UNIVERSITY of SALFORD DEPARTMENT of SURVEYING

THE USE OF INTELLIGENT SIMULATION IN COST-TIME FORECASTS FOR HOUSING REHABILITATION WORKS

Final Report

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Abstract

The research aimed to investigate the feasibility of using intelligent simulation for construction cost-time forecasting in order to provide an aid to strategic decision-making in housing rehabilitation work. Essential features were anticipated as being the provision of probabilistic forecasts and the ability to reflect the operational consequences of alternative design and management strategies.

The intelligent simulation envisaged was essentially a hybrid of stochastic simulation and knowledge based systems such that:

- an operational plan for the project would be generated automatically by the system, using knowledge drawn from expert planners;
- stochastic simulation would be used to evaluate project time and cost from the production plan, thus providing probabilistic forecasts;
- site management control of the production process would be emulated by interaction of the simulation with a knowledge base representing the expertise of the site managers;
- a graphics-based user interface would permit real time monitoring and interaction with the simulation.

Low-rise multiple-unit housing rehabilitation projects of a clearly defined type were used as the vehicle for this investigation, as these projects are characterised by high levels of uncertainty and sensitivity of cost and time to operational factors.

The approach adopted was to seek to build a trial system or concept demonstrator. As the aim was to investigate feasibility, no attempt was made to acquire full domain knowledge, effort being concentrated upon establishing the structure and nature of the knowledge to be encapsulated, and determining appropriate methods of knowledge representation and system architecture. Conceptual design of the system was completed within the grant period, but some work remains to be done to achieve an operational concept demonstrator.

The main findings were as follows:

System design

1. A system integrating knowledge-based approaches with stochastic simulation is readily achievable within an object-oriented structure.
2. Automatic operational planning for repetitive works of these kind is also readily achievable,

within an object oriented structure.

Knowledge acquisition

3. The domain of planning expertise examined proved suitable for KBS development. The techniques and heuristics employed are well established and consensus between experts is strong.

4. The domain of site management expertise presented problems; this knowledge appears difficult to both acquire and represent. Only limited progress was made with the simple and direct knowledge elicitation techniques used: there is some evidence that more sophisticated indirect techniques may perform better but it was not possible to test this within the grant period.

5. The experts in housing rehabilitation that were consulted strongly reinforced the view that there is a real need for tools to support both strategic decision making and planning on this type of project.

1. *Feasibility of the intelligent simulation approach*

6. The research indicated that current levels of hardware and software technology are capable of supporting the development of a working intelligent simulation-based construction cost and time forecasting system, where:

   - an object-oriented structure is adopted;

   - the construction projects involved are repetitive, multiple-unit schemes of a type for which a well established body of planning expertise exists;

   - the variety of construction work to be handled by the system is limited;

   - a very limited and crude representation of site management control decisions and actions is acceptable.

1 Introduction

Housing rehabilitation projects are characterised by high sensitivity of cost and duration to operational factors, and by high levels of uncertainty. The most notable causes of these characteristics are the generally piecemeal nature of the work, delays in the availability of workplace through prior occupation, difficult working conditions and variable amount of work required between units. Conventional methods of construction cost and time forecasting, based on unit rates and rules of thumb, are incapable either of reflecting operational consequences or explicitly recognising and evaluating the effects of uncertainty (Beeston, 1987; Brandon, 1982). Consequently, these methods perform rather poorly when used as tools to evaluate alternative rehabilitation strategies. Above all, they lack the important link between strategic design/management decisions and the resulting construction process. Methods based on operational models and providing probabilistic rather than deterministic output, would therefore seem to be more appropriate in this situation.

Much research interest has been shown in recent years in the potential of production plan based stochastic simulation models for construction cost-time forecasting. A number of systems have been postulated (Baxendale, 1984; Bowen *et al*, 1987; Jackson, 1986) and at least two, the Construction Project Simulator (Bennett and Ormerod, 1984) and CASPAR (Thompson and Willmer, 1985), have been developed into working prototype systems. These systems however, although generally fulfilling their intended purpose, are known to have limitations, the most significant of which are:

(1) An operational plan for the construction work must be prepared. The conventional construction planning techniques employed are detailed and time consuming, and, at the critical formative stages of a project, the knowledge necessary for the task is not normally accessible to designers.

(2) The key aspect of management control during the construction process is not represented in the stochastic systems reviewed which contain what are essentially random walk models and as such tend consistently to over-estimate the dispersion of possible outcomes.

1.1 Background

Hybrids of simulation and knowledge based systems offer a potential solution to these problems. A knowledge based approach can be used to support the formulation of the production plan upon which the simulation will be based, making the process at least semi-automatic. This may speed the setting up of the simulation to a level where 'what if' experimentation can take place, and enable the participation of users with limited expertise in contract planning.

A knowledge based approach can also be used to emulate the monitoring and control actions of site management through run-time interaction with the stochastic simulation. Under this control action, simulation runs should more accurately represent feasible real time situations. The dispersion of simulated outcomes should therefore be a better estimate of dispersion in the population of real outcomes.

Marston and Skitmore (1990) reviews some of the extensive research that has been undertaken, most notably in the United States, on knowledge based approaches to the automation of construction planning. Outside the construction field, there has been some work on both the development of hybrids of simulation with knowledge based systems (Doukidis and Paul, 1985); Doukidis, 1987; O'Keefe and Roach, 1987; Paul and Chew, 1987; Paul, 1989) and the use of knowledge based systems in the control of discrete event simulations (Flitman and Hurrion, 1987).

The above work will be examined in more depth in the next chapter.

1.2 Goals of the Research

A one year study was made to investigate the feasibility of an intelligent simulation approach to construction cost and time forecasting. The objective was to develop a pilot system capable of acting as a concept demonstrator and provide a basis for further system development.

The purpose of the proposed system was to facilitate the evaluation of alternative strategies under uncertain conditions. As indicated in Fig. 1, the system is intended to enable the user to test alternative management strategies (decanting of tenants, extent of tenant participation, etc.) and design requirements (eg., the extent of renewal or repair) and output probabilistic estimates of total cost and contract duration.

Current research is limited to low-rise housing internal modernisation projects. These projects have been found to exhibit all the characteristics of multi-unit rehabilitation work in general, yet provide a manageable scope for knowledge elicitation.

Fig. 1: The system action

2 Methodology

2.1 Programme determination

The study was carried out in the following stages:

A literature survey was conducted for both computerised and rehabilitation fields. At the same time, knowledge acquisition commenced for low-rise housing refurbishment work. Consequently, a research programme and general methodology were established. These have included the research aims in general and objectives for developing the system prototype in particular. Techniques for plan generation and calculation were chosen and the goals of stochastic simulation and graphics visualisation clarified. The pilot system prototype was then developed and an example of a real project was used for system verification.

Housing rehabilitation work may be either external or internal (modernisation). In contrast with new construction, there is little technological dependence between internal and external work. As a result, they are not only often done by different contractors, but also at different times during the construction programme. In order to keep the research work within practical bounds therefore, it was decided to restrict the field to internal modernisation work as this is more extensive and problematic than external work and also provides a model for others environments.

As a construction domain, low-rise housing was chosen not only because of being the most frequent type of work encountered in the construction industry, but also because of variety and complexity of managerial problems involved.

2.2 Literature Survey

Computer simulation offers a means of experimenting with representations of complex systems. The experimentation can be interactive gaming or classical experimentation designed to represent stochastic behaviour (Pidd 1989). There has been a lot of interest in computer simulation of construction projects, based on conventional planning models of the production process. Jackson (1983) advocates the stochastic simulation in the evaluation of conventional critical path network plans. CASPAR, developed at the University of Manchester Institute of Technology (Thompson and Willmer, 1985), is a project management tool aimed at risk assessment of strategic development decisions for major civil engineering projects, again employing stochastic evaluation of a network plan. The Construction Project Simulator (CPS), developed at Reading University (Bennett and Ormerod, 1984), models building projects using Gaantt charts and is particularly interesting because it invokes uncertainty in two forms, the 'normal' variability in the durations of activities, and interferes with (or disruptions to) the production process, such as the effects of weather, late instructions, sub-contractor default etc.

Such systems give probabilistic output and, being based on planning models of the production process, are capable of representing operational consequences. However, they require extensive and skilled work to formulate the production plan. This mitigates against their being used to experiment in a gaming, interactive way. Problems also occur if the simulation is to be undertaken in the early stages of project development, because detailed information is not available and contract planners are not yet involved. There is a more fundamental problem however. These systems rely on the stochastic evaluation of a predetermined plan. The reality of construction projects is different. It involves extensive tactical planning by the site management during the production process together with management control action. In the real world the stochastic element is not allowed to run unchecked, but triggers responses from management. Actual project cost and time is a product, not just of planning and chance, but also real-time management control. Building interdependence into the model may deal with some aspects of this problem, but has a severe penalty in increased complexity, and demands considerable skill to the model builder. A different structure is necessary to tackle the problem at its root.

Hybrids of simulation and knowledge based systems offer a potential solution to these problems. Adding intelligent components increases the capacity to simulate complex systems, particularly those with significant behavioral components (Paul 1989, Flitman and Hurrion 1987, O'Keefe and Roach 1987). A knowledge based approach can be used to support the formulation of the production plan upon which the simulation will be based. This will speed the process of setting up the simulation, and make it accessible to users with limited expertise in contract planning. The same knowledge based systems can also be used to allow replanning to take place during the simulation, where events have caused unacceptable deviations from the original plan. This latter facility can be enhanced by the provision of a second knowledge based module representing the construction management domain, and enabling the tactical decision making and control actions of site management to be emulated within the system.

Construction contract planning is a very complex process, and the use of expert systems in plan formulation has been the subject of extensive work, particularly in the USA (see for example Hendrickson et al 1987, Ibbs and De La Garza 1988, Navinchandra et al 1988, Alshawi and Jagger 1989, Moselhi and Nicholas 1990). The greatest successes have been with constrained or simplified situations, such as oil platform construction (Levitt and Kunz 1985), where a limited set of activities occur with largely definite precedences. However, because of the high level and set pattern of repetition involved, relatively simple construction preceding and a limited number of activity types on a given project, multiple unit housing rehabilitation appears to offer the potential for at least semi-automatic plan formulation.

Outside the construction field, work has taken place on the use of expert systems in the control of discrete event simulations (Flitman and Hurrion 1987), from which some lead may be taken in the emulation of management control in the simulation of construction projects.

2.3 Knowledge Acquisition

For the purposes of the feasibility study, research was limited to multi-unit low-rise housing internal modernisation work. These projects exhibit the characteristics of multi-unit rehabilitation in general, yet provide a manageable scope for knowledge elicitation. The knowledge domain to be represented covers three related areas: *technology and resources*, *planning and organisation*, and *site management*, and these are described below.

Housing rehabilitation projects are characterised by sensitivity of cost and duration to operational factors, and by high levels of uncertainty. As a result, the knowledge elicitation domain chosen was as wide as possible - comprising consultancy firms, private contractors and subcontractors, Direct Works Organisations, academic staff, etc. Several experts were interviewed, some of them more than once. The main difficulties encountered were in acquiring productivity and cost information, and information on *in situ* decision making strategies.

2.3.1 Technology and resources

This is knowledge of the technical implications of the proposed work. It includes elements (or topics) of modernisation work (eg., electrical renewal, plumbing installations, plastering), the operational precedence of the activities involved and resource requirements. The knowledge required comprised:

2.3.1.1 Elements and activities describing the full range of modernisation work

The specifications for Rehabilitation Works for Residential Buildings (RICS, 1990) describe the full range of possible work involved. The work can be described by ten elements (separated according to trades) with each one involving a number of activities (each activity being carried out by a specific gang). This information was incorporated into the knowledge-base in two levels (Elements and Activities) as shown in Table 1.

Table 1: Elements and Activities

Elements	Activities
Internal-joinery	First-fix joinery
	Second-fix joinery
	Ironmongery
	Joiners final fix
Plumbing operations	Gas service
	Water service
	Central heating
Plastering	Dry linings
	Gypsum plaster
Glazing	Glazing doors
	Glazing windows
Brickwork	Rake out / Repoint b/wk
Electrical renewal	Electricians first fix
	Electricians second fix
Clearance and Stripping out	Hack off plaster
	Plumbers strip
	Electricians strip
	Clearance of household effects
Internal finishes	Sealant
	Floor finishes
	Ceramic tiling
Painting-Decorating	Apply wallpaper
	Paint walls
	Paint ceilings
	Paint sundries
Preliminaries	Scaffolding
	Technical staff
	Plant
	Temporary electric
	Clerical staff
	Transport
	Sanitation/Compound
	Main office

The Elements level is essentially the user interface. As a result, a person who is not familiar with technical details may use the system. Also, the system may also used in the preliminary stages of projects where only a work program is defined. Thus, a description of the extent of the work is needed for the automated selection of the activities required.

2.3.1.2 Operational sequence of the work

This is the order in which activities are carried out and it is essentially dictated by the technological relationships between the activities. Information was obtained from construction planners to whom possible scenarios of required work were presented, triggering their suggestions upon the activity sequence which should be followed. The information gathered concerned the standard precedence or concurrences of the activities and the effects of the context or extent of the work.

One example of a standard activity precedence is that plastering can only start after the joinery, plumbing and electrical first fix have been completed - the respective second fixes only being carried out when the plastering has been completed. (There is clearly an established relationship between these activities which does not depend on the extent of the work and will not therefore be altered even if plumbing work is not required.)

Further to this it was found that the main effect on the activity order is whether the housing units are tenanted or decanted as this affects activities such as the provision of temporary services (temporary immersion heater and sink).

2.3.1.3 Durations of the activities and resource requirements

The values of activity durations are decided by the resource levels involved. There is a range of possible gang sizes which can be used to carry out an activity, and a planned duration will result for each possible gang size. From this range of gang sizes (and therefore planned durations), there is a size which results in optimum productivity (minimum or non-existent redundant time). The nature of the task is such that the judgement on gang size is very much a matter of experience of the individual planner. Fortunately, there was a good consensus between the planners on the optimum gang sizes (and planned durations) and possible values for each activity. Table 2 gives the gang compositions obtained.

2.3.1.4 Productivity rates and costs

Rates of productivity and costs for items of work related to internal modernisation were extracted from published databases (Wessex, 1987a, 1987b; Spons 1985, 1989). The productivity rates apply for specific gang sizes and compositions (the ones indicated above as optimum).

Construction planners often base their estimations on productivity records from past projects which may result in more realistic duration calculations. Unfortunately access could not be gained to such kind of information due to commercial sensitivity. However information concerning existing productivity differences when the housing units are tenanted or decanted, or when the activity takes place in the initial or final housing units (impact of learning) was extracted from site managers and could therefore could be incorporated as procedures in the knowledge base. An indication of how productivity increases when the properties are decanted is provided in Table 3 where it can be seen that some work items can be carried out up to 20% or 40% more efficiently.

Table 2: Gang Compositions

Activity	**Optimum gang size**	**Possible gang size**
First fix joinery	2 joiners 1 labourer	1 joiner 1 labourer
Second fix joinery	1 joiner 1 labourer	2 joiners 1 labourer
Joiners final fix	1 joiner 1 labourer	2 joiners 1 labourer
Rake out/ Repoint Brickwork	2 bricklayers 1 labourer	1 bricklayer 1 labourer
Clearance and Stripping out	3 labourers	2 labourers or 4 labourers
Plastering	2 plasterers 1 labourer	1 plasterer 1 labourer

Table 3: Increased efficiency in working in decanted rather than tenanted areas

Items up to 20% more efficient	**Items up to 40% more efficient**
paint-to-woodwork	seal-window/door-frames
paint-to-pipework	carpets
hack-off-wall-plaster	take-up-carpets
hack-off-stud-plaster	strip-internal-joinery
clear-out-rubbish	clear-roof-space
install-lighting circuit	strip-flue-pipes
plasterboard-to-walls	strip-water-pipes
plasterboard-to-ceilings	strip-gas-carcassing
plasterboard-to-soffits	strip-kitchen-units
form-new-stud	strip-wiring/fittings
ceilings-linings	plaster-kitchen
wall-linings	replace-waste/soil-pipes
install-rising-main	install-kitchen-worktops
mains-pressure-branch	
pipework-to-sanitary-appliances	
ventilation-pipes	
central-heating-pipework	
waste-traps-to-appliances	

The cost rates were classified in five categories:

1. Trade-costs per hour of work for bricklayers, joiners and labourers directly employed by the contractor. The overall cost of their work is the product of the trade-cost per hour multiplied by the number of hours required for each activity in each housing unit multiplied by the number of housing units.

2. Specialist costs of subcontracted activities per housing unit. These costs include all the elements of cost required to carry out the activities.

3. Material costs per unit of work for the activities carried out by the contractor. The overall cost of these activities is the product of the material cost multiplied by the quantities of work for a specific house type.

4. Plant costs per hour for the activities carried out by the contractor. The overall plant cost is the product of the hourly plant cost multiplied by the number of hours required for each activity in each housing unit multiplied by the number of housing units.

5. Overhead expenses. These include salaries of technical staff, scaffolding, temporary accommodation for tenants, etc.

2.3.1.5 Quantities of work

The quantities of work for 1, 2 and 3-bedroom house types was extracted from bills of quantities of past typical projects. These were provided by building surveyors and organised according to the trades involved.

2.3.2 Planning and Organisation

This is knowledge concerning the planning and scheduling methods employed. The techniques themselves are well established and documented, but choice of technique and heuristic knowledge on the method of application to this type of project required elicitation. The main source here was: contract planners from construction companies with experience of modernisation work; professional literature; and academics. The technique found to be the most convenient to apply was the line of balance method. The application of which the line of balance method requires the following parameters to be incorporated in the calculations:

2.3.2.1 Optimum pace of work

Repetitiveness of the work in a multi-housing environment makes continuity of the work one of the most significant factors for planning. In order to maintain the continuity of work by avoiding delays caused by interferences between the gangs within a housing unit, a certain pace for the activities has to be maintained. This pace, which is established and maintained for the activities carried out by the contractor, has an important impact on the overall duration of the project, the overall cost, and also on sub-contracted work (its continuity or otherwise).

The construction planners indicated that the pace of the activities depends on whether the properties are tenanted or decanted. For tenanted properties the preferred pace is 5 days for each activity, while for decanted properties it is 4 days, as the operations in each unit can be accelerated when the occupants are not present.

2.3.2.2 Criticality

Whatever the context the work is undertaken, a number of activities are always critical to the overall project duration. In all scenarios examined, it was found that all the activities undertaken by the contractor together with plastering (from sub-contracted activities) are critical and are therefore used in calculating the project's overall duration.

2.3.2.3 Handover rate

The handover rate is the expected number of units, usually defined in the contract, which has to be completed and delivered each week. The handover rate determines the overall duration of the contract as well as the resource requirements necessary to complete the work within the contract period.

2.3.2.4 Possession-rate

The number of housing units that can be worked on concurrently also determines the overall duration and resource requirements, as well as the number of tenants who may have to be accommodated elsewhere.

2.3.3 Site management

This is the knowledge necessary to represent monitoring and control actions taken on site during the construction process. In particular, it is necessary to represent decisions that would be made on site as a result of deviations from planned progress. This knowledge is central to the process of intelligent simulation. The knowledge source was contract managers from construction companies. Informal and then semi-structured interviews were the main methods employed, plus some introspection on both simulated and real case studies. It was not necessary, for the purposes of this feasibility study, to attempt to achieve full domain knowledge although it became clear that a small amount of introspection on simulated case studies could be an effective method of completing acquisition in this domain.

More specifically, the following were investigated:

2.3.3.1 General rules of thumb

In order for construction work to be carried out more efficiently, certain directions have to be followed depending upon the site layout. For example it is commonly accepted that work should begin from the most remote unit. This minimises the movement of workers and materials transportation distances at the end of the project by concentrating them around the centre of the site and therefore closer to the material storage areas. Moreover, delivering materials direct to the house units by suppliers makes the order of work less important than with new construction, especially when the interest is in total duration and cost only.

There is also a general consensus that, in the case of multi-storey buildings, roofwork and work in the top floors are carried out first. As the work moves downwards, this is obviously more effective than having to transfer labour and materials to higher floors through the completed lower ones and thereby increasing the probability of damages occurring.

2.3.3.2 Risk and uncertainty

Experience indicates that some potential problems which are inherent in the work are more likely to occur than others. For example, plastering is often delayed because of the extra amounts of plaster required to those estimated by the Surveyor. Also wood rot, which is also difficult to anticipate, causes unexpected work not incorporated in the plan.

Another common problem is that, although every week a number of houses have to be decanted in order for the work to commence, tenants may not vacate the premises on schedule, creating delays and additional problems (eg., subcontractor and supply delays).

In the case of multi-storey properties problems also occur with the replacement or renewal of electrical and plumbing installations. Work has to be carried out in a number of dwellings in order to renew the services in a individual dwellings because of existing connections. It is therefore impossible to estimate the amount of time required to complete the work with any accuracy.

2.3.3.3 Sub-contracted activities

Part of the workforce which carries out the work is directly employed by the contractor while other activities are sublet to specialists. The amount of subcontracting varies if the contractor is private or a local authority. Usually private contractors only employ directly joiners, labourers and bricklayers, while local authorities (direct labour organisations) also employ directly plumbers and electricians (mainly for the final fixes) and painters.

It was decided that the productivity of subcontracted activities would not be simulated as delays are not frequently experienced. The activities for which productivity is simulated are the ones undertaken by the contractor. In the case of delays the most usual way to improve productivity and therefore bring the activity back on schedule is by reallocation of resources, i.e. using alternative gang sizes. According to the construction managers consulted, this is their primary strategy when falling behind schedule for, although it creates increased costs, it is essential to take this action in order to avoid exceeding the contract duration.

Problems were experienced with commercial sensitivity in acquiring knowledge which bore directly on issues of productivity and cost, and this area in particular requires further work with simulated case studies.

Knowledge acquisition of site management decision-making was initially tackled using informal interviews only, and success has been limited. A significant shortfall remains in this area at the time of writing. However, it is felt that a machine recorded protocol analysis is likely to be the most appropriate way forward, using a development version of the system itself specially modified to allow the interactive participation of the experts (site managers) in simulated project runs.

2.3.3.4 Extra-pay

There was a general agreement amongst managerial staff not to use pay incentives when delays occur. It was thought that this would prevent reduced productivity in regular time.

2.4 Pilot System Development

One of the aims of the feasibility study was to investigate the possibility of building an expert system which will allow the user (either planner or contractor), not only to obtain a probability distribution of cost and time for given low-rise housing modernisation projects, but also to check the sensitivity of the schedule to different factors (such as delays, low productivity, bonuses, politics, etc.) through a simple and friendly graphic interface (see Fig 1).

Thus, the aim of the pilot system prototype development was defined by two pragmatic goals:

- realisation of the proposed theoretical approach to multi-unit low-rise housing refurbishment.
- developing the methodology for possible use in other construction environments.

As a result, the development of the prototype was concentrated two important issues - *knowledge base plan formulation* and *knowledge based simulation*.

Fig. 2: Theoretical System Schema

The theoretical schema for an intelligent simulation approach to construction cost-time forecast, following Marston (1991), was adopted for the pilot system (Fig. 2). Here, it is envisaged that the user inputs the requirements for the project in terms of a work description (design) and execution strategy (management), including such matters as decanting of occupants, hand over rate required, subcontracting policy, etc. A knowledge based module then automatically formulates the plan which will act as the model of the production process during simulation, accessing data such as productivity rates from a database of technical information. The production process itself is then simulated, drawing productivity rates and occurrences randomly from appropriate probability distributions and again accessing information from the database. During simulated production the knowledge base control facility emulates management control by triggering and specifying action such as revision of the subsequent plan, resource level adjustment etc. The resources consumed are costed to give a project total cost, and this value and the total project duration are recorded. The simulation iterates through the specified number of trials and the resulting probabilistic time and cost estimates provide the main system output.

3 Research Approach

3.1 Object-Oriented Approach

The suitability of an object oriented-approach to the automation of planning is well established, not least because it avoids the need to use complex algorithms to determine precedence (Ref 10). In addition the features of frame-based representation are particularly relevant to this problem - the repetition of similarity in multi-unit housing modernisation clearly suits inheritance features, and the ability to implement a procedure from within a frame provides an elegant mechanism to effect stochastic simulation.

3.2 Computerised System Choice

Taking into account the complicated and sophisticated problems to be solved (primary by using heuristic knowledge and methods) on one hand and the literature description of analogous projects and the authors' experience on the other, an object-oriented programming approach was chosen. *GoldWorks II* object-oriented expert system shell was selected as the main development environment on both *SUN SPARC* Station and PC-386 computers.

GoldWorks provides a full object-oriented system for knowledge representation that includes classes (frames), instances, methods and inheritance. A superclass of a frame, from which all slots are inherited, is a parent frame. The slots of a frame are the items within it that are organised to hold information. A facet is a property of a slot that further defines it and adds functionality to it.

Methods in *GoldWorks* are called handlers. These message-passing handlers are procedures that can be attached to frames and are inherited down the hierarchy just like slots.

There are three types of rules in *GoldWorks*: forward, backward and bidirectional. These rules may refer to instances and slot values with variable names, so general rules may be created. Moreover, rule sets may be created by defining a specific goal.

GoldWorks includes graphics tools, which allow creation of planar graphic images and the manipulation with them in dynamic mode. In addition, an interface to *Dbase III+* exists, which provides flexibility in storing and updating the database information.

The following computer equipment was dedicated specifically for the research:

- *Sun SPARC WorkStation.*
- *Toshiba PC-386 Portable*
- *Elonex PC 386SX-160*

- *Epson Printer 1050*

3.3 The System Structure

The conceptual structure of the proposed system is shown in Fig. 3.

Fig. 3: Conceptual structure of the system

Fig. 4: Hierarchical structure

3.4 Knowledge base structure

There are four class levels, organised in a hierarchical structure as shown in Fig 4, which connect high level user input of the proposed work through to low level technical detail. Strategic decisions concerning the requirements and context of the proposed work are thus linked to resource consumption implications.

The structure can be seen implemented in the screen dump illustration Fig C1 in Appendix C.

Considering the frame levels in more detail:

3.4.1 Level 1

Table 4: Project Level Structure

Object	**Type of Constraint**	**Range**	**Value**
Contract duration	RANGE	0-1000 (days)	to be specified by user
Handover rate	RANGE	1-30 (number of houses to be delivered per week)	to be specified by user
House number	RANGE	1-300 (overall number of houses)	to be specified by user
House types	RANGE	1-20 (number of types)	1 (default)
Possession rate	RANGE	1-30 (number of houses where work takes place concurrently)	to be specified by user
Project name	LISP TYPE		project's name to be specified by user
Project place	LISP TYPE		project's location to be specified by user
Tenants	ONE OF	IN/OUT	IN (default)

The project level carries information which is common to the whole project. In part, this information is descriptive i.e. project name, project location, etc. In part, it provides data for calculation and decision making, i.e. number of houses, possession rate, handover rate, house type, if the properties are decanted or tenanted during the work, etc. All information at this level is be obtained interactively from the user through a special window-menu and is stored in an instance of the frame 'Project'. The menus are implemented as graphic objects and be activated by messages. More specifically, at this stage the Project Level structure contains the slots shown in Table 4.

3.4.2 Level 2

The Elements level consists of groups of activities i.e. major work sections such as plumbing operations, electrical renewal, internal finishes, internal joinery, etc. There are 10 elements describing the full range of possible internal modernisation work although not all of them are needed for each individual project. Each Element frame contains a predefined menu, which helps to specify the kind of work to be done under the element. The information obtained is stored mainly in the Element instances. Table 5 gives the slots containing the Element structure:

Table 5: Element Level Structure

Type	**Type of Constraint**	**Value**	**Default**
Actual	ONE OF	Y/N (to indicate whether work under this element will or will not take place)	y
Place size	ONE OF	EACH HOUSE / WHOLE SITE (to indicate whether the workplace for a group of activities will be each house in a predefined sequential order or if the group of activities serve the purposes of the whole project, for example the Element Preliminaries which includes activities like scaffolding or temporary accommodation for the tenants.	to be specified by the user

Together with the slots described above, the Elements contain the slots inherited from the Project level (parent level). The default value for place size is **EACH HOUSE** for all Elements except Preliminaries

3.4.3 Level 3

The Activities level includes all work that is likely to occur within a particular element and is in effect a library of approximately 50 activities. By using information inherited from the previous level together with predefined rules, the required activities are selected.

Table 6: Activities Level Structure

Type	**Type of Constraint**	**Values**	**Default**
Contract	ONE OF	SELF, SUB, MIXED	to be specified by the user
Critical	ONE OF	Y/N	to be specified by set of rules.
Dur-actual	ONE OF	Y/N indicating whether the specific activity has to be carried out or otherwise)	to be specified by set of rules
Finish date	RANGE	0-1000 (days)	to be specified by set of rules in each house where the work will take place.
House type	ONE OF	1-BR, 2-BR, 3-BR (1 bedroom, 2 bedrooms, 3 bedrooms respectively)	to be specified by the user (the house type will indicate which of the in included in the cost-time
Pace	RANGE	1-50 (days)	to be specified by set of rules
Seq-no	RANGE	1-10000 (the preceding activities always have lower values).	have been defined for maximum work programme according to technological demands and heuristic knowledge. To be changed by set of rules for actual context of work.
Start date	RANGE	0-1000 (days)	no actual values: to be calculated by set of rules and procedures in each house where work will take place.
Workload	ONE OF	NORMAL, OVERLOADED	NORMAL: actual values: to be specified by set of rules for the SELF-contracted activities according to employed gang size.

In addition to setting up the project plan, this level is also used during simulation. The creation of instances for each activity is automatic. The number of instances is usually the same as the number of houses in the project. An example of objects at this level is given in Fig A3 in Appendix A. The data necessary for duration calculation in the planning stage (gang sizes, productivity, quantity of work, etc.) and 'actual' values of productivity in the simulation stage are obtained from the bottom level, ie. items. The knowledge of possible work sequences and their influence on project duration is contained within the slots as default values. These values (sequence, criticality, etc.) may be modified by special sets of rules and functions according to the context in which the work is undertaken.

These slots, together with those inherited from the parent levels, comprise the Activities level (Table 6).

3.4.4 Level 4

The Items level allows the activities to be connected to their component resources. The slots contain the data necessary for cost calculation in the planning and simulation stage (ie. cost of gang per hour of work for the contractors activities, cost of sub-contracted activities per housing unit, quantity of work depending on the house-type, etc.) and the data necessary for duration calculation in the simulation stage (ie. values of productivity and range of possible values, and the effect of context variables such as work stage, season, conditions, etc.).

These slots, together with those inherited from the previous

3.5 Rule Bases and Procedures

There are four main categories of rules and procedures in the system:

3.5.1 Plan content selection

This set of rules selects the activities required by the project and determines their sequencing from a predefined set of technological precedences (slots of seq-no in Level 3).

3.5.2 Plan information generation

These consist of rule sets for the establishment of pace and gang sizes. Messages and procedures are used to create and update slot values, as well as for automatic creation of instances for the Activities level. The main goal of this set of rules is to establish a realistic pace by taking into account desirable gang sizes and organisational constraints.

3.5.3 Duration and cost calculation

The rules and procedures are applied to the line of balance technique. In the planning stage, the same working pace is assumed for all instances of an activity. During the simulation stage, simulated actual durations are substituted for the planned duration for each activity in each workplace.

Table 7: Items Level Structure

Type	Type of Constraint	Values	Default
Actual cost	ONE OF	Y/N (indicating whether the specific item of work has to be carried out or otherwise)	Y or N: actual value to be specified by set of rules
Material cost	RANGE		per unit to be specified by the user.
Productivity \	RANGE		to be specified by the user for the SELF-contracted activities: actual values to be updated by connection to the Data Base of specific user for the SELF-contracted activities.
Min-Prod	RANGE		default value to be specified by the user for the SELF-contracted activities according to employed gang (to be used as boundary value for triangular function - Monte-Carlo Method).
Max-Prod	RANGE		to be specified by the user for the SELF-contracted activities according to employed gang (to be used as boundary value for triangular function - Monte-Carlo Method).
QTY-1BR	RANGE	values for each item of work in one-bedroom properties	
QTY-2BR	RANGE	values for each item of work in two-bedroom properties.	
QTY-3BR	RANGE	values for each item of work in three-bedroom properties.	

3.5.4 Decision making in response to monitoring of the construction process

The rules here cover situations where the planned schedule requires updating and/or changing. In such cases the appropriate solution is adopted, and its influence on cost and duration calculated.

3.6 Data Base

For the present feasibility study, productivity rates, labour and material costs etc., are taken from published catalogues and defined as default slot values. For an operational system these values would be drawn from a linked database. The possible structure of such a database is shown on Fig 5. It allows for ranges of productivity rates as functions of different factors (seasons, project stage, project location, etc.), available gang sizes, trade and labour costs, etc.levels, comprise the Items level (Table 7).

Fig. 5: Possible database structure

3.7 Verification and Validation

The prototype needs to be validated against live project results. Different solutions and tactics should be tested and the results compared with known outcomes. For example:

{tenants in; tenants out}
{keeping constant time or cost}

4 System Operation Stages

This chapter describes the proposed implementation of the above approach by developing an Knowledge Based Expert System.

There are two main stages of system operation:

- generation of a planned schedule
- simulation of site production

Fig. 6 shows the system operation as a process, the two main stages being separated by a dotted horizontal division.

4.1 Plan Generation

An operational plan for the work is generated automatically from the description of project requirements and constraints input by the user, together with the knowledge and data contained in the system rules and database. The technological and heuristic knowledge is used to establish the order and sequence of activities. The total planned duration is calculated using the line of balance technique. **As the purpose of the system is to emulate reality, it does not seek to determine an optimum solution, but simply a realistic and operable plan.** The main purpose of the plan is to provide the basis for the simulation process. Planned cost and duration are calculated from average productivity rates and resource costs.

The development phase of the system is based on the default values of productivity, gang sizes and compositions, material and unit costs, etc. Once the system becomes specific construction domain oriented, this information may be updated/upgraded prior to project description input.

4.1.1 Input project description

Common project information and descriptions (project name, place, number of houses etc.) as well as decanting and managerial strategies is entered into the system interactively by the user by a special window-menu. The information is stored in the instance of the Project main frame and, as a result, inherited by all other system frames.

Project content, which in the preliminary stages is defined as a work programme only (ie. which kind of work to be done), is entered in the next stage.

Fig. 6: A process representation of the system operation

During data input it is important that the user should be guided and asked properly. Also, the system should complete/generate any lack information. To do so, the Elements level of frame is used. Each frame contains a set of predefined menus, which are chained between menus from different Elements (see examples in Appendix). These menus are implemented as graphical objects and activated by messages.

This information is stored mainly in Element instances, which also contain technological information (and type of contractor) and default values in case the user does not know the exact context of the work.

4.1.2 Break down into activities

Each Element class consists of sufficient groups of activities to suit any reasonable modernisation programme. Each Element has a different number of activities (e.g. one for Brickwork and five for Plumbing operations) and different kinds of connections (e.g. only one Plastering activity may be selected - dry linings or Gypsum plaster finishes; only specific combinations of Plumbing operations are allowed depending on the chosen central heating system). As a result, the breaking down of work descriptions into activities is actually a process of heuristic rule based **selection** of an appropriate set of activities within each Element group for a given context of work. These rules have been derived as a result of the elicitation of knowledge based on recommended technological solutions for housing modernisation work.

4.1.3 Establishing the sequence and pace of the work

All activities have a predefined sequence of work. This sequence, together with the criticality of the activities, are determined as default values for. These values may be modified by special sets of rules and functions according to the context in which the work is undertaken. The knowledge acquisition phase showed that there are only very few changes in work sequence and criticality when the work programme is shorter than the default one.

The default values are defined in units of ten to make the order exchange easier. Thus, for example, moving activity number 30 forward involves changing its slot value from 30 to 15. An example of a rule updating the sequence of the activities is the following:

Rule name:ORDER - IRONMONGERY - R1

Rule text: IF
(INSTANCE ?IRONMONGERY IS IRONMONGERY WITH SEQ-NO ?ANY)
AND
(INSTANCE ?NEW-DOORS IS NEW-DOORS WITH DUR-ACTUAL NO)
THEN
(INSTANCE ?IRONMONGERY IS IRONMONGERY WITH SEQ-NO 202)

The pace of the work for refurbishment modernisation work is defined mainly by the decanting policy. As mentioned earlier, the pace of 5 days per house was found to be the most suitable for main contractor work for non-decanted properties, while 4 days is preferred for decanted properties. This pace is desirable not for the appropriate quantities of the work involved and composition of gang sizes, but they are also convenient for technological and control purposes.

4.1.4 Cost calculation

The overall cost consists of the following elements:

Ctotal = Cprel + Csub + Cmat + Clab + Ctemp

where

Cprel includes the sum of expenses per week for scaffolding, hired plant, salaries of technical and clerical staff, temporary electric supply, main office establishment, sanitation/compound services and transport. The overall preliminary cost is obtained by multiplying the sum of weekly rates by the number of weeks needed to carry out the project.

Csub includes the sum of costs for all the subcontracted activities carried out during the work. The cost of each activity per housing unit (including material and plant cost) is incorporated into the system and therefore needs to be calculated with the number of houses required to be refurbished. Table 8 gives the activities found to be subcontracted in the projects investigated.

Table 8: Subcontracted Activities

Activity	**Cost per house**
Ironmongery	276
Gas service	520
Water service	903
Central heating	1129
Dry linings	1004
Gypsum plaster	851
Glazing doors/windows	754
Electrician's first fix	620
Electrician's second fix	349
Plumber's strip	213
Electrician's strip	125
Sealant	108
Floor finishes	635
Ceramic tiling	457

Cmat includes the sum of material costs for all the activities carried out by the contractor. The material cost for each activity in each house is calculated by multiplying the quantity of each work item comprising the activity by the respective unit material costs. This product is multiplied by the number of houses in order to calculate the overall material cost of an activity.

Clab includes the sum of labour costs for all the activities carried out by the contractor. The labour cost for each activity in each house is calculated by multiplying the labour hourly rate by the number of hours required to carry out the activity in a housing unit (which is the product of the work item quantities for each activity and their respective productivity rates). The overall cost of an activity obtained by multiplying this by the number of housing units.

Ctemp includes the weekly cost of providing temporary accommodation for tenants when the work is carried out in their property. The overall cost is found by multiplying this by the number of weeks required to carry out the project.

4.2 Stochastic simulation

At this stage, the site production process is simulated by the Monte Carlo method. 'Actual' values of productivity rates are drawn randomly from probability distributions defined according to work context, load and domain. The resulting 'actual' duration of the involved activities is recorded.

Progress is monitored to identify where departures from the plan cause interferences between activities or unacceptable delay and management decisions are simulated to take corrective action where necessary.

At the end of each simulation iteration, the 'actual' duration and cost is calculated, prior to a further simulation run being commenced. After completing a preset number of iterations, the final results are computed and reported.

4.2.1 The simulation process and scenarios

The principal simulation stages are as follows (see also Fig. 4):

(1) The 'actual' duration of each instance of each activity is determined by random sampling following the planned operational sequence. At intervals, status checks compare 'actual' with planned to detect interferences and/or delays.

Several main possible scenarios are provided for decision making. Each scenario is based on a consistent managerial strategy. For instance, one scenario is to keep the project as close to planned schedule as possible (Fig. 7a). Another is to try to reduce the amount of extra-payments to directly employed workers. As a result, it is not necessary to take immediate action whenever a delay occurs (Fig. 7b). The scenario (strategy) should be selected by the user **before** the simulation cycle. The planned schedule is updated at least a week ahead by passing messages to the affected instances. When delays or interferences are unavoidable, a decision is called and its results are calculated.

Fig. 7a: The simulation (constant cost scenario)

(2) Several possible decisions may be made following those employed in practice. The kind of decision depends on contractor type (private or direct works), tenant occupation (in/out), project constraints (overall duration), etc. As a result of these decisions, the schedule is updated as necessary and appropriate cost and/or time changes incorporated.

3) At the end of every cycle (complete production simulation), the total cost and duration are reported (Fig. 7).

4) A graph of cost and time distribution is made and drawn after an appropriate number of cycles (about 100).

Fig. 7b: The simulation (constant time scenario)

4.2.2 Integration of knowledge for realistic simulation

The most important aspect that distinguishes our approach from others is the integration of heuristic knowledge in order to generate a more realistic stochastic simulation phase. This is accomplished in two ways: (1) by monitoring work progress and cost control; (2) by adjusting the planned schedule to the work domain and conditions. The first is dealt with by constructing appropriate scenarios, as described above. The second is done through by defining the correct productivity probability distributions parameters. The following factors are taken into account for each particular project in defining and updating of default values of the parameters in the knowledge base:

4.2.2.1 Gang size

Parameters are updated according to the productivity of the real gangs involved. These values depend on gang size and analysis of previous productivity figures for given company. At present, the system contains values from the Wessex and Spon (Wessex, 1987a, 1987b; Spons 1985, 1989) price databases.

4.2.2.2 Actual work load

During a simulation run, some of the activities become underloaded (with a higher actual pace than planned) and some become overloaded. The delays caused by overloading may be taken into account by the system by an appropriate adjustment to the distribution parameters.

4.2.2.3 Learning effect

The influence of the learning effect (learning curve) is significant in refurbishment modernisation projects as many houses in a given project are of the same type. This effect may be taken into account by an adjustment to the distribution parameter values. This is necessarily an individual matter for each activity and will be the subject for further knowledge elicitation.

4.2.2.4 Season influence

The influence of the weather is less strong in refurbishment projects than in new work, but it is still is a subject for consideration. Its effects may be incorporated as above by updating the distribution parameter values.

4.2.2.5 Experience

All possible effects or influences (knowledge about specific gangs, expected disturbances, holidays, etc) may be taken into account at this point.

4.3 Result representation, analysis and visualisation

The primary outputs of the system are probabilistic estimates of total project cost and duration, presented both graphically and numerically. Various additional outputs are produced for the purposes of explanation and validation including a graphical representation of the operational plan, reports on the decision responses to interferences and delays, and a facility to produce a trace of any simulation run.

Presentation of the project schedule, as created by the system, will be by line of balance. It will allow not only validation of the proposed solution, but also a medium for presentation of the 'real' or 'actual' situations to the user.
Because a large number of simulation cycles are necessary to achieve representative cost-time distributions, conflict situations will be stored in the computer memory together with the decisions taken. 'Post-mortem' analysis will then be possible (Fig. 8).

Fig. 8: Example of 'post-mortem' analysis

5 Pilot System Implementation

The pilot system was developed to check the proposed approach. Emphasis was given to the principal stages of plan generation and simulation.

5.1 Project scope

An example 'live' project was chosen to represent a typical internal modernisation contract. The number of houses was reduced to 15 in order to reduce working memory and shorten the simulation cycle. All prices, quantities and productivity rates were defined within the pilot system prototype as default values in associated slots.

5.2 The development scope and status

The main purpose of the system prototype development was to trigger and boost the feasibility study rather than providing any commercial end-product. On the other hand, the development was done with a view to possible future extensions.

The current status of the pilot system prototype is as follows (see also Appendix C):

5.2.1 Knowledge base

This was the central aspect of the development work and is the basis for all operation and calculation. Hierarchical representations of refurbishment modernisation work were proposed and implemented.

A special lattice of frame objects was devised. The frames contain in their slots useful default values which can be used for both academic or user orientated development. The description of each class-level has been presented in Chapter 3.

5.2.2 Rule base and Procedures

Only the rule base and procedures necessary for project scope have been developed. These include: updating the sequence of activities, enumerating sub-contracted and self-contracted activities, duration and cost calculation, etc. Some examples are provided in Appendix C.

5.2.3 Database

An example of the database structure was proposed on a theoretical basis only. The development of this subject was not found to be important for the purposes of the feasibility study.

5.2.4 User interface

Few communication windows with the user were developed by using *GoldWorks* utilities. Their development were suspended not only as of lesser importance at this stage but also because of shortage of working memory.

5.2.5 Simulation procedures

This part is currently under development and only a limited scope is likely to be completed. The procedures will allow the simulation of decanting strategies (for both tenant in/out cases) and a site managerial scenario - keeping the progress of the work as close as possible to planned schedule - as it was found that both private contractors and local authorities prefer this approach. Further scenarios are possible but difficult to simulate without comprehensive knowledge elicitation because of the implications of delays to the planned supply of materials, creation of claims and associated penalties.

5.3 Example problem

Extensive refurbishment work has to be carried out in 15 semi-detached 2-bedroom dwellings in the Withenshaw area of Manchester. The work to be done includes the following:

(a) Repair or replacement of internal joinery
(b) Renewal of plumbing installations
(c) Removal of defective plaster and replastering
(d) Replacement of glazing to doors and windows
(e) Replacement of defective brickwork
(f) Rewiring
(g) Internal painting and decorating

The purpose of the simulation in this case is to decide on decanting policy. As a result, two cases will be checked. The system's approach and decision making are demonstrated here assuming that the properties will be tenanted throughout the execution of the work.

The handover and possession rate are assumed to be one unit.

5.3.1 Establishing the work programme

The activities needed are be picked up from the all possible activities for each programme Element and they will inherit as a result all default attributes such as sequence, criticality, etc. The system also decides whether the activities will be carried out by the main contractor or whether they will be subcontracted, and the number of days required for each housing unit

(Table 9).

Table 9: Work Programme

Activity	**Contractor**	**Pace**
Hack off plaster	main	5
Rake out/repoint brickwork	main	5
First fix joinery	main	5
Plumber's strip	subcontracted	1
Electrician's strip	subcontracted	1
Water service first fix	subcontracted	2
Central heating first fix	subcontracted	2
First fix electrician	subcontracted	3
Dry linings	subcontracted	5
Second fix joinery	main	5
Second fix electrician	subcontracted	4
Central heating second fix	subcontracted	2
Glazing doors/windows	subcontracted	2
Joiner's final fix	main	5
Ironmongery	subcontracted	2
Painting	subcontracted	2
Mastic sealant	subcontracted	2
Apply wallpaper	subcontracted	2
Floor finishes	subcontracted	2

5.3.2 Planned duration calculation

During the planning stage, the duration is calculated by the 'critical' activities which ensure continuity of the work. In this case:

(1) Hack off plaster
(2) Rake out/repoint brickwork
(3) First fix joinery
(4) Dry linings
(5) Second fix joinery
(6) Joiner's final fix
(7) Ironmongery
(8) Painting
(9) Mastic sealant
(10) Apply wallpaper
(11) Floor finishes

The rest of the activities may either be done concurrently or they have no influence on the technological order of the work.

Planned duration is calculated according to an empirical formula based on line of balance technique. This formula takes into account the continuity of work done by the main contractor, and possible 'breaks' in subcontracted work, in order to adjust the paces to main contractor.

$$\textbf{Planned duration} = p1\,(m1 + n - 1) + p2\,(m2 + n - 1) - 2n$$

where: p1 = pace of self-activities
m1 = number of self-activities
p2 = pace of sub-activities
m2 = number of sub-activities
n = number of houses

and therefore

Planned duration = 5 days (6 activ. + 15 houses - 1) +
2 days (5 activ. + 15 houses - 1) -30 = 108 working days
= 22 weeks

Because the pace of the work is dictated by the plan, the activities carried out by the contractor have to be checked to establish whether it is feasible to achieve this pace by using the predefined gang sizes and their associate productivity rates collected during the knowledge acquisition stage. If, for example, the activity hack off plaster is examined, results are obtained as shown in Table 10.

Table 10: Analysis of 'Hack off Plaster' activity

Activity	**Items of work**	**Qties**	**Av. Prod.**
Hack off plaster	hack off wall plaster	71.5	0.23
	hack off stud plaster	11.5	0.23
	strip off wall coverings	4.0	0.80
	hack off ceiling plaster	28.0	0.37
	clear floor coverings	8.5	0.18
	strip internal joinery	31.0	0.20

With a pace of 5 days, the specific gang size carrying out the work will have to work for approximately 40 hours in each housing unit. The sum of the products of the quantities and the respective productivity rates is the number of required hours of work. In this case:

Number of hours/house =71.5(0.23)+11.5(0.23)+4(0.80)+28(0.37)+8.5(0.18)+31(0.2) = 40.39 hours

Relevant calculations will take place for all the activities carried out by the contractor, i.e. rake out/repoint brickwork, first fix joinery, second fix joinery and joiner's final fix. If a gap of more 5 hour/week remains available in frame instance gang composition, the activity will be flagged as either 'overloaded' or 'underloaded'.

5.3.3 Planned cost calculation:

The elements comprising the overall cost exists are described elsewhere in this report. For this project, the calculation provided the following results:

Cprel	scaffolding	£600 per week
	hired plant	£456 per week
	staff salaries	£2372 per week
	temporary electric	£342 per week
	main office expenses	£768 per week
	sanitation/compound	£465 per week
	transport	£428 per week

therefore the sum of preliminaries per week is £5431 and the overall amount related to the project is 5431(27.6) = £149896.

Csub	Apply wallpaper	£2457 per house
	Painting	£3340 per house
	Sealant	£108 per house
	Floor finishes	£635 per house
	Plumber's strip	£213 per house
	Electrician's strip	£125 per house
	First fix electrician	£620 per house
	Second fix electrician	£349 per house
	Glazing	£754 per house
	Ironmongery	£276 per house
	Dry linings	£1004 per house
	Water service	£453 per house
	Central heating	£1129 per house

The overall cost of the subcontracted activities per house is the sum of the above costs, and it is therefore £6463. The cost for the whole project is 15(6463) = £96945.

Cmat	Hack off plaster	£0 per house
	Rake out/repoint brickwork	£52 per house
	First fix joinery	£753 per house
	Second fix joinery	£1387 per house
	Joiner's final fix	£58 per house

The overall cost of the materials per house is the sum of the above costs, and it is therefore £2250. The cost for the whole project is 15(2250) = £33750.

Clab	Hack off plaster	£7 per hour
	Rake out/repoint	£12 per hour

brickwork	
First fix joinery	£12 per hour
Second fix joinery	£12 per hour
Joiner's final fix	£7.5 per hour

The overall cost of labour for each housing unit is the sum of the above costs multiplied by 40 hours, i.e. £2020. The cost for the whole project is 15(2020) = £30300.

Ctemp = £0 because the properties are tenanted

The overall planned cost is therefore:

Ctotal = 149896 + 96945 + 33750 + 30300 = **£310891**

5.3.4 Simulation

As it was mentioned above, the approach has been to try to keep to the planned time schedule by addressing delays and maintaining the planned schedule irrespective of cost (by increasing the resources).

The parameters to be simulated are productivity - random values are selected on a predefined range based on information collected from estimating handbooks, published databases and our research work on the implications of factors on productivity. Productivity rates are to be simulated only for the activities carried out by the contractor, subcontracted activities do not usually create problems. The gang sizes for each of the main contractor's activities, and their respective productivity rates defining the range of possible rates for each of the work items comprising the activities, are selected. These are updated for work context and load ('overload'/'underload') for each activity.

The actual productivity for each housing unit is simulated to give the actual duration of the activity. As the pace of the work is 5 days for each activity, this implies that a specific gang carries out the activity in a different housing unit each week. Thus, for example, the activity 'second fix joinery' will be carried out (according to the plan) in the second unit during the sixth week. By simulating the productivity rates for each work item following results are obtained:

Duration of second fix joinery in the second housing unit is 0.3(56)+0.33(22)+0.18(22)+0.93(2)+0.51(5)+1.31(1)+2.12(1)+2.26(1)+2.41(1)+1.69(1) = 42.22 hours, which is compared with the 40 hours required for the gang to carry out the activity. In this case no remedial action will take place because the delay of 2.22 hours is not regarded as significant.

In cases where action will take place (when delays of more than 5 hours occur) the cost of this action is added to the planned cost of the activity and is equal to the gang's cost for one day's extra work, increased by up to 50%.

At the end of each cycle, the extra cost of the work is assumed and added to planned cost. At the end of whole simulation process, the number of possible project cost values (number of performed cycles) is obtained and a frequency distribution is plotted.

6 Summary and Conclusions

6.1 Aims and objectives

The research aimed to investigate the feasibility of employing intelligent simulation in construction cost-time forecasting in order to provide an aid to strategic decision making in housing rehabilitation work. Essential features were anticipated as being the provision of probabilistic forecasts and the ability to reflect the operational consequences of alternative design and management strategies.

The intelligent simulation envisaged was essentially a hybrid of stochastic simulation and knowledge based systems such that:

- an operational plan for the project would be generated automatically by the system, using knowledge drawn from expert planners;

- stochastic simulation would be used to evaluate project time and cost from the production plan, thus providing probabilistic forecasts;

- site management control of the production process would be emulated by interaction of the simulation with a knowledge base representing the expertise of site managers;

- a graphics based user interface would permit real time monitoring and interaction with the simulation.

6.2 Methodology

Multiple-unit housing rehabilitation projects were used as the vehicle for this investigation, as these projects are characterised by high levels of uncertainty and sensitivity of cost and time operational factors. The research considered only internal modernisation works of low-rise properties of traditional construction, as a representative subset of housing rehabilitation works in general.

The approach adopted was to seek to build a trial system or concept demonstrator. As the aim was to investigate feasibility, no attempt was made to acquire full domain knowledge, effort being concentrated upon establishing the structure and nature of the knowledge to be encapsulated, and determining appropriate methods of knowledge representation and system architecture.

Strong support for the investigation was given by a number of surveying firms and contracting organisations, particularly in providing many hours of experts' time and extensive access to project documentation and to operational construction sites (see Appendix B for contact names).

6.3 Progress achieved

Conceptual design of a system was completed within the grant period, but some work remains to be done to achieve an operational concept demonstrator. The structure and code to effect automatic plan generation and iterative simulation is complete, but work is still required to provide an effective user interface, database support, and automation of system progression through its operational stages. The structure developed also permits implementation of the key aspect of site management control emulation, but further work is needed on knowledge acquisition in this area and the code written so far only permits a very rudimentary demonstration of control emulation.

This was an ambitious project for so short a grant period, and the original application reflected this by requesting staffing with two post-doctoral research fellows so that rapid progress could be made from the outset. The grant awarded was for one post-doctoral and one post-graduate research fellow. With this staffing 12 months proved inadequate fully to meet our objectives. The strength of the team assembled and the progress achieved at the end of the grant period were such that the Department of Surveying has itself funded a 3 month extension to the appointment of the post-doctoral fellow so that more of the potential of this project can be realised. The University had earlier funded the purchase of some £11,000 worth of software to support the Department's work in AI applications, including the *GoldWorks* development environment and *Oracle* database used on this project.

6.4 Significant findings

The main findings were as follows:

System design

1. A system integrating knowledge based approaches with stochastic simulation is readily achievable within an object-oriented structure.

2. Automatic operational planning for repetitive works of this kind is also readily achievable, within an object- oriented structure. Such a structure was developed, taking the form of a hierarchical tree of object classes, linking high level user input to low level technical detail. A full set of rules representing the relationships between a production plan and resource requirements were encoded, and this part of the system was made operational by the use of default values for variables that would be accessed from a database in a full working system.

Knowledge acquisition

3. The domain of planning expertise examined proved suitable for KBS development. The techniques and heuristics employed are well established and consensus between experts is strong. A set of rules and default values were established that appear robust, although it was not possible formally to validate this expertise within the grant period.

4. The domain of site management expertise presented problems. This knowledge appears difficult to both acquire and represent. Informal interview was the only knowledge elicitation technique employed within the grant period and although some limited progress was made it is clear that there is less structure and consensus in this domain than is the case with planning. Had time permitted, the research team believe that the best way forward would have been to develop an interactive gaming simulation, with machine recording of user response, as a tool for knowledge elicitation.

5. The experts in housing rehabilitation that were consulted strongly reinforced the view that there is real need for tools to support both strategic-decision making on this type of project.

Feasibility of the intelligent simulation approach

6. The research indicated that current levels of hardware and software technology are capable of supporting the development of a working intelligent simulation based construction cost and time forecasting system, where:

- an object oriented structure is adopted;
- the construction projects involved are repetitive multiple-unit schemes of a type for which a well established body of planning expertise exists;
- the variety of construction work to be handled by the system is limited;
- a very limited and crude representation of site management control decisions and actions is acceptable.

6.5 Further work

It is hoped that the extended research period funded by the University (see 6.3 above) will enable a skeletal, but demonstrable, system to be completed. If this is achieved, the system will be demonstrated as widely as possible to disseminate the work and encourage its furtherance. An updated version of this report will also be produced at the end of the extension period.

There are three main directions for further research and development emanation from this project:

1. To continue development of the proposed system as a whole, to a working prototype stage. Such a prototype would act as a model for more general development of intelligent simulation applications in construction management.

2. To further investigate the following specific aspects of the work:

a) Using a knowledge based approach to emulate management control in the simulation of site production appears to be feasible with current technology. This is an area of considerable interest and great potential which warrants specific research.

b) The knowledge elicitation undertaken for this project indicated that there is much to learn about the mechanism and motivations of site management control on repetitive hosing rehabilitation projects. It is clear that the differences between these and conventional construction projects are significant yet little understood.

c) Intelligent systems and sophisticated graphics offer the technical capability to develop user interfaces which significantly improve the potential of simulation methods in construction industry applications. One of the subsidiary aims of this project was to look at such interfaces, but little was achieved in the grant period and further work is needed.

d) A skeletal system for automatic plan generation has been developed under this grant. This aspect of the work was of considerable interest to the industrial collaborators and may have the potential for further development and commercial exploitation.

3. To consider the wider application of an intelligent simulation approach to construction cost-time forecasting. This research has indicated the considerable potential of the approach where repetitive planning problems are involved and other applications, such as motorway bridge repair and high rise building, are worthy of investigation.

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Appendices

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C System Structure

Fig. C1: Extract from the hierarchical structure.

Fig. C2: Examples of objects at 'project' level.

Fig. C3: Examples of objects at 'elements' level.

D LISP Codes - Program Listing