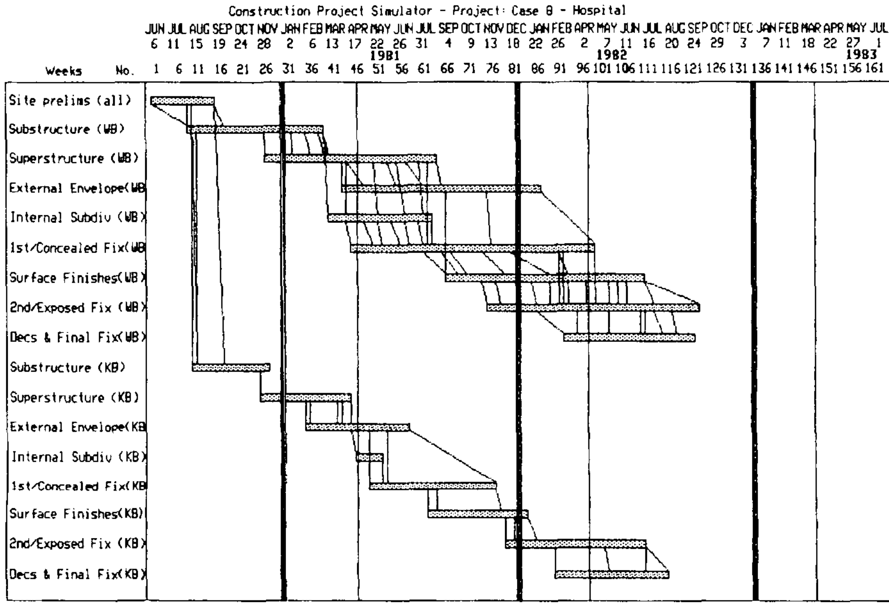


Fig. 6. Typical primary bar chart.

but the maximum number of logical links is set at 200. Thus in the unlikely event that all PWPs were expanded, the maximum number of SWPs in the entire plan would be 1521 and they would be restrained by a maximum of 7800 logical links. It is not expected that this facility will ever be fully utilized, but the upper limit was set to accommodate the largest possible number of SWPs and links in one PWP, which are likely to be found in practice. During use of the CPS the largest number of SWPs found in practice has been 410, with just less than 2000 secondary logical links, contained in 28 PWPs. This was for a complicated £9 million, 1.8 year project.

A typical secondary level bar chart is illustrated in Fig. 7 and represents the expanded plan of PWP2 - substructure (WB) in Fig. 6.

Cost entry

The direct cost in labour, materials and small plant needed to carry out the operations described by a PWP or a SWP must be entered into the relevant cost program. The cost program takes the work package titles from the relevant bar chart and presents them in a table. Numbers up to eight characters in length may be entered. A running total of the labour and material costs are displayed on the screen along with a grand total.

As the bar charts are arranged as a hierarchy the structure of the cost information is arranged in a similar manner. Thus, there are as many cost tables as there are bar charts and the cost totals for a PWP are made up of the sum of the constituent SWPs. The totals from a secondary cost

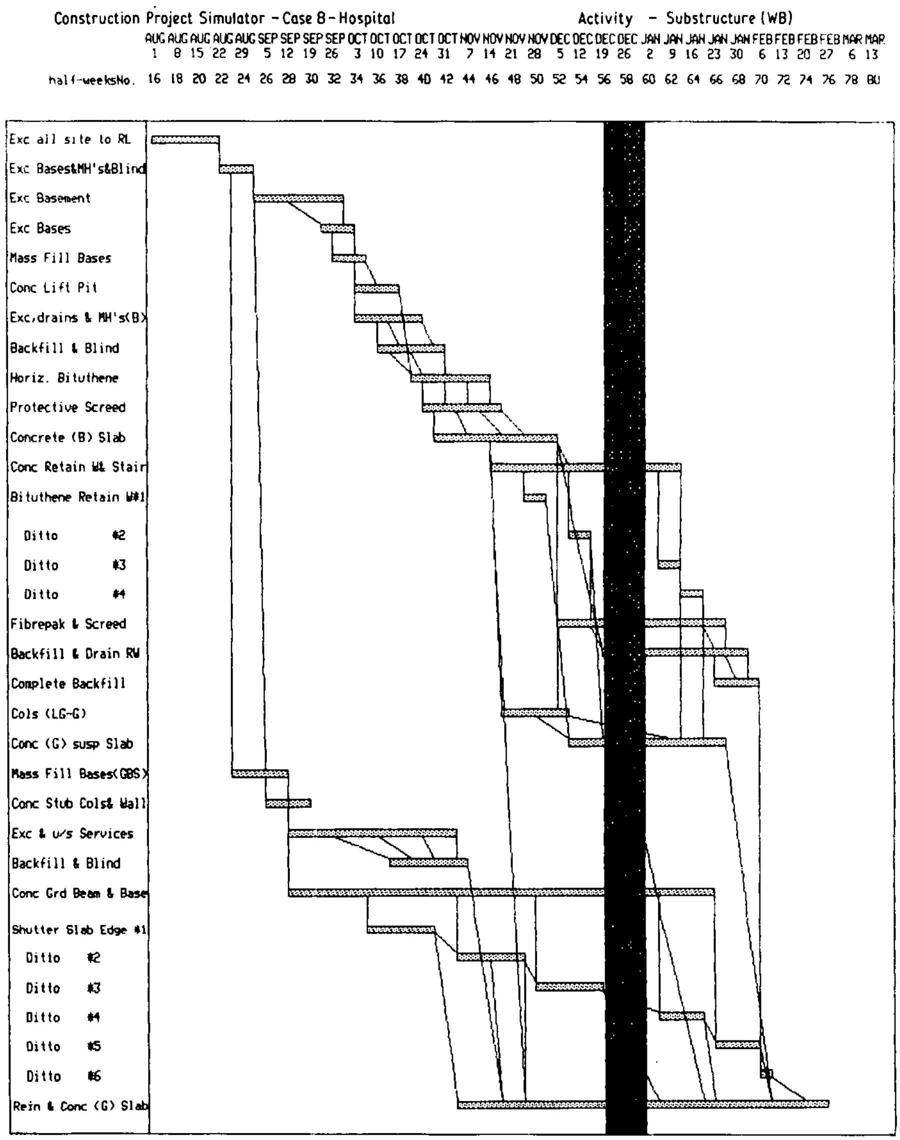


Fig. 7. Typical secondary level bar chart – expanded plan of PWP 2 in Fig. 6.

table when saved are automatically placed in the primary cost table, thus removing a potential source of user error. A typical cost screen, as it appears to the user, is illustrated in Fig. 8.

The costs discussed so far are those for the materials and effort required for incorporating them in the building. However, in construction a significant element of the cost is contained in cost centres which will not be permanently incorporated in the building, but which are

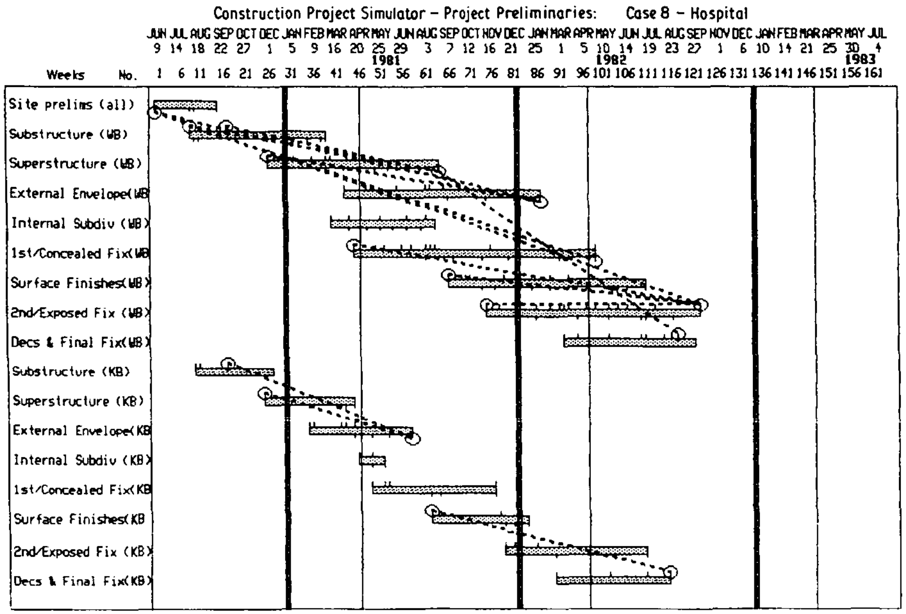
```
PWP No. 2                AMEND COST DATA        Substructure (WB)
Activity                 Labour Cost   Material Cost
Exc all site to RL       <11610   >    <9395    >
Exc Bases&MH's&Blind     <8645    >    <6680    >
Exc Basement             <14925   >    <12875   >
Exc Bases                <6635    >    <5365    >
Mass Fill Bases          <520     >    <1300    >
Conc Lift Pit            <1615    >    <3565    >
Exc.drains & MH's(B)     <7900    >    <11705   > LABOUR TOTAL   |
Backfill & Blind         <1065    >    <450     >   <      118520>
Horiz. Bituthene         <775     >    <1590    >
Protective Screed        <440     >    <905     > MATERIAL TOTAL|
Concrete (B) Slab        <3500    >    <7735    >   <      160300>
Conc Retain W& Stair     <4040    >    <8920    >
Bituthene Retain W*1     <250     >    <455     > GRAND TOTAL    |
   Ditto         *2      <245     >    <455     >  <       278820>
   Ditto         *3      <245     >    <455     >
   Ditto         *4      <245     >    <455     >
Fibrepak & Screed        <1445    >    <2955    >
Backfill & Drain RW      <12020   >    <10725   >
Complete Backfill        <3510    >    <2845    >
Cols (LG-G)              <2150    >    <4755    >
```

Fig. 8. Typical cost screen.

nevertheless essential for the construction of the building. These are the 'preliminaries' costs for a building project and the most significant elements are: supervisory staff, plant, scaffold access, temporary accommodation, temporary services and materials-handling/cleaning (Gray, 1981). These costs are often shared by more than one activity on the plan, and they are specifically dependent on the duration and logic of certain elements of the plan. For example, the tower crane may be erected when a certain SWP in the substructure PWP has been completed and may be dismantled when a certain SWP has been completed in the superstructure PWP. The timing and hire period of the item of plant is linked to the logic of the plan, and if the durations of activities are extended in practice then the crane will be required for a longer period and the cost will increase.

This logic has been modelled in the CPS by the provision of a preliminary schedule where up to 15 separate 'preliminary categories' may be attached to the logic of the primary bar chart. Once this program is engaged all the information entered into the primary bar chart is reproduced, except the majority of the logical link graphics is omitted for clarity and the link positions merely marked by short vertical lines. The user may then enter preliminary categories to define the start and end of a category, using the same procedure as drawing logical links in a bar chart. The only difference being that the cursor moves from link position to link position, rather than in time unit steps, and the start and end can thus only be attached to a logical link position. Heavy dashed lines are used to represent a preliminary category on the screen. Categories may also be deleted if required.

The effect of setting up a preliminary category, is that the logical links associated with the start and end positions are specifically identified, or 'flagged', to allow computation of the number of weeks between the start and end position. This information is then presented in a preliminaries cost table where a title, a weekly cost and a fixed cost can be entered for any preliminary category – to form the basis of the indirect cost calculation. A typical preliminaries schedule and cost table are presented in Fig. 9.



Construction project simulator – Preliminaries description and costs

Week start		Week end		Description	Labour	Materials
1. Site prelims (all)	(0)	to 2nd/Exposed Fix (WB)	(115)	Staff, hutting, power, clean, other, profit	2480	333 285
2. Site prelims (all)	(0)	to External Envelope (WB)	(81)	Structural foreman 2 No.	380	0
3. Substructure (WB)	(16)	to Superstructure (WB)	(60)	Tower Crane No. 1	655	5150
4. Substructure (WB)	(8)	to 1st/Concealed Fix (WB)	(92)	Assistant engineer + chain boy	315	0
5. Substructure (WB)	(8)	to Superstructure (WB)	(60)	Engineer + assistant	400	0
6. Superstructure (WB)	(60)	to Decs & Final Fix (WB)	(110)	Hoists 2 No.	255	800
7. Superstructure (WB)	(25)	to External Envelope (WB)	(81)	Scaffold	890	0
8. 1st/Concealed Fix (WB)	(42)	to 2nd/Exposed Fix (WB)	(115)	Services coordinator	230	0
9. Surface Finishes (WB)	(62)	to 2nd/Exposed Fix (WB)	(115)	Finishing foremen 3 No.	485	0
10. 2nd/Exposed Fix (WB)	(71)	to 2nd/Exposed Fix (WB)	(115)	Completion agent	205	0
11. Substructure (KB)	(16)	to External Envelope (KB)	(54)	Tower Crane No. 2	660	4650
12. Superstructure (KB)	(24)	to External Envelope (KB)	(54)	Scaffold	155	0
13. Surface Finishes (KB)	(58)	to Decs & Final Fix (KB)	(108)	Finishing foreman	165	0

Fig. 9. Typical preliminaries schedule and cost table.

Resources

Where resources are desired to form the basis of resource restraint or cost calculation then three stages of data entry are required. However, the structure of the data entry has been designed to minimize the typing of resource titles, etc., many times. The first two stages are the creation of a library of standard trades and trade gangs, which once created need only be occasionally updated. Thus the entry of resource data is particularly rapid.

The first stage is to enter typical trades and their cost per time unit into a table of 100 available categories. This is accomplished in much the same way as direct costs are entered, with the user moving between defined fields to enter trade descriptions and costs. The number associated with a particular trade is then used as the trade reference number. This data entry takes place in the top half of the screen, and although there are only ten trades on display at any one time the top half of the screen scrolls independently.

This information is then used to build up typical trade gangs in the lower half of the screen. A gang title is entered and up to five different trade members may be assigned to any one gang. It is common for there to be only one member of a gang, and the average number is for two or three. In this way a library of typical gangs is built up, although without any quantities of members, to allow a gang to be used in many different instances and then have different quantities added later. The number associated with a particular gang is then used as the gang reference number. The data entry takes place in the lower screen, and although only 10 gangs are displayed at one time the lower screen scrolls so that all the 100 available gangs may be viewed. A typical resources screen, as it appears to the user, is illustrated in Fig. 10.

Once the library of resource gangs has been assembled the business of applying them to particular activities can proceed. Resource restraint can only apply to the more detailed secondary level plans. Thus as many resource screens as there are secondary bar charts may be entered, although if resource restraint is desired in only a few PWPs then only these require data entry.

```
                     CREATE RESOURCE SETS
  TITLE                  COST
23.  <Grdwk bricklyr >  <150     >
24.  <Grdwrk plantdvr>  <120     >
25.  <Drainlayer     >  <105     >
26.  <Formwork Carp  >  <125     >
27.  <Steelfixer     >  <120     >
28.  <Concretor      >  <100     >
29.  <Conc. finisher >  <105     >
30.  <Scaffolder     >  <165     >
31.  <Bricklayer     >  <185     >
32.  <Bricklyr Labour>  <190     >
   RESOURCE SET                  |    | CODE REFERENCES        |
11. <RC Stairs : TC/P             > <27>   <26>   <28>   <  >   <  >
12. <RC Stairs : H/ D             > <27>   <26>   <28>   <  >   <  >
13. <RC Foundations               > <26>   <27>   <28>   <  >   <  >
14. <Formwork                     > <26>   <  >   <  >   <  >   <  >
15. <Steel fixing 8 concreting    > <27>   <28>   <  >   <  >   <  >
16. <Structural steel erection    > <60>   <  >   <  >   <  >   <  >
17. <Asphalt roofing              > <35>   <  >   <  >   <  >   <  >
18. <Tiled roofing                > <36>   <  >   <  >   <  >   <  >
19. <Scaffolding                  > <30>   <  >   <  >   <  >   <  >
20. <Brickwork                    > <31>   <32>   <90>   <  >   <  >
```

Fig. 10. Typical resources library screen.

For the selected PWP, expanded into a secondary level plan, another program presents the user again with a screen split horizontally, with each half again containing a table. In the lower screen the table of resource gangs is presented again for reference, and may not be changed. The upper screen displays the SWP titles from the relevant bar chart in a table. Each SWP title has twelve fields displayed against it. The second, fourth, sixth, eighth and tenth fields are displayed in reverse video, and the user is not permitted to enter these fields. The rest of the fields are defined by brackets and are allocated for user input. The upper screen is used to enter the number of a resource gang and to enter quantities against each constituent trade member.

In the first field of the upper screen the user enters a resource gang reference number. This has the effect of automatically displaying the trade members in the reverse video fields. This presents the user with details of gang members and an adjacent empty field in which to enter the quantity of members required. Member quantities may only be placed in fields with an adjacent trade reference number. Thus the same gang structure can be used for all similar activities (e.g. brickwork), but the numbers varied to reflect relative resource usage. In the last field the cost per time unit of the whole gang is automatically computed from the data entered previously, and is displayed when the data is saved. A typical resource allocation screen, as it appears to the user is illustrated in Fig. 11.

```
PWP No. 2              ALLOCATE RESOURCES AND COSTS   Substructure (WB)
  ACTIVITY             RESOURCE SET      [TRADES]+<NUMBERS>
 4.[Exc Bases               ]  <26>*24<1 >:91<1 >:22<1 >:  <  >:  <  >:<  298>
 5.[Mass Fill Bases         ]  <24>*28<3 >:  <  >:  <  >:  <  >:  <  >:<  300>
 6.[Conc Lift Pit           ]  <13>*26<2 >:27<2 >:28<3 >:  <  >:  <  >:<  790>
 7.[Exc,drains & MH's(B)]     <26>*24<1 >:91<1 >:22<2 >:  <  >:  <  >:<  396>
 8.[Backfill & Blind        ]  <27>*12<1 >:13<2 >:  <  >:  <  >:  <  >:<  410>
 9.[Horiz. Bituthene        ]  <27>*12<1 >:13<3 >:  <  >:  <  >:  <  >:<  540>
10.[Protective Screed       ]  <27>*12<1 >:13<3 >:  <  >:  <  >:  <  >:<  540>
11.[Concrete (B) Slab       ]  <2 >*27<4 >:26<2 >:28<3 >:  <  >:  <  >:< 1030>
12.[Conc Retain W& Stair]     <8 >*27<2 >:26<2 >:28<3 >:  <  >:  <  >:<  790>
13.[Bituthene Retain W*1]     <27>*12<1 >:13<2 >:  <  >:  <  >:  <  >:<  410>
     RESOURCE SET                   CODE REFERENCES
18.  [Tiled roofing                 ][36]   [  ]   [  ]   [  ]   [  ]
19.  [Scaffolding                   ][30]   [  ]   [  ]   [  ]   [  ]
20.  [Brickwork                     ][31]   [32]   [90]   [  ]   [  ]
21.  [Window fixing                 ][37]   [38]   [  ]   [  ]   [  ]
22.  [Plumbing                      ][43]   [  ]   [  ]   [  ]   [  ]
23.  [Mastic pointing               ][39]   [  ]   [  ]   [  ]   [  ]
24.  [Concreting only               ][28]   [  ]   [  ]   [  ]   [  ]
25.  [Excavation [large scale]      ][24]   [92]   [  ]   [  ]   [  ]
26.  [Excavation [small scale]      ][24]   [91]   [22]   [  ]   [  ]
27.  [General labouring             ][12]   [13]   [  ]   [  ]   [  ]


                          RESOURCE TOTALS
24. Grdwrk plantdvr: <2 >
92. Excavator      : <1 >
91. JCB            : <2 >
22. Grdwk Labourer : <2 >
28. Concretor      : <3 >
26. Formwork Carp  : <4 >
27. Steelfixer     : <4 >
12. Ganger         : <1 >
13. Labourer       : <3 >
```

Fig. 11. Typical resources allocation screen.

Once all the resource data for the desired SWPs has been entered, one final data input procedure is necessary to set the upper limit of resource availability for this PWP. The program displays all the separate trade members used in all the gangs employed and this information is displayed as a table. The user can then enter the maximum number for each resource type and the computer validates this to ensure it is not less than that entered previously. These totals act as the upper limit for resource restraint during simulation, and the user by manipulating these figures can experiment with different combinations and quantities to determine the best mix.

Creating and allocating distributions

Frequency distributions, or histograms, must be created and assigned so that variability and interference routines in the simulation programs have the correct information. Certain areas of the distribution program are reserved for specialist purposes; 1 to 50 are available to the user to save created distributions, 51 to 62 are reserved for the weather, and 63 to 140 are reserved for secondary simulation results.

The four most common distributions used in simulation, namely, uniform, triangular, normal and beta, are permanently available. The user can also create skewed distributions for the triangular, normal and beta to model pessimistic or optimistic production rates. Bimodal distributions can also be created in a wide variety of shapes, and actual histograms of real data can be entered and saved as the histogram or as a 'best fit curve' (see Fig. 2). Some typical distributions are illustrated in Fig. 12.

The distributions created in this program are contained in a library or data base which will rarely require updating once compiled. The distributions in this data base should be regarded as a library to aid the manager in applying his intuition to the simulation processes. As each can be regarded in a similar manner to the familiar PERT three-point estimate, and the different shapes used to express feelings about an activity, e.g. it is optimistic, thus allocating a distribution with a pessimistic skew. Some familiarity with this concept is obviously required, however there is evidence that it coincides with how people view the real world.

All the activities, at whatever hierarchy level, must have certain parameters defined pertaining to a particular activity before a simulation may be executed. Values for interferences, productivity variability and relevant distributions must be assigned to each activity by the user. The structure of these programs follow the same hierarchical structure as the bar charts, so there is one for the primary bar chart and one for each PWP. The structure of the screen display is similar to the cost programs with the activity title displayed along with fields to accept user input. In this program three fields are defined for use by the user.

The first field defines the interference factor acting upon the activity. A figure between 0 and 99 firstly defines the percentage chance that an interference will occur at any link position on the activity bar. This is separated by an oblique stroke '/' from an optional frequency distribution number between f1 and f50, which is held on file in the distribution program. This, if entered, is used to select a period of an interference from a user input distribution. If no distribution number is present the simulation programs will assume an interference period of one time unit.

The second field defines the range of the variability amount affecting an activity. A figure between 0 and 99 defines the plus and minus ($\pm$) percentage variation about the midpoint of the distribution, which defines the range of possible activity durations that may be chosen during

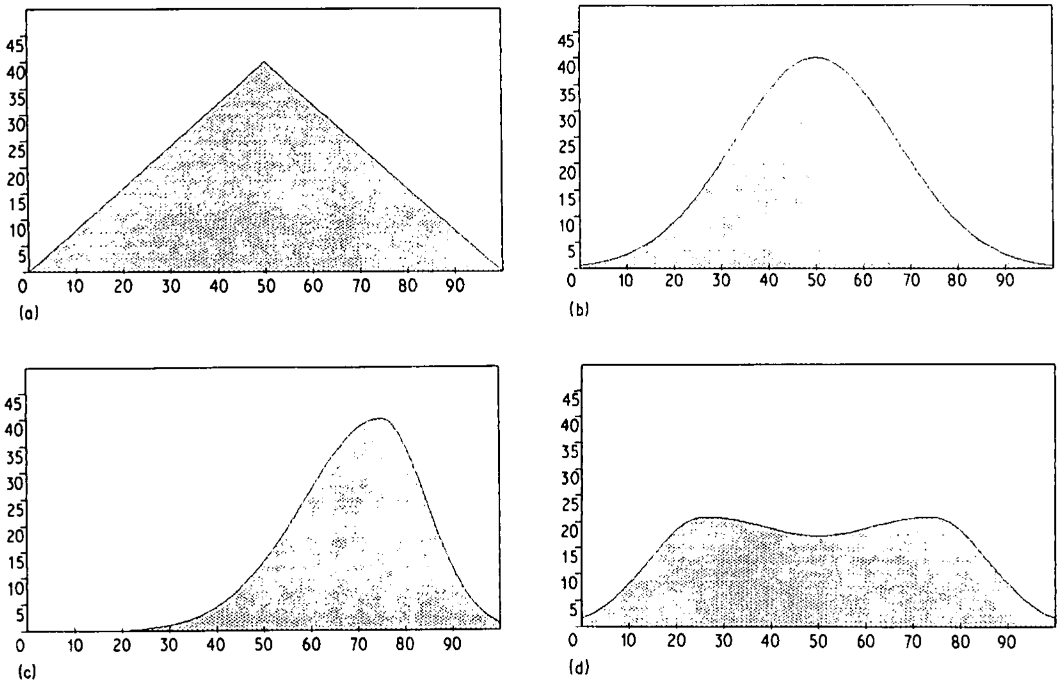


Fig. 12. Typical frequency distributions. (a) Triangular distribution, (b) normal distribution, (c) skewed beta distribution and (d) bimodal distribution.

simulation. The third field defines the number of the frequency distribution which applies to an activity.

Weather data

The inclusion of weather processing in simulation is particularly suitable as the basic problem with weather data is that typical weather behaviour may be known historically, but the *actual* weather which will be encountered during construction is not known. The effect is qualitatively detectable, but not enough knowledge exists to assess the risk quantitatively. However, weather data is a classical stochastic problem (Dressler, 1974) where a frequency distribution can be obtained from reliable historic records and repeatedly sampled randomly to reflect the possible weather effects on a project. The treatment of weather information is thus an ideal candidate for simulation.

The availability of data is excellent and can be purchased from the Meteorological Office for a very modest fee. The data used in the CPS is based upon a combined plot when the rainfall during the working day was greater than 0.1 mm h^{-1} *and/or* the wind was gusting greater than 10 m s^{-1} *and/or* the air temperature was less than 2 °C *and* the mean wind speed is greater than 4 m s^{-1}. This combined plot is then available for each month of each year for the last 20 years to provide a frequency distribution for the hours per working month lost through the effect of the weather. Two such distributions are reproduced in Fig. 13 to illustrate the difference between February and July when the data is presented in this format.

The twelve histograms for the weather for each month of the year are entered into a separate program. The weather data is specific to one location, so that new data should be collected for projects in different parts of the country as well as other countries. Also this program allows the

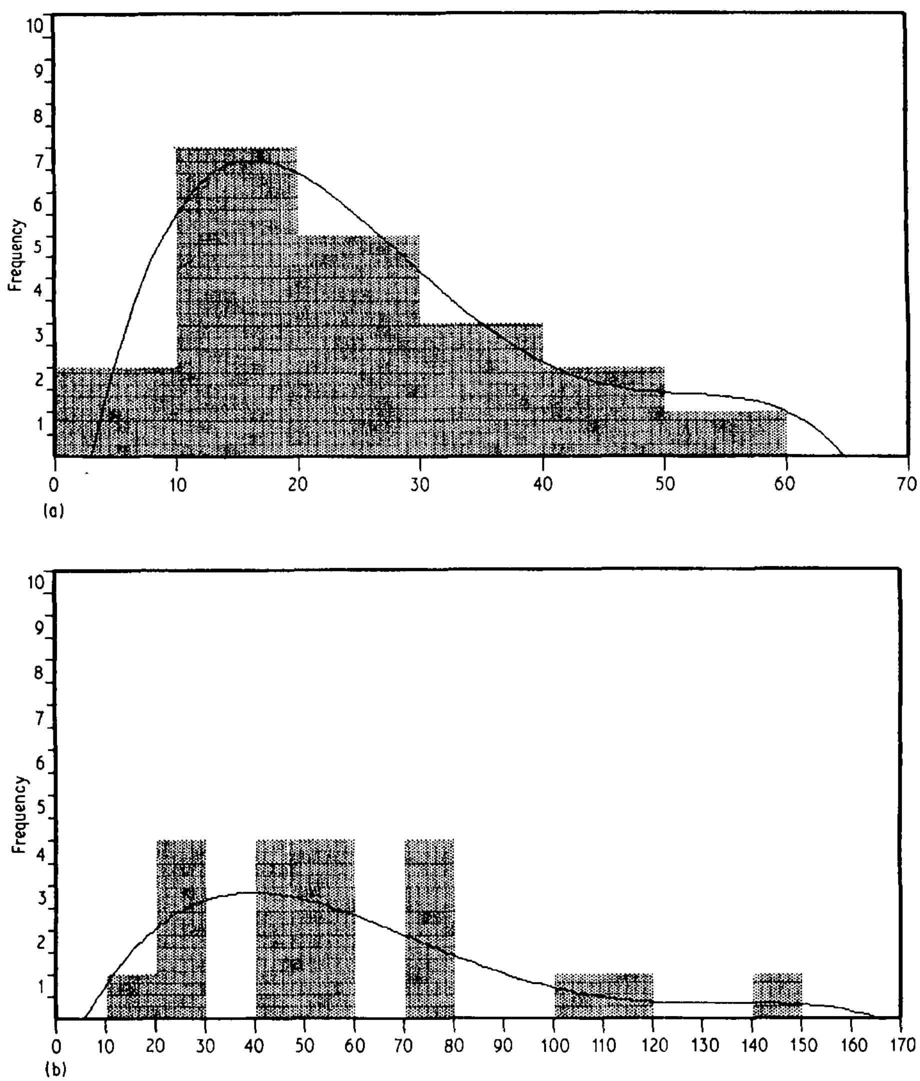


Fig. 13. Typical weather frequency histograms. (a) Hours lost in the working month of February and (b) hours lost in the working month of July.

identification of each PWP on the primary bar chart as being sensitive to weather effects or not. Thus the 'substructure' would be designated as weather sensitive while 'decorations and final fixes' would not. In this way the likely effect of the real weather can be included in a simulation.

Simulation programs

Once the data input procedure has been completed, then the simulation of the project can be carried out. However, the CPS has been designed as a hierarchy to facilitate the simulation of schemes at various stages, so that data input can have different degrees of detail and simulations still performed.

A simulation of the primary level only may be carried out after the primary bar chart and weather data, and optionally the preliminary schedule and primary cost table, have been entered. This allows a quick assessment of schemes at an early stage in their development, or at a tendering stage.

A simulation of one or more secondary plans may be carried out after a secondary bar chart, and optionally the secondary cost table and resources details, has been entered. This allows an assessment of single PWPs when design details become available as the scheme develops, or allows re-assessment of a PWP after some change to the construction method.

A full scale simulation of all the secondary plans, followed by a simulation of the primary level can be carried out automatically. This allows an assessment of the whole scheme, at a level consistent with a good contract programme, to produce the most reliable simulation result. The duration of this most detailed simulation procedure is one and a half to three hours, depending on the size of the project plan.

Simulation method

The purpose of simulation is to imitate the conditions of a system with a model or simplified representation of the system, so that the model mimics important elements of the system under study. The end result is to produce a prediction of the likely range and pattern of contract duration and cost which are feasible under the conditions and constraints of a specific project.

This is carried out inside the computer in a mathematical process using the data provided by the user. The basic problem is to choose from the range of possible durations for one bar of the plan – represented by the assigned frequency distribution and variability percentage – in a manner which is representative of the original data.

The manner in which this is achieved is via the use of random numbers (RNs). Random numbers are generated by the computer and are applied to the assigned distribution to see if the chosen value is representative of the original data. If it is representative then this is the value which is used in the simulation. If it is not representative then the value is rejected and more RNs are generated. The whole process being repeated until a feasible value is chosen. The random numbers are used in conjunction with a frequency distribution which limits the randomness to that found in practice. Thus the process is not totally random, but has a random element, hence the term stochastic. The use of random numbers is really only a device to produce unbiased choices of duration, and although we cannot say precisely what the duration will be after any one choice we can say what the pattern and range will be after a sufficiently large number of choices. So it is necessary to make a large number of choices to produce the confidence that the resulting choices are representative of the original data. The number of choices are referred to as *iterations*, and the number of iterations performed is critical to the final accuracy of the whole process. The minimum number of iterations acceptable is 100, and this produces an accuracy of $\pm 2\%$. For an increase in the number of iterations to 200 the accuracy can be improved to $\pm 1\%$. However, there is a penalty to be paid for increasing numbers of iterations, as the simulation takes progressively longer. Thus the number of iterations chosen is a balance between accuracy and processing time. The CPS has the ability to perform any number of iterations between 100 and 200, the final decision being left to the user.

Briefly, the procedure on one iteration of a simulation is to take each bar segment defined by logical links in turn and to choose an actual duration via RNs, the assigned distribution and the variability amount. This actual duration will not be the same on every iteration, but will reflect the possible values and their frequency of occurrence found in practice. Each link position is then examined to see if an interference occurs there. This is governed by the assigned interference amount and the use of RNs. The duration of the interference is chosen by RN if an assigned interference distribution is present. The next bar is then taken and the same process followed until all bars have been considered. The whole bar chart is then 'rescheduled' by the logical restraints. If resource restraint is to be simulated then the resource usage is compared to the available resources to see if progress is impeded. The cost of the bar is then calculated from the ratio of the actual bar duration to the original bar duration multiplied by the labour cost and added to the material cost, or if resources are involved the labour cost is calculated from the resource costs. The final duration and cost are then recorded. The whole process is then repeated up to another 199 times to complete the simulation.

Each iteration of the simulation creates a result. Due to the presence of RNs and the duration of each bar being chosen from a feasible range, there are a bewildering combination of possible bar durations and interactions which lead to a range of results being obtained rather than one single result. The results are also presented as a frequency distribution giving the range and pattern of outcomes.

The process just described is true of the general simulation process at whatever hierarchy level. However, two further facilities are employed to feed the results of the secondary level simulation into the primary level and to include weather and preliminaries processing in the primary level simulation. Each secondary level bar chart can be simulated to produce a distribution of results for the duration and costs. These distributions are saved onto disc to be used as data input to the primary level simulation process, and to allow the fine detail to affect the overall result.

The effect of the weather is included in the primary level simulation, where the start and end dates of a bar are known after the actual duration has been chosen in a stochastic manner. The actual weather delay each month is chosen via RNs from a distribution of feasible weather delays (see Fig. 13), and this period is added to the bar to extend its duration. In this way a slightly different amount of weather delay is experienced on every iteration of the simulation. Thus the likely effect of the weather can be analysed, although nobody can predict what the actual weather will be except perhaps a day or two ahead.

The costs of the preliminary categories are also calculated at the primary level. As the start and end dates of each logical link is known it is an easy matter to calculate the period between the start and end of a preliminaries category and multiply the weekly hire rate by this figure. This is added to any fixed materials costs to arrive at a total preliminaries cost. As the position of the start and end links will rarely be the same in the simulation a range of preliminaries costs will be produced.

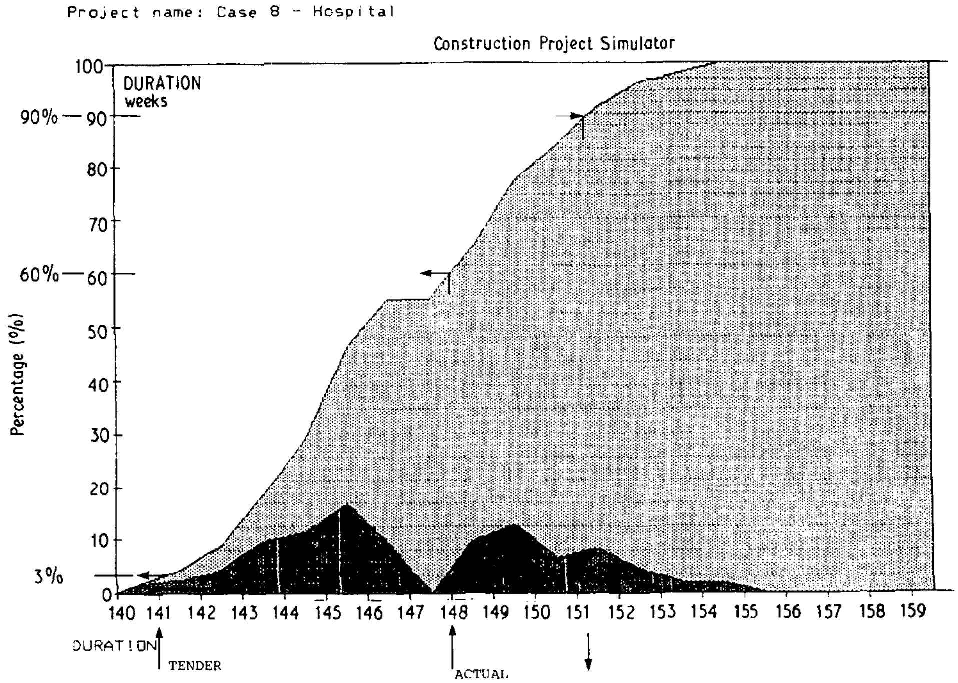
This then briefly represents the process which occurs during a simulation. However, the myriad choices of duration and the combination of these factors is almost inconceivable to the human mind, and it is only through the use of computers that problems of this nature can be assessed. Thus the computer has brought techniques to the aid of human affairs which would not be applicable without it.

Simulation results

Typical results produced by a simulation are illustrated in Fig. 14. The results are presented in two forms, as a frequency histogram (darker shading) which gives the user an impression of the pattern of results, and as a cumulative frequency curve (lighter shading) which allows the user to read off risk levels or confidence factors from the vertical scale. This vertical scale is labelled 'percentage' and represents the chance of a certain result occurring. This represents the 100 (or more) simulation results sorted into ascending order, so the lowest one had a small chance of occurring (or is a high risk), while the highest result had a very high chance of occurring (or is a small risk). The cumulative frequency curve is often the most useful as it is possible to read the risk associated with a particular result (or vice versa) directly from the graph. As there are a number of varied results there are also a number of varied patterns of possible expenditure over the life of the project. This gives rise to cumulative cash flow curves which may be examined at different risk levels to determine likely cash flow targets, and establish cash flow levels (see Fig. 15) which are unlikely to be exceeded.

The CPS has been used with several projects and the results for a hospital project are presented to indicate the use the output may be employed for. The tender period for the project was 141 weeks and the tender cost (not including an allowance for inflation) was £4 856 115. The actual period for the project was 148 weeks and the final uninflated cost was £4 631 785 with the final cost including inflation being £5 769 600. The inflation rate affecting the project was 16%.

The result of the most detailed simulation, including weather, for project completion is presented in Fig. 14 and the associated project uninflated final cost is presented in Fig. 16. From these figures it can be seen that the tender period only had a 3% chance of success, i.e. it was very risky, while the actual period had a 60% chance of success, i.e. it was very much less risky. This indicates that the contract period fixed in the tender documents was too optimistic, and if the client was serious about obtaining completion in 141 weeks then the design solution should have been reviewed or extra management effort expended. However, if the client could accept some later completion date he would have been aware from the output what the upper limits to his risk were, and so plan accordingly. If a risk judgement had been made based on a high confidence level of 90% then the client would have been aware that a possible time contingency of 10 weeks would be advisable, of which seven weeks was expended. The tender cost was not feasible and was £224 330 higher than the actual cost, even though the project was extended by seven weeks.



Interference = from secondary level
Variability = from secondary level
Distribution = from secondary level
Minimum = 139
Maximum = 156

Mean total duration = 147.76

Fig. 14. Typical simulation result, including weather, for project completion.

The professional adviser to the public client clearly overestimated his project contingency, which in this instance was included in the building budget. However, if a risk judgement had again been based on a high confidence level of 90% then the client or his professional adviser would have set the building budget at £4 637 700. This would have represented a reduction in the overall budget of £218 415 or 4.5%, which could have been crucial in the viability assessment of the scheme by the client. The contingency amount then built into the contract budget assuming a feasible tender cost at the 5% confidence level of £4 559 380, would have been £78 320 or 1.7%, of which £72 405 would have been expended.

The effect inflation can have on a project can be included in the simulation, and Fig. 17 illustrates the cost graph with the anticipated inflation amount included. No estimate of the inflated tender cost was available, but the actual value had an 80% chance of success.

As the weather routine in the simulator is an additional feature, to model a specific

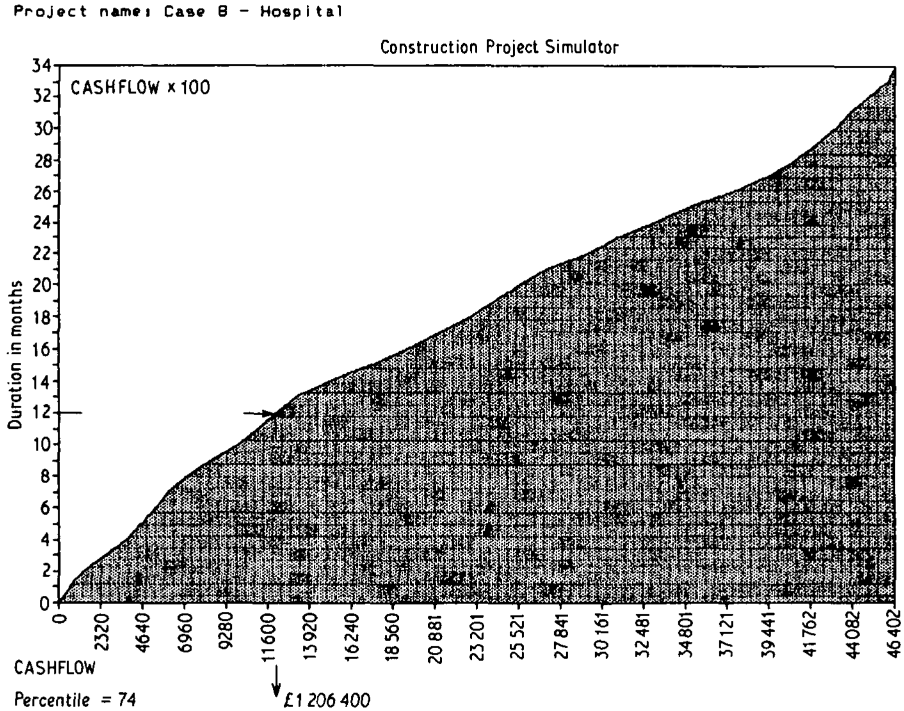
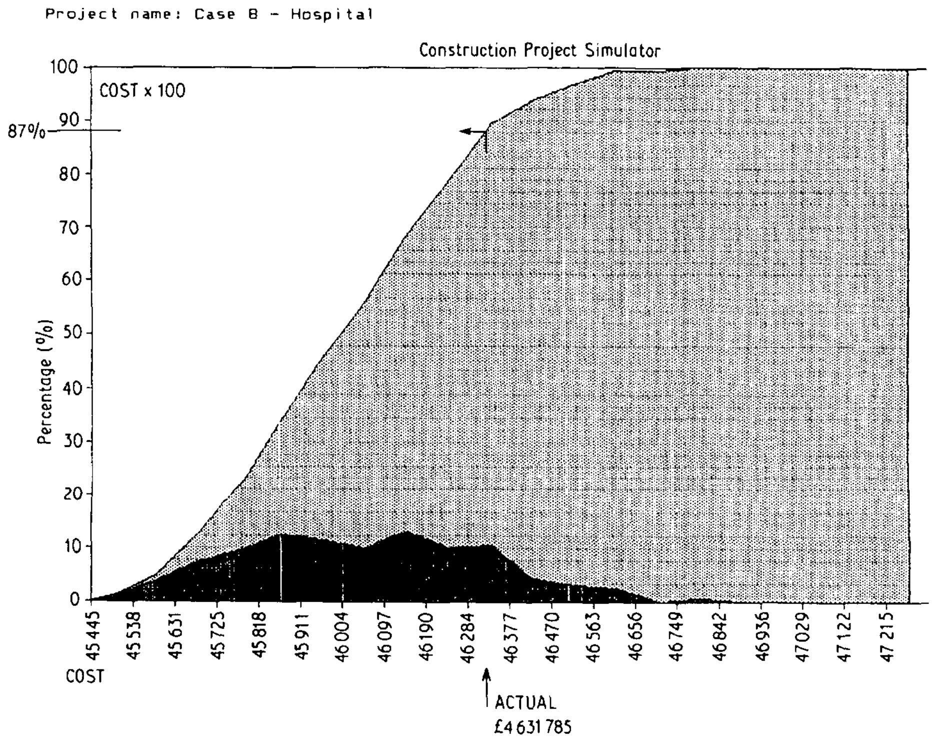


Fig. 15. Cash flow curve associated with the 74% confidence level, and the likely expended sum at month 12.

component of interference, it is possible to simulate the project behaviour as if it had not been subject to the effects of weather. The results of the simulation omitting the effects of weather are illustrated in Figs. 18 and 19. These show that the tender period had a 82% chance of success, while the actual period was not feasible. The increase in mean project duration solely attributable to the effects of the weather is 8.5 weeks or an increase of 6.1%. The increase in the mean total cost is £107 201 or an increase of 2.4%. The increase in the mean project preliminaries cost due to weather is £42 411 or an increase of 4.5%. This indicates that the preliminary costs are more sensitive to the weather than the total cost.

As well as judging a project's vulnerability to weather it is possible to judge a project's sensitivity through changing the project start date. To this end the actual start date of 9 June 1980 was changed to 9 November 1980. The holiday periods in the primary bar chart were adjusted, but otherwise everything else was unchanged. However, in this case the risk levels were not significantly changed through starting the project at a more unfavourable time of year for construction operations, and the conclusion in this case was that the project was not significantly sensitive in time or cost to a change in the project commencement date.

The use of the cash flow facility has not been validated against actual expenditure, as it is a recent addition to the suite of programs. However, Fig. 15 is used to illustrate one of the 100 cashflow curves available.



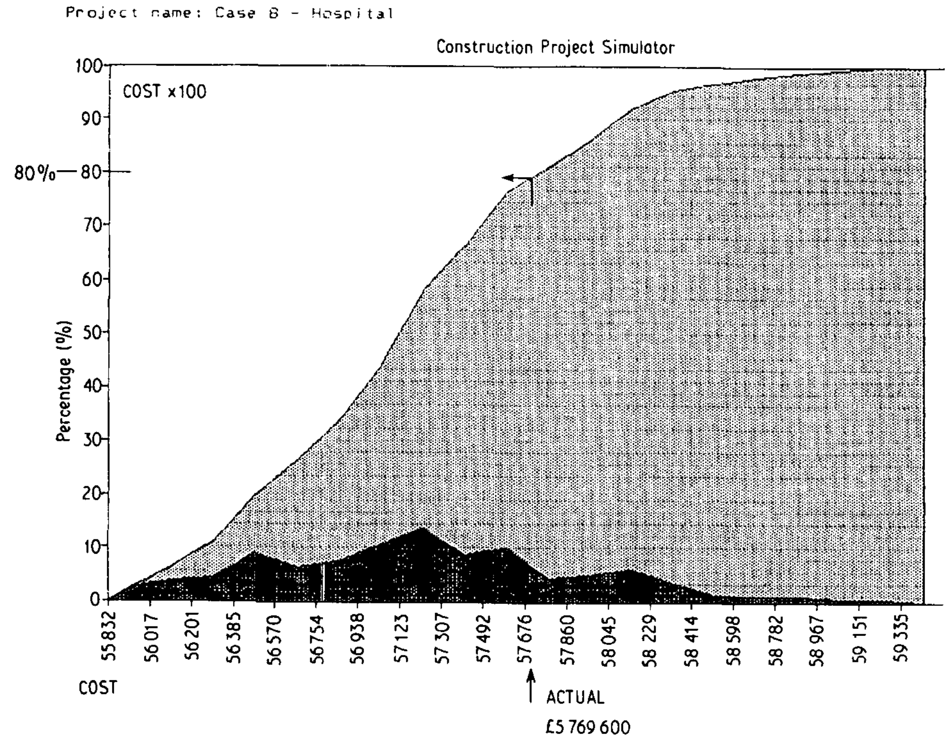
Interference = from secondary level
Variability = from secondary level
Distribution = from secondary level
Annual inflation rate 0%
Minimum = £4 553 529
Maximum = £4 678 396

Mean total cost = £4 617 358
Mean preliminaries cost = £1 001 172
Mean additional direct weather cost = £68 390.24

Fig. 16. Typical simulation result, including weather and zero inflation, for project final cost.

Conclusions

One particular example has been used to illustrate the output of the simulator and how it can be applied to a specific project. However, during the development phase of the research four different projects were simulated to test the model's ability to accommodate a representative range of construction projects – new build office block, refurbished office block, new build



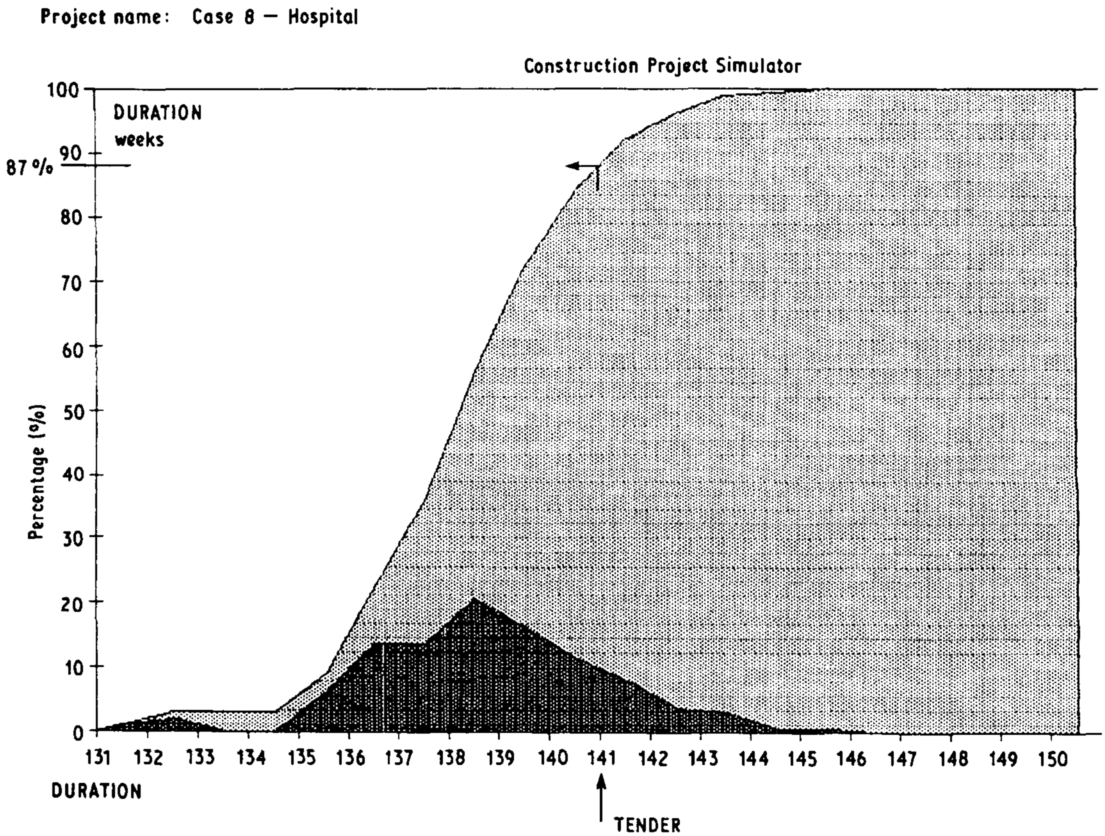
Interference = from secondary level
Variability = from secondary level
Distribution = from secondary level
Annual inflation rate 16%
Minimum = £5 669 177
Maximum = 5 815 731

Mean total cost = £5 741 440
Mean preliminaries cost = £1 001 416
Mean additional direct weather cost = £68 063.22

Fig. 17. Typical simulation result, including weather and 16% inflation, for project final cost.

hospital, and a housing estate – to establish the apparent level of interference affecting the projects and to compare the simulators' predictions with the deterministic predictions of the tender stage, and the final outcomes.

The final construction period for all the case studies was predictable using high confidence factors between 55 and 86%. However, the initial tender periods in all instances were too optimistic. In only one case study did the tender period have a possible confidence factor and

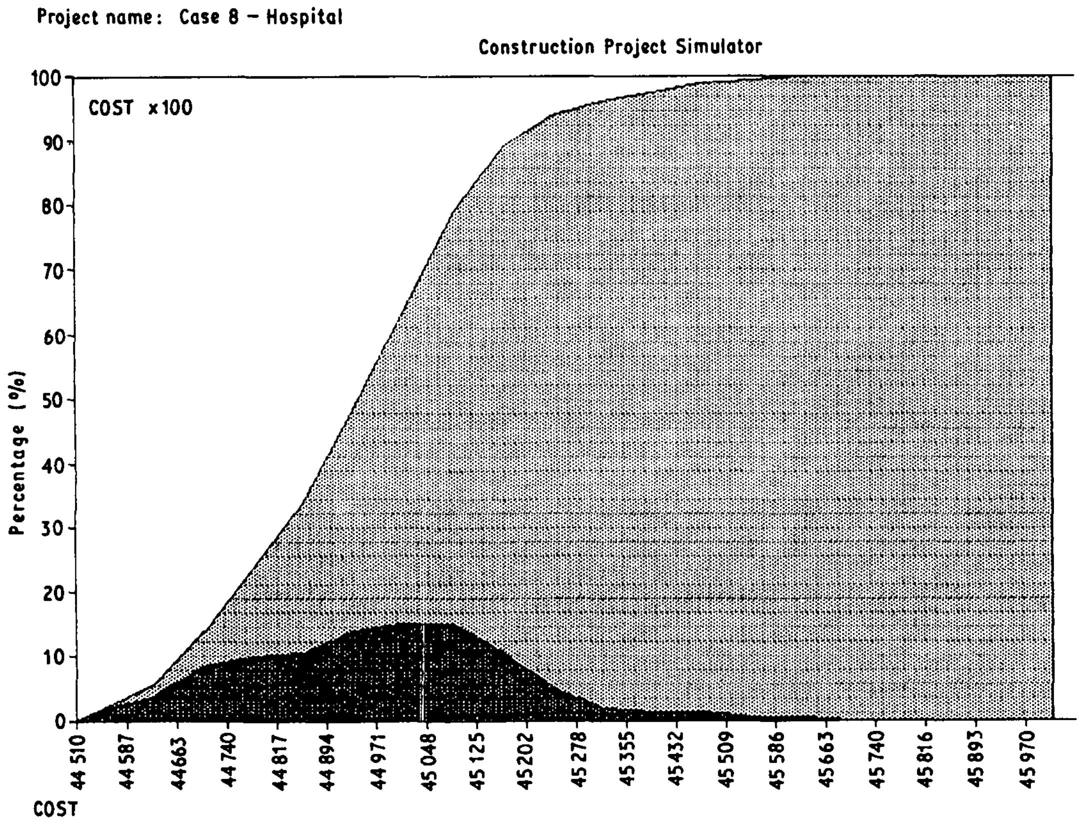


Interference = from secondary level
Variability = from secondary level
Distribution = from secondary level
Minimum = 133
Maximum = 144

Mean total duration = 138.93

Fig. 18. Typical simulation result, excluding weather, for project completion.

then of only 26%, and for all the others the tender period was either unrealistically optimistic or had a very low, between 5 and 10%, chance of being attained. In all cases the tender period had been set by the client's advisers in the tender enquiry, and from the results of the simulation were too low and unrealistic. If the client had not been aware of the risk involved and had taken the tender period as a serious estimate then severe practical problems could have resulted. If realistic tender periods had been established by using reasonable confidence levels (30–50%)



Interference = from secondary level
Variability = from secondary level
Distribution = from secondary level
Annual inflation rate 0%
Minimum = £4 461 245
Maximum = £4 544 869

Mean total cost = £4 500 928
Mean preliminaries cost = £953 947.2

Fig. 19. Typical simulation result, excluding weather and zero inflation, for project final cost.

with the simulator predictions then this might have led to a less defensive and 'claims-conscious' attitude by the contractor and a more positive construction process. The client would also have been aware of the extent and risk of more unacceptable outcomes which could form the basis of time-contingency management and been assessed during the scheme viability process.

The final construction cost for all case studies was predictable using high confidence factors

Table 5. Case study tender and actual outcomes contrasted with the simulation predictions.

	Tender		Actual		Simulation			
					Time		Cost	
Case study	Time (weeks)	Cost (£)	Time (weeks)	Cost (£)	(weeks) $\bar{x}$	90%	(£) $\bar{x}$	90%
New build office block	73	1 313 950	82	1 449 890	80	83	1 422 422	1 451 020
New build hospital	141	4 856 115	148	4 631 785	146	150	4 609 558	4 646 000
Refurbished office block	75	4 006 595	79	4 241 000	79	83	4 241 089	4 271 000
Housing estate	130	3 968 425	135	3 884 000	133	136	3 843 319	3 907 400

N.B. All costs exclude inflation allowances.

between 56 and 88%. However, the initial tender cost in all instances was unrealistic, with one cost being unrealistically optimistic and three being unrealistically pessimistic (see Table 5). These results illustrate weaknesses in the current, deterministic practice of cost contingency management. For two projects undertaken for public clients the bill of quantities was structured in such a manner as to produce a tender figure which would not be exceeded – as this would be unacceptable to government accounting. The contingency amount built into the contract for both cases, however, was higher than necessary. A more realistic contingency budget and tender cost could have been predicted using the simulation results and a high confidence factor of 90%. The other two projects were undertaken for private clients and illustrate two current methods of contingency structuring. In one case the tender cost was unrealistically optimistic, and if the client were not finally to be financially embarrassed a contingency amount over and above the tender cost must have been included in an overall project budget although not in the building fund. In the other case the tender cost was unrealistically pessimistic and higher than the final cost. In this case the contingency amount had been included in the building fund and it is assumed that no additional contingency was allocated in an overall project budget. In both cases an upper level of cost could have been realistically set at high confidence levels using the simulation results. The strategic decision would then have been necessary as to which section of the budget the contingency amount should have been allocated to. If the simulation results had been available to the client and his advisers then all parties would have been aware of the exposure to risk and contingency management placed on a more accurate, objective and explicit footing than occurred in practice.

In all cases, for both time and cost predictions, the simulators prediction of a contract duration and cost was better than that available through current UK working practices. The further highlighting of other possible outcomes – both better and worse – and the quantification of these other values would add a new dimension, not previously available, to the management of the project.

A major element of the research was to demonstrate that the important characteristics of variability and interference, which dominate much construction activity, can be explicitly identified and incorporated in a model of the construction process. This effort has produced a reasonable amount of data for the variability, such that the magnitude of this effect could be identified and determined for use as an input parameter in the simulator. Typical distribution shapes have also been identified for several trades and incorporated in a data bank in the CPS. Also through the distribution entry program it is possible to produce skewed distributions for use where activity durations are considered optimistic or pessimistic. This facility allows the experienced construction manager to include his important intuitive assessment into the simulation.

A similar effort was devoted to the definition and identification of interference. It soon became clear that the more general and inclusive category of interference would have to be refined for a greater theoretical and practical acceptance. This resulted in the identification of the major components of interference into: weather, design, procurement, and 'all other'. This has proved to be more acceptable. The data available for interferences, with the notable exception of weather, has been sparse despite an intensive search in both literature and practice. Data on the weather has been found to be plentiful, in the correct format and cheap. The appropriate value for use as an input parameter to the simulator at the secondary level for the interference category (with the effect of weather modelled separately) has been determined by validating values through sensitivity analysis of real projects.

This process has identified the general interference magnitude to be 7%, with the weather modelled separately, for three of the four case studies. The odd result being for the housing case study where values of 2% had to be employed to produce sensible results. This result is not unexpected, as the design interference in a project with many identical repetitions is inevitably reduced after only a few repetitions of the task. In a similar manner once procedures have been established to procure materials they become a matter of routine and become less susceptible to interruption. In a similar vein it would be expected that the design element of a refurbishment project would be more open to interruption through the need to accommodate new work and existing work – the extent of which is not always known – than that for an entirely new build project. However, the refurbishment project chosen as a case study did not produce sensible results at higher levels of interference. The design effort was particularly responsive to the construction operation as up to six architects were based on site available for almost instant design decisions and inevitably forming a more cohesive and responsive design/construction team. Thus it is postulated that the interference magnitude on this project was beneficially affected by the project management structure. Also it has been demonstrated that interference can be adequately defined and typical values identified through sensitivity analysis.

The CPS now exists as a useful means of modelling important management characteristics of construction projects. It is being used at present to help control a live project and to form the basis of further research in construction management.

References

Ahuja, H.N. (1982) A conceptual model for probabilistic forecast of final cost, in *Proceedings of the PMI/INTERNET Symposium*, Toronto, Canada, Project Management Institute, pp. 23–31.

Bennett, J. and Fine, B. (1980) Measurement of complexity in construction projects: SERC Research Project GR/A/1342.4: Final Report. University of Reading (Available as Occasional Paper No. 8.)

Bishop, D. (1966) Architects and productivity—2. *Building* **272**, 533–63.

British Property Federation (1983) *The British Property Federation System for Building Design and Construction*, London.

Clapp, M.A. (1965) Labour Requirements for Conventional Houses: Current Paper 17. Building Research Establishment, UK.

Crandall, K.C. (1977) Scheduling under uncertainty, in *Proceedings of the PMI/INTERNET Symposium*, Chicago, USA, Project Management Institute, pp. 336–43.

Dressler, J. (1974) Stochastic scheduling of linear construction sites. *ASCE Journal of the Construction Division* **100**, 571–87.

Feiler, A.M. (1972) Project risk management, in *Proceedings of the Third International Congress on Project Planning by Network Techniques*, Stockholm, Sweden, INTERNET, Vol. 1, pp. 439–61.

Feiler, A.M. (1976) Project management through simulation. School of Engineering and Applied Science, Project TRANSIM, LA California, USA.

Fine, B. (1982) The use of simulation as a research tool, in *Building cost techniques: New directions* (edited by P.S. Brandon). E. & F.N. Spon, London, pp. 61–9.

Gray, C. (1981) Analysis of the preliminary element of building production costs, MPhil thesis, University of Reading.

Hall, B.O. and Stevens, A.J. (1982) Variability in construction: Measuring it and handling it, in *Proceedings of the PMI INTERNET Symposium*, Toronto, Canada, Project Management Institute, pp. 559–66.

Harris, R.B. (1982) *Precedence and Arrow Networking Techniques for Construction*. J. Wiley & Sons, London.

Lichtenberg, S. (1981) Real world uncertainties in project budgets and schedules, in *Proceedings of the INTERNET Symposium*, Boston, USA, INTERNET, pp. 179–93.

McLeish, D.C.A. (1981) Manhours and interruptions in traditional house building. *Building and Environment* **16**, 59–67.

Nunnally, S.W. (1981) Simulation in construction management, in *Proceedings of the CIB Symposium on the Organization and Management of Construction*, Dublin, Eire, International Council for Building Research, Vol. 1, pp. 110–25.

Relf, C.T. (1974) Study of the Building Timetable: The Significance of Duration (Part 1). Building Economics Research Unit, University College London.

Riggs, L.S. (1979) Sensitivity analysis of construction operations, PhD thesis, Georgia Institute of Technology, USA.

Roderick, I.F. (1977) Examination of the Critical Path Methods in Building: Current Paper 12. Building Research Establishment, UK.

Rogge, D.F. and Tucker, R.L. (1982) Foreman delay surveys: Work sampling and output. *ASCE Journal of the Construction Division* **108**, 592–604.

Stevens, A.J. (1969) Activity Sampling on Building Sites: Current Paper 16. Building Research Establishment, UK.

Tavistock Institute (1966) *Interdependence and Uncertainty: A Study of the Building Industry*. Tavistock Publications, London.

Traylor, R.C. *et al.* (1978) Project management under uncertainty, in *Proceedings of the PMI Symposium*, Los Angeles, USA, Project Management Institute, Vol. 2, pp. f1–f7.

Tucker, R.L., Rogge, D.F. and Hendrickson, F.P. (1982) Implementation of foreman-delay surveys. *ASCE Journal of the Construction Division* **108**, 577–91.

United Nations: Economic Commission for Europe: Committee on House Building and Planning (1965) *Effect on Repetition on Building Operations and Processes on Site*, Geneva.

Woolery, J.C. and Crandall, K.C. (1983) Stochastic network model for planning scheduling. *ASCE Journal of Construction Engineering and Management* **109**, 342–54.