

**A KNOWLEDGE BASED FRAMEWORK FOR PLANNING
HOUSE BUILDING PROJECTS**

by

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TO LISA

ABSTRACT

This thesis describes the development of a knowledge based system which encapsulates some of the expertise used by a number of experienced construction planners for planning the construction stage of low rise house building projects in the U.K.

The general objective of the research was to investigate the feasibility of using knowledge engineering for developing models of construction planning expertise, which could be employed for tackling some of the existing knowledge bottlenecks in the construction industry.

The resulting system can be described as a knowledge based framework designed for supporting the decision making process involved in planning house building at a tactical level. One of the main features of this framework is its ability to cope with incomplete information.

The knowledge acquisition process involved both the elicitation of knowledge directly from experts, and the analysis of construction plans from several past housing developments. The model was implemented on an expert system shell called LEONARDO Level 3, which runs in any standard IBM-PC micro-computer or compatibles.

The evaluation of the system focused on the validity of the model, i.e. the degree at which the outcomes of the system resembled the outcomes of the human expertise being modelled in the knowledge base. A prescriptive method of validation was devised specifically for this study, involving both experts that had provided expertise for the system, and external experts.

CHAPTER 1: INTRODUCTION

1.1 The emergence of knowledge engineering

Artificial intelligence is a branch of computer science that emerged in the Fifties, concerned with symbolic processing, as opposed to numeric processing. Nowadays, this field deals with the issue of designing and programming machines that emulate humans, by appearing to be intelligent or by mimicking human intelligence or human problem solving (Fenves, 1987). It covers a number of diverse areas, such as natural language processing, image recognition, knowledge engineering, and robotics. Newton (1986) stated that the term artificial intelligence is a misnomer, since this topic covers not only intelligence but also all the qualities that distinguish the human from the empty box, such as flexibility, reasoning, communication, etc.

Knowledge engineering is the process of encapsulating knowledge into computer systems to solve problems that normally require human attention and intelligence, using knowledge representation and processing techniques from the field of artificial intelligence (Sagalowicz, 1984). Such systems are popularly known as expert systems or knowledge based systems.

The need for knowledge engineering has emerged because traditional software engineering has some limitations in supporting decision-making. The application of conventional computer programs has been limited to very definite and routine tasks, for the following reasons:

(i) Conventional computer programs are developed in a prescriptive manner. Every sequential step must be determined in the very early stages of development, like someone else's interpretation of the problem - not the user's (Newton, 1986);

(ii) They are primarily designed for computer efficiency, rather than for human understanding. Usually only their developers are able to understand and modify them (Lansdown, 1982);

(iii) They cannot provide the user with justification for their results nor explain why they need a particular piece of information (Lansdown, 1982); and

(iv) Information is usually input in a standardised way and they cannot perform their task if any piece of information is missing (Hamilton & Harrison, 1986).

On the other hand, many important problems do not have tractable algorithmic solutions. They originate in complex social or physical contexts, in which the available information is often "noisy", full of uncertainty and errors, incomplete, and sometimes inconsistent (Schutzer, 1987).

Ortolano & Perman (1987) pointed out that there are two basic characteristics that distinguish knowledge based systems from conventional computer programmes. The first one, often termed as transparency, refers to the ability of a user to stop a program in the middle, in order to find out why a particular question is asked or what reasoning was used by the system to deduce a particular conclusion. The second distinctive feature is that the knowledge pertaining to a problem, placed in the knowledge base, is kept distinct and separate from the procedures, or inference mechanism, which manipulate that knowledge.

There are some other characteristics commonly associated with knowledge based systems, which may also be found occasionally in conventional programs. These are:

(i) They contain a great deal of information about very specific domains (Lansdown, 1982);

(ii) They give advice in a way similar to a consultant (Lansdown, 1982);

(iii) Uncertain data to reach probable conclusions can be used (Hamilton & Harrison, 1986); and

(iv) The knowledge is represented in a very explicit and uniform way, normally embodied in separate modules (Lansdown, 1982).

Brandon et al. (1988) stated that knowledge based systems have expanded the range of problems that can be tackled by the use of computers. As these systems represent a more human-like form of computing than do conventional systems, they allow computers to deal with less structured problems. However, those authors stressed that the current state of knowledge engineering does not allow knowledge

based systems to replace completely domain experts in all kinds of problems. Knowledge based systems still have a number of shortcomings in comparison to human thinking capabilities, such as:

(i) Knowledge based systems can only be used for relatively deep and narrow areas of knowledge (Brachman et al., 1983);

(ii) They cannot take into account the kind of wide-range information that humans use for solving some problems (Brandon et al., 1988);

(iii) They cannot easily process the unstructured information that is usually obtained by human senses, such as touch, smell, sound, or sight (Basden, 1983); and

(iv) They are not able to easily discover similarities between complex, non-identical objects (Brandon et al., 1988).

Sagalowicz (1984) stated that the most important benefit from extracting knowledge from humans and representing it in a computable form is the reduction in the costs of knowledge reproduction and exploitation, especially in domains where there is a knowledge bottleneck, i.e. fields where knowledge is unavailable, poorly distributed, difficult to maintain, update or organise.

In the long term, knowledge based systems have the potential of becoming depositories of knowledge for specific domains. Because the knowledge base is usually an explicit representation of domain knowledge, it is possible to maintain it in a form which is accessible for more than one kind of use Schutzer (1987). Some authors, such as Kidd & Welbank (1984) and Hayes-Roth et al. (1983), pointed out that the ultimate importance of knowledge engineering may be in formalising, structuring and making public an expert's knowledge, rather than in the production of high performance computer programs.

1.2 Knowledge based systems and expert systems

Some authors make a distinction between the terms "experts system" and "knowledge based system". Harmon & King (1985), for instance, referred to expert systems as large systems, and to knowledge based systems as small systems.

Ibbs (1986) reported on a seminar about the future for computerized construction research in the USA, in which a distinction was made

between "expert system", "knowledge based system" and "knowledge based expert system". An "expert system" was defined as a computer program that contains some particular human expertise (surface knowledge), based exclusively on heuristics or rules of thumb. On the other hand, a "knowledge based system" was regarded as being founded on knowledge of physical processes (deep knowledge). The term "knowledge based expert system" was used to describe systems that combines both surface and deep knowledge.

However, there seems to be no widely accepted definition for any of them. In practice, the terms "expert system" and "knowledge based system" have interchangeably been used to describe a wide range of computer systems that are able to hold human-like knowledge as well as to process this knowledge in a more human-like fashion than do conventional computer systems (Basden, 1983; Fenves, 1987).

The expression "expert system" suggests that such a system captures knowledge from experts. In reality, these systems very rarely contain knowledge that has been exclusively elicited from humans (Harmon & King, 1985). For this reason, the term "knowledge based system" was chosen to be used throughout this thesis. It generally refers to all computer systems that have both the characteristics of transparency of knowledge, and separation between the knowledge base and the inference engine, as discussed above.

1.3 The relevance of knowledge engineering for the construction industry

Several authors, such as Lansdown (1982), Wager (1984), De La Garza & Ibbs (1986) and Ashley & Levitt (1987), have pointed out that the nature of the construction industry puts it in a position to get many benefits from artificial intelligence techniques, and, in particular, of knowledge engineering. They all agree that the great potential of knowledge engineering in construction is related to the fact that knowledge from experts, such as designers, planners, managers, and estimators, is intensively used in this industry during all phases of the construction process.

Construction projects are characterized by a high variability, resulting from both its one-off production technology and from external influences such as weather, site conditions, regulatory

agencies, etc. (Bishop, 1972). The decision making process must be fast, and is very much influenced by site- and time-specific events, involving both technical and managerial issues (Levitt, 1986). Also, the acquisition of meaningful data to use in formal optimization models is difficult and costly to obtain, since the processes involved in construction are far less repetitive than in the traditional manufacturing industry (Wager, 1984). For these reasons, practical experience and intuition are much more fruitful sources of knowledge in construction than are scientific investigation or mathematical modelling (Levitt, 1986).

There seems to be a considerable number of knowledge bottlenecks amongst the several distinct specialities involved. Traditionally, the industry is faced with a sharp division between the design team and the construction team (Bishop, 1972; Gray, 1983). The design team usually does not have access to the construction team's expertise, and vice versa. Also, the increasing sophistication of construction projects have forced a further partitioning of the design activity into a number of specialized disciplines (Newton, 1986; Logcher, 1989).

As a result, there is a large number of independent organizations involved in the construction process, each one having its own specialists. Specialist groups are frequently physically separated from each other, which makes their inter-communication difficult. Moreover, some of these organizations operate in a relatively small scale, and cannot afford to have as many highly qualified experts as they need.

Knowledge based systems have the potential of providing individual organizations involved in the construction process with some expertise which is needed, but that is not available directly from their staff. This could greatly improve the quality of decision making in construction. Even large companies which have a wide range of specialists are able to get benefit from the use of knowledge based systems, by freeing the experts available to give more attention to less trivial tasks.

Another important potential role for knowledge engineering in construction is training (Basden, 1983). Experts usually gain their knowledge through experience, long periods of training, apprenticeship, and observation. The learning process normally takes

many years, and may be expensive in the case experience is gained through mistakes made in real situations. The access of students to the formalized domain knowledge could improve the cost-effectiveness of their training, and shorten the learning period needed to become an expert. Also, this type of knowledge based system can protect an organization from the loss of expertise when key experts retire or leave for other jobs.

The potential of knowledge engineering for refining construction expertise is highlighted, amongst others, by Ashley & Levitt (1987). They pointed out that, because construction research has not reached much beyond the empirical stage, there is a potential for knowledge based systems to become "an important stepping stone toward a robust body of theory" in this field.

1.4 The motivation for the work

The initial motivation for this study was the issue of improving the effectiveness of the construction industry. The author comes from Brazil, a third world country that has a tremendous shortage of good quality buildings. The country is faced with a colossal housing deficit, which has been estimated as something between six and seven million dwellings for the following ten years, as well as with a large shortage of hospitals, schools, and other public buildings (Fundação João Pinheiro, 1984). At the same time, there is a high potential demand for civil engineering investments, since the country needs urgently to improve the amount and quality of public services provided to its population, such as water supply, sanitation, electricity, and transportation.

The resources available to carry out so many building and civil engineering projects at the same time are limited. The amount of money the government has been able to invest in such projects during the last twelve years has been drastically cut because of the huge external debt which the country is faced with (Roddick, 1988). Pressure for a rational use of resources also comes from the need to preserve the environment. The extensive use of some natural resources, such as hardwood, aluminium, crushed rocks, sand, etc., has been recently associated to the rapid destruction of the natural environment.

Construction planning is one of the knowledge intensive tasks within the construction process that is closely related to the aim of improving the effectiveness of construction projects in terms of cost, time, and quality. Baker et al. (1979) described a survey amongst people experienced in project management, in which satisfaction with the project and control system was perceived as an important factor for the success of a project. The Business Roundtable (1982) report concluded that an effective use of planning techniques can potentially improve methods of project management, leading to shorter durations of construction projects, and, consequently, to cost savings to clients. Arditi (1985) reported on two studies conducted at the Illinois Institute of Technology, in which planning received the highest score in terms of importance amongst contractors as one of the factors of productivity improvement in construction, at company headquarters.

Construction planning usually involves the choice of alternative construction technologies, the definition of work tasks, the estimation of required resources and durations of individual tasks, and the identification of any interactions or constraints amongst different tasks (Hendrickson et al., 1987).

There are indications that this domain is suitable for knowledge engineering applications. It is a very time consuming task (Laufer & Tucker, 1988), and the domain experts generally perform it in a very intuitive and unstructured fashion, with a great deal of reliance on their judgement (Hendrickson et al., 1987; Levitt & Kunz, 1985). The ill-structured nature of the problem makes it difficult to develop a precise and efficient algorithm for generating plans and monitoring construction projects (McGartland & Hendrickson, 1985; Navinchandra et al., 1988). Moreover, a knowledge bottleneck exists because the number of experts available is very small (Mason, 1984; Gray, 1986; Levitt et al., 1988), training people in this field takes a considerably long time, and there are very few textbooks that contain real expertise.

Since the introduction of the first software tools for construction planning in the early Sixties, computers have had relatively little impact in supporting decision making in this field. Levitt & Kunz (1985), Hendrickson et al. (1987), and Echeverry et al. (1989) pointed out that most existing commercial tools are completely knowledge independent, i.e. the knowledge which experts use for defining activities, estimating durations, and establishing the pace of work

cannot be captured and re-used by these tools. They all agreed that such tools are employed only as a computer aided framework where planners input their decisions whenever a new cycle of planning is performed. Also, the reasoning used for making the programme is not made available to other people involved in the subsequent stages of planning, for tasks such as interpreting and updating the schedule, evaluating project performance, and performing real time control (Levitt & Kunz, 1985).

Several authors have claimed that there is a demand for knowledge based tools for construction planning, which could expand the expert's capability to manipulate and utilise qualitative and experiential information, making production planning a less painstaking task, and freeing experts for the work that essentially requires human decisions (Levitt & Kunz, 1985; Hendrickson et al., 1987; Logcher, 1987; Warszawski, 1988). They also stressed that explanation facilities available in such systems could be useful for providing credibility for correct decisions, as well as for highlighting decisions which are inconsistent.

Knowledge based tools for construction planning also seem to have a great potential amongst contractors that do not have a scale of operation in which it is cost effective to employ highly qualified construction planners. In such companies this task is usually carried out in a very informal way by people that have only general knowledge about the domain, or that do not have enough time to perform formal planning. Knowledge engineering could provide the means for these companies to access some of the expertise they lack, quickly, and at a reasonable cost.

The innovating effect that models of construction planning expertise can potentially have in terms of enhancing the communication between design and production have drawn the attention of several authors, such as Flanagan (1980), Gray (1986), Atkin (1987), Beeston (1987).

Cost planning procedures have been systematically used in the UK by consultant quantity surveyors, seeking to improve the economic performance of construction projects. It is widely accepted that cost planning is most effectively applied during the early design stages, when the major cost significant decisions are made (Ferry & Brandon, 1980).

The cost models traditionally employed by quantity surveyors, based on price information collected in bills of quantities from past projects, have suffered intense criticism from researchers in the field of cost estimating. Beeston (1987) stated that the way in which construction prices are estimated in such models has only a remote relationship to the way costs are incurred on site, making it difficult to examine accurately the effect of design changes in the production costs. A research study carried out at the University of Reading (1981) suggested that the most hopeful source of more efficient improvement in the quantity surveyors' method of estimating lies in considering the way construction costs actually arise on site. Another drawback of the traditional cost planning methods is the fact that, although time usually is a factor of major importance for construction projects, such methods do not offer any reliable guide for the relationship between design and the duration of activities on site (Flanagan, 1980).

The main obstacle for the use of contractors' cost estimating techniques for cost planning is the fact that the design team do not have enough expertise about construction methods. Although non conventional forms of contracting have been used in order to bring the advice of contractors to the early design stages, the contractor's role still commences too late during the design process to have a major impact in the economic efficiency of a project (Gray, 1983).

Unless the structure of the construction industry radically changes, it seems that knowledge engineering is the most promising means through which the existing knowledge bottleneck between the contracting side of the industry and the design team can be overcome. Knowledge engineering has the potential of being used for developing sound models of construction planning expertise. Such models could be used by clients and their consultants for considering the effect that their decisions are likely to have in the production process.

1.5 Aims of the research

Based on the discussion presented in the previous sections, three hypotheses were formulated. These are:

(i) Knowledge engineering can provide tools for improving the construction planning experts' capability of manipulating qualitative

and experiential information, removing some of the painstaking work from their hands, as well as allowing them to analyse a large number of construction alternatives in a short time;

(ii) Knowledge engineering can improve the integration of the construction industry by establishing a knowledge link between the construction team and the design team. Such link consists of making available to the design team construction planning expertise that could be used for several tasks, such as estimating the amount of resources required, forecasting the project duration, etc.; and

(iii) Knowledge engineering can provide the means for formalizing, structuring, and refining a robust body of knowledge on construction planning, that can be accessed for more than one kind of use, improving the dissemination of expertise within the industry as well as being used as a basis for establishing the research needs in this field.

Considering the limitations of this research project in terms of time and resources available, the decision was made to focus the research on testing the first hypothesis. Based on that, the general objective of this study was established. It consists of investigating the feasibility of using knowledge engineering for developing models of construction planning expertise, which could be applied for tackling some of the existing knowledge bottlenecks in the construction industry.

This investigation was carried out by developing a practical application, which encapsulates knowledge elicited from a number of construction planning experts from the industry. The specific objectives of such development are depicted below:

(i) To examine the suitability of available knowledge elicitation techniques and methodologies specifically for developing applications in the field of construction planning, considering the practical constraints of carrying out the study in collaboration with the industry;

(ii) To understand the nature of the expertise employed by construction planners in practice, and to find out how much of this expertise can be modelled in a knowledge engineering application;

(iii) To analyse the difficulties of implementing a model of

construction planning expertise as a knowledge base system, in relation to issues such as knowledge representation, inference control mechanism, man-machine interface, etc.; and

(iv) To assess the extent to which the expertise encapsulated in a knowledge based system for construction planning can be formally validated.

Although the scope of the study excludes formally examining the second and third hypotheses outlined above, this research can also be expected to provide some guidance towards their investigation in further studies.

1.6 Outline of the thesis

The thesis is divided in two main parts. The first part comprises Chapters 1 to 4, and consists of a review of the theoretical background which this research is based on. The second one embodies Chapters 5 to 8, and focuses on the description of the knowledge engineering application.

Chapter 2 discusses the planning problem, with particular emphasis on the task of planning the production stage of construction projects. It also examines the limited impact that the traditional construction planning techniques have had in the construction industry.

Chapter 3 provides a general discussion on the application of artificial intelligence techniques to construction planning. It reviews some of the main knowledge engineering applications developed in this field so far, and establishes a number of general guidelines for the development of the application.

Chapter 4 presents a general description of the production process involved in house building. Such description is mostly based on several activity sampling studies which have particularly investigated this kind of project.

Chapter 5 covers some basic aspects of the application, such as system specification, sources of knowledge, knowledge elicitation techniques, and software tool choice. The basic structure of the model of expertise developed in this research is presented in Chapter 6, while Chapter 7 concentrates on describing the main features of the implemented system.

Chapter 8 discusses the problem of validating knowledge based systems, as well as describes the approach adopted in the current study. Finally, a summary of the conclusions, lessons for the future, and suggestions for further research are given in Chapter 9.

Through this thesis, the author uses a number of expressions widely used in the field of artificial intelligence, such as rules, frames, forward and backward chaining, object oriented programming, etc. The meaning of such expressions have been exhaustively defined in several publications. They can also be found in the glossary of terms presented at the end of this work.

CHAPTER 2: THE PLANNING TASK

2.1 Introduction

Planning is a cognitive activity familiar to everyone. It plays a key role in decision making by enabling individuals to deal with changing and complex situations. Planning influences a wide range of activities, from the most trivial ones, such as how to get to work in the morning, to the most consequential, such as the allocation of resources in a country's economy. Plans are used, either formally or informally, for guiding any activity that has not been entirely automatized (Hoc, 1988).

Planning is one of the essential ingredients of construction management. Although a lot of research has been made during the last few decades, some dissatisfaction with the application and results of construction planning still remains (Business Roundtable, 1983; Laufer & Tucker, 1987). However, it seems that people involved in construction management still consider that a more effective approach to construction planning can bring considerable improvements in the performance of the industry (Baker et al., 1979, Business Roundtable, 1983; Arditi, 1985).

This chapter initially discusses the meaning of planning as well as the basic cognitive mechanisms that are behind the planning task. The second part of the chapter is devoted to the role of planning in construction management. The vertical and horizontal dimensions of planning throughout a construction project are discussed, and the major deficiencies of construction planning in practice are presented.

2.2 Planning in general

2.2.1 Definition of planning

There is a large number of distinct definitions of planning as far as the literature in this field is concerned. Hayes-Roth & Hayes-Roth (1979) defined planning as the first stage of a two stage problem-solving process named 'planning and control', in which planning is the predetermination of a course of action aimed at achieving a certain goal, and control consists of monitoring and guiding the execution of the plan to a successful conclusion. Hoc (1988) defined planning as

making a decision on the basis of predictions of the probable outcome of a situation through extrapolation from past events, considering that the decision to act usually has the effect of modifying the events to more satisfactory goals. Laufer & Tucker (1987) accepted the definition of planning as a decision making process performed in advance of action that attempts both to design a future and effective ways of achieving it. In summary, planning can be defined as the process of setting goals and establishing the procedures to attain them, being only effective if intertwined with the process of controlling activity execution.

According to Hoc (1988), planning mechanisms intervene in situations where a response cannot be obtained from rules triggered by current environment information. He also points out that when this occurs, individuals must anticipate on future information, usually in a schematic fashion, based on previously acquired information. Therefore, if a task requires a totally new elaboration, no anticipation and, consequently, no planning can be carried out.

Uncertainty about the future is a common feature of most problems involving planning, since much of the knowledge human beings use for anticipation is qualitative, uncertain, and judgmental, defying rigorous analysis (Fiksel & Hayes-Roth, 1989). In very unpredictable situations, individuals may have to elaborate plans in the form of working hypothesis (Hoc, 1988).

The necessity of using a schematic representation of a task is a consequence of both the limited capacity of the human working memory and the uncertainty involved in anticipation. When dealing with very complex problems, individuals usually abstract only a number of relevant data from details, increasing the portion of problem space that they are able to tackle, resulting in the construction of schematic representations. Additionally, a schematic representation enables plans that are generated in a very uncertain environment to remain probable, since they can summarize a large family of possible alternative solutions. This schematization process raises the level of control a human being has over an activity (Hoc, 1988).

The choice of the level of representation is usually a kind of compromise, since it must be detailed enough in order to be able to guide activity, but it must also be schematic enough so as to cope

with the limited capacities of individuals' working memory (Hoc, 1988). Plans for very simple tasks include very detailed information, at a level close to activity execution. Complex and uncertain problems need plans at a higher level, where only strategic information is taken into consideration.

Plans can be state anticipations, named declarative plans (e.g. an architectural plan), or procedure anticipations, known as procedural plans (e.g. a computer programme). They are often not only schematic, but also hierarchical, since their structure expresses the organization levels of what they represent as well as the relations between these levels (Hoc, 1988).

The planning process can be assumed to operate in a two dimensional planning space, the two dimensions being time and abstraction level (Hayes-Roth & Hayes-Roth, 1979). The lowest abstraction level is named 'basic level', where plans include all the detailed information necessary for action execution (Hoc, 1988).

2.2.2 Planning models

Although it is accepted that planning is a multi-stage, multi-level process, some describe it as a top-down, systematic, complete, and hierarchical process, while others hold that people plan in a multi-directional, incremental, and heterarchical mode (Laufer & Tucker, 1987). None of the cognitive models of planning proposed so far have been widely accepted as reliable by researchers in the field of planning (Laufer & Tucker, 1988).

Early models of planning, adopted in pioneering artificial intelligence systems, described planning as a top-down, systematic, complete, and hierarchical process (Hoc, 1988). They assume that plans are initially generated at the more abstract levels, and are successively refined into the lower level spaces, towards the basic level. Also, they presuppose that complete plans exist at all levels of abstraction and that all decisions involved fit a hierarchical structure.

Hayes-Roth & Hayes-Roth (1979) proposed a less rigid approach to planning, named "opportunistic" model. This approach assumes that planning involves both coherent and incoherent decision sequences, in extreme cases appearing to be chaotic. The opportunistic approach

assumes that planning is a multi-directional, incremental, and heterarchical process.

Multi-directional means that both top-down and bottom-up processing are simultaneously employed, i.e. conclusions arisen from planning at a more abstract level can guide subsequent planning at a lower level, and vice versa. The incremental aspect of planning is concerned with the fact that complete plans are rarely produced for each abstract level, and that tentative solutions are proposed without the requirement of fitting into a higher level integrated plan. In other words, a developing plan does not necessarily grow as a coherent integrated plan. Finally, heterarchical means that some of the planning decisions does not fit into a single hierarchical structure (e.g. decisions about how to allocate cognitive resources).

Hayes-Roth & Hayes-Roth (1979) regarded the top-down, systematic, complete and hierarchical approach as a particular case of the opportunistic model. They stress that both models are suitable for describing different situations, and suggest a number of variables that can influence the approaches adopted by planners in particular problems. These are:

(i) Problem characteristics: some problems have an inherent hierarchical structure that planners can naturally use in their schematic representations. Also, individuals tend to adopt a top-down approach if a problem imposes severe time constraints;

(ii) Expertise: an experienced planner working on a familiar, constrained problem may have well-learned, reliable abstract plans available. In cases where planners are not so experienced, or the problem is relatively unconstrained, opportunistic methods tend to be more advantageous; and

(iii) Individual preferences: some individuals have a strong preference for bottom-up approach, regardless of problem characteristics, while others are more flexible, adopting an appropriate approach in response to problem characteristics or instructions.

2.3 Planning in construction management

2.3.1 The complexity of construction

A construction project usually poses a unique problem to the people involved in managing the production process (Bennett & Ormerod, 1984). The design and location of each project are distinct from all others. A large number of different organizations and individuals are involved in the design and in the production process, each one having a different set of priorities and objectives (Bishop, 1972).

Construction generally involves a large number of different technologies, as well as alternative combinations of labour and equipment. Additionally, a large number of imponderable factors are bound to affect the production process, such as weather, material shortages, labour problems, unknown sub-surface conditions, inaccurate estimates of durations and cost, changes in the design, etc. (Levitt, 1986). All these considerations make the problems that construction managers have to face of a type and magnitude not usually found in other industries (Bennett & Ormerod, 1984).

Considering the limited capacity of human working memory, construction managers normally need some kind of formal plans that can expand their capacity for understanding complex situations.

Construction plans can be regarded as procedural plans, since they anticipate and represent in a schematic way a group of actions to be executed. However, before generating a construction plan, planners need to translate all the information available, such as architectural plans (brief, sketch design, or detailed design), and site conditions (if known), into another abstract representation of the project. Such representation is possibly a sort of declarative plan, which consists of the planner's own view of the final product, expressed in terms of its main construction components.

2.3.2 The role of planning

People involved in construction management are required to perform a large number of functions (Harrison, 1985; Neale & Neale, 1989), which can be classified under four main headings: guiding execution, co-ordination, control, and searching for improved solutions. The basic role of planning is to assist managers to fulfil each of those functions (Laufer & Tucker, 1987).

Guiding execution is concerned with directing the parties involved in the implementation of a project. A construction plan can be seen as a model of the installation of components and assemblies, which provides information about the tasks required, their sequence, their duration, and their required resources (Echeverry et al., 1989). Plans can be used as either direct assignments or at least as guidelines for lower management to make decisions later on (Laufer & Tucker, 1987).

The second function consists of providing a means of communication amongst the different project participants, such as owner, designers, site management, sub-contractors, suppliers, etc. This is done by informing which tasks each participant is expected to do (Echeverry et al., 1989). Here, the planning role is focused on harmonizing and facilitating clusters of tasks that are characterized by a high degree of interdependence (Laufer & Tucker, 1987).

Control involves measuring and evaluating performance, and taking corrective actions in order to ensure that the course of action is maintained and the project goals are reached. In this respect, planning must establish the targets and the course of action to attain such goals, in a format that is convenient to the control function (Echeverry et al., 1989).

Searching for improved solutions is concerned with generating and comparing several alternative plans for the production process, in terms of cost, time, and demand for resources. This function can be carried out at different points in the construction stage. For example, alternative plans can be used at the design stage for comparing a number of design solutions from the point of view of the duration of the construction stage (Gray, 1983). Contingency planning could also be included under this heading. It consists of preparing several plans for likely contingencies in order to minimize response time when a new plan is needed (Laufer & Tucker, 1987).

Planning the construction process is a highly complex task that involves a large number of activities, a great deal of uncertainty, being usually subjected to a number of conflicting constraints, such as time, space, cost, and availability of resources (Levitt, 1986). Consequently, the optimization approach, often employed in other engineering fields, is largely ineffective in construction practice (Warszawski, 1987). Generally construction planning searches for an

acceptable, or feasible arrangement of actions, rather than an optimum one.

2.3.3 The vertical dimension of planning

In most medium and large construction projects, construction management is usually carried out by a number of different people, each one tackling the problem at a distinct level of specificity. The different levels of management for which plans are produced define a vertical dimension of the planning process.

Laufer & Tucker (1987), for instance, divided construction management in three levels: top, middle and lower management. Top management is mostly involved in setting the objectives of a project. Middle management is more involved in selecting the resources for reaching those objectives. And finally, lower management assists middle management in selecting and devising the solutions.

Each level of management requires construction plans at a convenient degree of detail. If plans contain too many details, a long time is needed to elaborate and update them, making them ineffective to influence short term decisions. Also, very detailed plans can make the planning and control process very expensive and time-consuming, since a huge amount of paper work is necessary, both for issuing instructions and for reporting the work carried out. On the other hand, if activities are planned without the necessary details, a plan cannot fulfil its functions of execution, co-ordination and control, since important relationships between activities can be lost, and major deviations in the course of the project cannot be picked up by the control system.

The most adequate level of detail of a plan is also affected by the level of uncertainty, as discussed in Section 2.2. In a highly unpredictable environment such as construction, changes often disrupt the original plans, making frequent modifications necessary. Otherwise, plans become out of date, losing the confidence of users very quickly (Harrison, 1985). Plans that contain too many details may be ineffective in the presence of high uncertainty, due to the excessive effort needed for constantly updating them.

Several authors, such as Nuttal (1965), Bishop, (1972); Harrison (1985), and Neale & Neale (1989) suggested that very unpredictable

situations can be more effectively dealt with by giving lower level management some discretion in the day-to-day work. In this case, plans must have some degree of flexibility, working as a general framework where lower level managers can fit their decisions. This approach is what Neale & Neale (1989) named as dynamic planning.

The construction process is often divided into fundamental units of work, named work packages, each one consisting of a continuous action taken by an operative or group of operatives working together, without being interrupted by any other gang (Forbes, 1977). The amount of work packages in each project usually ranges from several hundreds to dozens of thousands, depending on the complexity and size of the work to be done (Harrison, 1985).

Plans for top managers are usually much less detailed than the work package level. They are first generated early in the project cycle, often before its location and design are known, integrating the production activities into a more general framework, which includes also events related to other stages of the building process, such as design, contractual procedures, and commissioning the project (Neale & Neale, 1989).

The level of work package is probably convenient for site managers, who have to co-ordinate and control the work of all gangs. At a lower level of management, such as first level supervisors on site, or sub-contractors, plans probably have to be elaborated at a level of detail finer than the work package level, since the work of each operative has to be controlled on a short term basis. Table 2.1, extracted from Neale & Neale (1989), illustrates the level of detail plans are likely to have among the different levels of management.

MANAGEMENT LEVEL	POSITION IN THE COMPANY	TIME SCALE	LEVEL OF DETAIL	TIME UNIT
Top	Managing director	From feasibility to commissioning	Project phases	month
Middle	Construction manager	Tendering and production phases	Stages of work	week
Lower	Site manager Sub-contractors Foreman	Production phase Stages of work Stages of work	Work package Work package/Task Task	day day day

Table 2.1: Degree of detail of plans for each level of management (compiled from Neale & Neale, 1986)

In summary, construction planning can be described as a multi-stage process, carried out by people situated at several different levels in the management hierarchy. The higher the level of management, the more comprehensive, abstract the plans are, and the greater the uncertainty involved in planning. Whether this process can be better described as a top-down, systematic, complete, and hierarchical process, or as multi-directional, incremental, heterarchical process is a question still to be answered.

2.3.4 The horizontal dimension of planning

Project planning should be a continuous process which starts at the conception of the project and extends until the project has reached satisfactory conditions (Harrison, 1985). The horizontal dimension of planning is concerned with the different phases involved in this continuous process, as well as with their timing.

Laufer & Tucker (1987) describes a theoretical model of the planning and control process in construction, reproduced in the Figure 2.1, which contains features that are often prescribed by textbooks in the field of project management, such as Harrison (1985), and Neale & Neale (1989). In this model, the planning process is divided into five stages, as follows:

(i) Planning the planning process: a number of key decisions concerning the planning process is made at this stage, such as what plans are needed, how they will be used, how detailed they will be, what techniques will be appropriate, when the plans will be prepared, etc. (Harrison, 1985). Projects that are unique are likely to require more effort at this stage than the ones that are carried out in a routine basis;

(ii) Information gathering: this stage generally requires a considerable amount of resources (Laufer & Tucker, 1987). There are several sources of information at the beginning of the project, such as design, contract documents, report on site conditions, data about labour productivity, and constraints or goals imposed by higher level management or by the client. Additionally, information concerning the actual progress on site has to be collected throughout the production stage;

(iii) Preparation of formal plans: the plans are worked out, using

some kind of construction planning techniques. At this stage, a number of alternative planning solutions can be considered;

(iv) Information diffusion: the information generated in the previous stage is disseminated in a convenient format to a number of users, such as other levels of management, sub-contractors, clients; and

(v) Evaluating the planning process: the whole planning process is periodically evaluated, as a basis for improving the whole planning process in future projects.

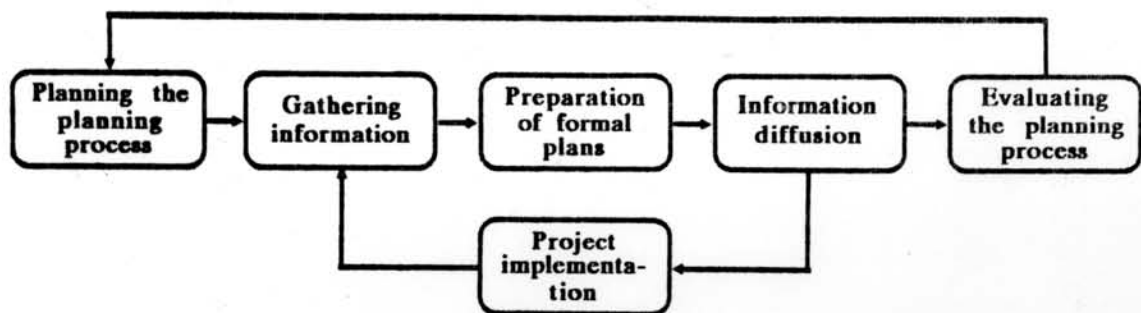


Figure 2.1: A model of the planning and control process (after Laufer & Tucker, 1987)

During the implementation of a project, its progress is monitored and feedback is used to update plans and prepare reports about the current performance of the project, as shown in Figure 2.1. Managers evaluate real progress against the plans, identify causes of delay, take corrective action, and, if necessary, revise the duration estimates of activities in progress and those that are yet to start (Ahuja & Nandakumar, 1985).

Laufer & Tucker (1987) pointed out that, from the five stages above, "planning the planning process", and "evaluating the planning process" are virtually non-existent in practice, while the remaining ones usually suffer from major deficiencies. These will be discussed in Section 2.3.5.

2.3.5 Construction planning in practice

2.3.5.1 Preparation of plans

The stage of preparation of plans is the one that usually receives most attention, to such a point that there is a confusion between the

concepts of project management and construction planning, and the application of planning techniques (Baker et. al., 1979).

There is a number of techniques that can be applied for the preparation of plans (Gantt bar chart, linked bar chart, critical path method, line of balance, etc.), each one having its own advantages and disadvantages (Harrison, 1985; Neale & Neale, 1989). Critical path method (CPM) based techniques have been usually accepted as the only ones that are able cope with the large number of activities involved in construction and their complex inter-relationships (Harrison, 1985). They are often mentioned as indispensable aids for planning and scheduling construction projects (Levitt et al., 1988).

However, the success of CPM based techniques have been reported as very limited, although they have been used for more than three decades. A survey published by Davis (1974) indicated that, amongst 400 large construction companies in the USA, 45% of them never or seldom used CPM. Another study regarding large companies in the same country found that only 43% used CPM effectively (Business Roundtable, 1982). Allam (1988) reported that only 4.9% of a sample of CPM users in the UK applied it in all projects and that 68.3% used it in less than half of their projects.

The limitations of CPM have been extensively discussed by several authors, such as Peer (1974), Birrel (1980), Roderick (1977), Parsons (1983), Heineck (1983), Jaafari (1984), Trimble (1984), and White (1985). Generally, CPM is criticized as being incompatible with the essence of the construction process, since it was created for projects of national importance in which cost control and efficient use of resources had low priority in relation to the project duration. In such projects, contractors usually have central control over the resources to be allocated, which does not exist in ordinary construction projects, especially considering the increasing role of sub-contractors in the industry (Piggot, 1972; Birrel, 1980). Other important weaknesses of CPM techniques can be summarized as follows:

(i) CPM techniques do not attempt to ensure full continuity of work for the gangs, which is the backbone of operational planning in construction, since they refer mainly to technological constraints rather than limitations of resources (Laufer & Tucker, 1987). Trimble (1984) pointed out that scheduling a project is more efficiently

carried out if critical resources are used as a starting point, rather than activities;

(ii) CPM is more suitable for sequential operations which characterize an assembling type of work. Construction usually involves a number of bulk operations, being similar to an installation type of work, in which the detailed sequencing of activities is not very important (Laufer & Tucker, 1987);

(iii) The sharp separation between the work of the various trades, as assumed by CPM techniques, does not exist for the majority of building activities, since they tend to overlap with a score of preceding and succeeding items, instead of being in sequence (Heineck, 1984; Jackson, 1986). The timings of activities are not only linked by start and finish relationships but also by rates of development (Roderick, 1977);

(iv) Creating or updating a CPM network for complex projects is a very time-consuming task that constantly requires the work of construction planning experts (Bromilow, 1978; Parsons, 1983; Levitt & Kunz, 1985). As discussed in Section 1.4, computers have had relatively little impact in this task, since most commercial scheduling tools require a complete construction plan as input. CPM software packages merely carry out computations on data provided by construction planners (Levitt et al., 1988). Laufer & Tucker (1987) pointed out that the development of sophisticated CPM based computer packages might have created the misconception that CPM techniques have progressed more than they actually had;

(v) CPM techniques require plans to be elaborated in a bottom-up approach, in which the crucial planning decisions are concerned with detailed construction activities, such as duration, resource allocations, probabilities, etc. On the other hand, research studies carried out by Birrel (1980) and Gray & Little (1985b) indicated that, in practice, planners' crucial decisions involve more general aspects of a project, such as its division in work locations, the sequence of work through these locations, and the pace of work; and

(vi) It has been reported that site managers have difficulties in understanding the complexities of CPM networks (Birrel, 1980; Business Roundtable, 1982; Allam, 1988).

Harrison (1985) and Allam (1988) reported that the disappointment

of several companies with CPM techniques have brought back to use the technique of Gantt bar charts. Birrel (1980) and Harrison (1985) pointed out that several companies carry out planning using CPM primarily because of clients' demands. Furthermore, there is a growing tendency to use CPM as an administrative tool for litigation and for allocating contractual responsibilities, rather than as a planning instrument (Jaafari, 1984; Royer, 1986).

The unavoidable frequent planning revisions and the long time needed to update formal plans, undermine to a great extent the influence that planning can have in regulating operations in a real time basis (Laufer & Tucker, 1987). The cycle that involves the stages of "information gathering", "preparation of formal plans", "information diffusion", and "project implementation" (see Figure 2.1) is often too slow, restricting the intended role of formal planning, which is to regulate operations while in progress (Laufer & Tucker, 1989). Consequently, updating formal plans is usually an archival record-keeping process, rather than a re-planning process (Levitt & Kunz, 1985).

2.3.5.2 Information gathering

The major deficiency in the information gathering stage is the fact that uncertainty is usually not adequately considered. One of the main reason for that seems to be the scarcity of information about the variability of labour performance, both in the industry and in published sources. Duff (1980) and Bennett & Ormerod (1984) reported on how the libraries of output rates kept by contractors have been reduced to databases of single figures, in order to attend deterministic demands of a commercial environment.

There have been attempts to develop simulation based planning models that incorporate the effect of variability in the planning process (Bennett & Ormerod, 1984; Ahuja & Nandakumar, 1985). However, the insufficiency of data about variability and the difficulty of accommodating the interdependency between variables involved have highly restricted their application as a comprehensive and detailed planning tool (Laufer & Tucker, 1987).

The usefulness of simulation techniques in practice has been restricted to analysing the construction process in qualitative terms,

such as for comparing the importance of specific uncertainties in relation to the main project objectives, or for highlighting those areas which would most benefit from attempts to reduce or control uncertainty. This is the case, for instance, of the study carried out by Legard (1983).

Laufer & Tucker (1987) reported that, besides the existing shortage of information about variability, the majority of planners make very little effort to seek additional information towards the use of stochastic models of planning. In practice, planning is usually carried out considering that variability is a brief intrusion into a predictable sequence of operations, although it is an undisputed fact that variability is the norm rather than the exception in the construction process (Heineck, 1983).

2.3.5.3 Information diffusion

The information diffusion stage suffers from two major deficiencies. Firstly, individuals may be prejudiced against planning, imposing obstacles to its implementation. This fact has been reported both inside (O'Brien, 1984) and outside (Laufer & Tucker, 1987) the construction industry. Secondly, an excessive amount of information, organized in an inappropriate format can be as harmful as a shortage (Laufer & Tucker, 1987; Birrel, 1980). The latter problem can be aggravated by the introduction of computers, that often induce the creation of over-elaborate, unnecessary, or irrelevant data (Mason, 1984).

Several authors offered evidence that project management currently deals with two separate systems of information that coexist side by side (Piggot, 1972; Trimble, 1984; Harrison, 1985; Laufer & Tucker, 1987; Levitt et. al., 1988). At a higher level the information system is formal and has a limited effect on site execution. It is based on the head office of the company and usually involves computerized resources. Its main functions are to monitor the current status of projects, and to keep historical data for future forecasts. At a lower level, a system of informal information and decision making exists. It is mainly situated at the site, and dictates the actual execution on a short term basis.

Field managers often abandon CPM networks for more informal bar charts or activity lists, when developing their detailed work plans

(Levitt et al., 1988). Harrison (1985) pointed out that, in extreme cases, complicated looking plans are produced not to be used in the management of the work on site, but are generated at the beginning of the project and then left unchanged on the office walls, for impressing clients.

2.3.6 Improving the effectiveness of formal planning

Laufer & Tucker (1987) argued that the lack of long term formal planning in construction works against the effectiveness of the industry as a whole, for the following reasons: (i) resources requiring long lead time cannot be delivered early enough; (ii) integrating the plans of several different projects is very difficult; (iii) maintaining consistency between decisions from several levels of management is not feasible; and (iv) improving efficiency of production through the analysis of alternative construction methods is ruled out.

Several suggestions have been made for improving the effectiveness of formal planning, including adequate training of managers and engineers (Arditi, 1983; Laufer & Tucker, 1987), concentrating research efforts on other stages of planning - not so much on the stage of preparation of formal plans (Laufer & Tucker, 1987); and the application of artificial intelligence techniques to the planning and control process (McGartland & Hendrickson, 1985; Levitt & Kunz, 1987; Hendrickson et al., 1987; Navinchandra et al., 1988; Alshawi et al., 1989).

The present research can be regarded as an attempt to improve the effectiveness of formal planning in the construction industry, by means of developing a knowledge engineering application in the field of construction planning.

2.4 Summary and conclusions

Anticipation and schematization are the two basic mechanisms of the planning task. Planning the production stage of construction projects is a very difficult task. Anticipation has to be carried out in a very uncertain environment, and the complexity and the scale of construction usually requires planning to be carried out at different levels of management, each one using a different abstract

representation of the construction process.

The planning and control process that exist in practice usually differs from what is prescribed in several textbooks on project management. There is an excessively large emphasis on the stage of preparation of plans, while other stages are neglected to a great extent. Moreover, despite all the research effort concentrated on the development of network based planning techniques during the last thirty years, they still present major deficiencies as practical planning aids.

Construction planning is perceived as being too informal. According to some research studies, on-site construction is usually based on short term informal planning, and formal plans have very limited use as real time control tools. This approach has imposed a number of limitations in the performance of construction management (Laufer & Tucker, 1989).

Knowledge engineering has been suggested as one of the fields of research that have the potential of improving the effectiveness of formal planning. In the next chapter, some of the research carried out in the field of artificial intelligence applied to planning will be described, and the main knowledge engineering applications developed specifically for construction planning so far will be discussed.

CHAPTER 3: ARTIFICIAL INTELLIGENCE IN CONSTRUCTION PLANNING

3.1 Introduction

In the previous chapter, the main problems related to the lack of effectiveness of formal planning in construction management have been discussed, and the application of artificial intelligence (AI) techniques has been pointed out as one of the measures that have the potential for improving the current situation.

The state-of-the-art of AI research concerned with the construction planning problem is reviewed in this chapter. Several studies that involved the development of AI planning systems or conventional knowledge based systems are discussed in some detail. AI applications for planning fall into two broad areas: (i) knowledge-lean, general purpose, domain-independent planning systems; and (ii) knowledge-intensive, domain specific planning systems (Levitt et al., 1988).

The current state of AI techniques for planning and the lessons learnt from the development of various systems were the basis for establishing the main features of the knowledge engineering application developed in this research. The general guidelines for setting the working objectives of this application are presented at the end of the chapter.

3.2 Artificial intelligence applications for planning

3.2.1 Domain independent planning systems

General purpose planning systems that can automatically produce sequences of activities have been an active research topic within AI since the early Sixties. Echeverry et al. (1989) described them as systems that are able to produce plans for any type of discipline, since they are properly given the available actions and the goal to be accomplished by the plan.

In general terms, domain-independent AI systems perform the planning task by defining a search space and then seeking a point within this space that is defined as a solution (Tate, 1985). Most systems use a means-ends approach, in which an initial state and a

goal state are each one represented by a set of facts (Levitt et al., 1988). A number of potential actions are defined, as well as their preconditions and their effects on the current state. Based on that, the system searches through available actions and select the action that can reduce most of the differences between the current state and the goal state. This procedure is repeated until a sequence of actions, or a plan, capable of transforming the initial state into the goal state, is generated (Levitt et al., 1988).

The two major problems related to applying AI planning systems to practical problems are combinatorial explosion and interactions between sub-goals (Cohen & Fiegenbaum, 1982). Combinatorial explosion is a consequence of the huge number of possible paths in the search, even for relatively simple problems, most of which do not lead to goal achievement. The problem of interacting sub-goals arises from the difficulty of making explicit all the preconditions needed for an action to be feasible (Fiksel & Hayes-Roth, 1989).

Of particular importance to construction are the systems that generate non-linear plans (i.e. plans in which activities can be carried out in parallel, rather than being strictly linear), since they could be used for supporting planning using CPM networks (Navinchandra et al., 1988). NOAH (Network of Action Hierarchies) was the first non-linear planning system to be developed (Levitt et al., 1988). Tate (1976) extended NOAH and developed NONLIN, which has been applied to the problem of generating plans for house building. Work is currently under way to rewrite and generalize NONLIN as O-PLAN, in order to enhance its abilities in the area of project scheduling and resource management (Levitt et al., 1988).

Despite the continuous advance in general purpose AI planning systems, several authors have recognised that there are still several limitations in using such systems for generating plans in very complex real situations (Hendrickson et al., 1987; Levitt et al., 1988; Fiksel & Hayes-Roth, 1989).

Levitt et al. (1988) pointed out that AI planning systems do have major limitations in terms of feasibility, expressiveness, and utility, since they do not provide powerful mechanisms for representing domain specific knowledge other than heuristics for search control. As an example, such authors discussed the limitations of NONLIN for tackling the construction planning problem. Their main

criticism was concerned with the fact that, like in CPM algorithms, no new knowledge was generated by NONLIN, but it only made explicit a number of implicit relationships that had to be input by experts.

Fiksel & Hayes-Roth (1989) stated that existing algorithms for generating and optimizing plans have had only limited success, even in relatively narrow domains, because the knowledge required for planning in most real situations has great temporal and conceptual complexity, as well as inherent instability and uncertainty.

In the specific case of construction planning, general purpose AI planning systems have also the following major drawbacks:

(i) They assume that a complete set of primitive actions is available and that the preconditions and effects of each actions are known. In contrast, in construction, and other problems involving human beings, a complete enumeration of possible primitive actions is not available, nor is a precise definition of their preconditions and effects (Darwiche et al., 1988);

(ii) They usually incorporate only a relatively small number of actions (typically fewer than ten), that are repeated many times. On the other hand, the number of activities involved in construction is very large, implying relatively little repetition (Levitt et al., 1988);

(iii) Construction planning involves the selection of the appropriate resources to be employed, while in problems such as block stacking and job shop scheduling, all resources are given (Hendrickson et al., 1987); and

(iv) The trade-offs between cost, technology, and activity duration, so important for construction planning, are not considered in such AI planning models (Hendrickson et al., 1987).

3.2.2 Domain specific planning systems

Some of the more recent AI planning research have focused on developing planning systems which are able to incorporate some problem-specific knowledge (Levitt et al., 1988). The production of such systems results from the application of knowledge engineering, and sometimes involves the use of techniques generated in the development of general purpose planning systems.

Domain specific planning systems have been developed with a specific narrow planning domain in mind. They have been much more successful than general purpose planning systems in terms of producing plans for real tasks (Levitt, 1990). However, they lack the generality of the general-purpose planners: as any knowledge based systems, they require significant amounts of re-programming before they can be applied to even a slightly different planning domain (Darwiche et al., 1988).

Such systems can be regarded as a particular type of knowledge based systems. They encapsulate models of human expertise, and use the same knowledge representation formalisms usually found in conventional knowledge based systems. Their only peculiarity is the fact that to some extent they have been built in an architecture oriented towards solving planning problems.

Callisto (Sathi et al., 1986), Construction Planex (Hendrickson et al., 1987), GHOST (Navinchandra et al., 1988), OARPLAN (Darwiche et al., 1988), and SIPEC (Kartam & Levitt, 1989), for instance, are among the AI applications specifically designed for the fields of construction planning and project management, which fall under this category of systems. They will be discussed later in this chapter.

3.3 Conventional knowledge based systems

There are also a relatively large number of AI applications which encapsulates some domain-specific knowledge from the field of construction planning, but that have been developed using a more general purpose architecture. Their scope is usually restricted to small number of planning tasks, and to a very narrow range of problems.

Such systems tend to be fairly small, and implemented in cheap hardware. Differently from AI planning systems, the development of some of them have involved very intensive knowledge elicitation exercises. They generally fit the description of conventional knowledge based systems.

Time (Gray, 1986), Elsie (Brandon et al., 1988), CONSAS (Ibbs & De La Garza, 1988), PREDICTE (Stretton & Stevens, 1990), MIRCE (Alshawi et al., 1990), Mason (Hendrickson; Martinelli & Rehak, 1987), and

Ratu-aj (Kähkönen, 1989) can be classified under this category of systems.

Section 3.5 will discuss some of the most important knowledge based systems developed so far, either planning systems or not. This review describes only those systems that have approached in a way or another the task of generating plans. It does not include systems that were developed for selecting mechanical equipments, such as for lifting (e.g. Gray & Little, 1985a; Wijesundera & Harris, 1987; Cooper, 1987) or earth moving (e.g. Christian & Caldera, 1987).

Before starting to describe such applications, it is convenient to make a brief introduction to the tools and languages used to develop them. This will be presented in Section 3.4.

3.4 Tools and languages

Knowledge based systems can be built using either high level languages or software tools specifically designed for knowledge engineering. High level languages can be AI oriented, such as LISP and PROLOG, or not, e.g. FORTRAN, BASIC, PASCAL. Knowledge engineering tools, on the other hand, can be classified as either programming environments or as shells (Ortolano & Perman, 1987).

Programming environment is a software tool associated with a particular high language, which contains chunks of code written in that language that are useful for particular programming tasks (Harmon & King, 1985). Such tools are generally characterized as hybrid, since they combine approaches from several different areas of computer science (Ortolano & Perman, 1987). They usually incorporate an editor, interfaces to the outside world, multiple knowledge representation schemes, interactive graphics, and a programming language. Generally, they require expensive, sophisticated hardware, such as workstations and mainframes.

There are a number of programming environments, named mixed AI planners, that have been particularly designed for developing domain specific AI planning systems. They are able to capture significant amounts of domain specific knowledge and, at the same time, incorporate some search and constraint propagation techniques (Levitt & Kunz, 1987). The BBl blackboard approach (Hayes-Roth, 1985), and SIPE (System for Interactive Planning and Execution Monitoring)

(Wilkins, 1984) are among such tools.

Shells are tools designed to facilitate the rapid development of knowledge engineering applications (Ortolano & Perman, 1987). They are normally much cheaper than programming environments, and run on widely available micro-computers. Generally, they incorporate very specific strategies for knowledge representation, and use fairly rigid inference control mechanisms. Their suitability is restricted to a much narrower range of problems than programming environments or high level languages (Harmon & King, 1985).

The range of facilities offered by commercial available shells have increased dramatically in recent years, in response to technological advance and market demands (Ortolano & Perman, 1987). Some of the micro-computer shells available in the market are able to replicate some the features that used to be found only in knowledge engineering programming environments (Alshawi et al., 1990).

Most shells currently available are to some extent oriented towards solving diagnosis and evaluation. Their basic principles have been extracted from abstracting high level representation and reasoning concepts from a series of domain-specific knowledge based system applications in those two types of problem (Levitt, 1990). Tools more adequate to tackle plan generation can be expected to appear when developers of planning systems manage to do likewise.

3.5 AI applications for construction planning

3.5.1 Early models of expertise

Models of construction planning expertise have risen the interest of the research community long before the emergence of knowledge engineering. In the early Seventies, a computer programme named COCO (COsts of Contractors Operations) was developed by the Department of Environment (1971), UK, for giving advice to the design team about the cost and the construction duration for fairly large buildings, at the tender stage.

COCO was developed to the stage of working prototype, using expertise from planning staff of four British contractors. It modelled the decision process of construction planners concerned with determining the required plant, labour, and construction time. The developed prototype covered a limited number of building components:

frame, cladding, and internal partitions. Based on a small number of design elements, such as frame type, length of reach required for the crane, number of floors, COCO was able to estimate the cost of a number of resources, as well as the duration of some stages of work. That was probably the first attempt in the UK to encapsulate the expertise of construction planners into a computer programme, in order to give cost advice to the design team.

Several years later, Flanagan (1980) proposed a building duration model that could be used by quantity surveyors for predicting the duration of the construction stage of building projects, during early design stages. This model was based upon pre-established CPM networks, using algorithms for estimating the duration of activities, and for establishing delay ratios between activities, i.e. the percentage of completion of one activity that allows the start of its succeeding. Such algorithms encapsulated some expertise of construction planners. The main objective of that research was to produce a price prediction technique for quantity surveyors, which could take into consideration both the construction method and construction duration.

3.5.2 Time

Time, developed at the University of Reading, was the first knowledge based system developed in the UK for generating plans for construction projects (Gray, 1986). Originally, its main objective was to compare different design alternatives from the point of view of the durations of major stages of work. The system is able to provide a prediction of the overall construction time at a very early, formative stage in the design process, when alternative forms of construction are being considered (Gray, 1988).

Time uses knowledge elicited from experts in construction planning for selecting activities, establishing precedences, and estimating their durations. Its scope is limited to a number of construction technologies and building types. The system asks questions about the dimensions of the building, construction technology employed, and the chosen lifting equipment. A construction programme is generated in a conventional bar chart format, being possible to interrogate the system about specific details of the chosen activities. An interesting feature of the system is that it is possible to nest into it another knowledge based system called Cranes, which contains specific

knowledge for the selection of an appropriate crane (Gray, 1987). Time is written in PROLOG, and runs in IBM PC compatible micro-computers.

One of the main contributions of the research was the identification of some common features in the decision making process followed by different construction planning experts. Gray & Little (1985b) were able to formalize heuristic procedures used by planners to break down construction projects into activities, as well as to extract from them a number of rules used for establishing precedences among activities.

3.5.3 Elsie

Elsie, developed at the University of Salford, is probably the only knowledge based system for the construction industry in the UK that has reached the stage of a commercial package so far (Brandon et al., 1988). Elsie was designed to be used in the strategic planning of a project, prior to formal design, and consists of four separate modules: Budget, Procurement, Time, and Development Appraisal.

The Time module is concerned with forecasting the duration of the whole building process, from the point at which the client decides to contemplate a project, through the design and construction phases, to completion. It encapsulates the expertise of both quantity surveyors and construction planners. A panel of construction planners provided the expertise for estimating the duration of the construction phase, while quantity surveyors provided the expertise for forecasting the duration of the other phases (feasibility, design, procurement, etc.).

Elsie asks questions concerned with the quality of the building, soil characteristics, site conditions, project cost range, a few project dimensions (average area per floor and number of floors), and whether there is a basement. A very general construction plan is generated in bar chart format, in which a project is divided only in major stages of work, such as "initial site works", "substructure", "superstructure", etc. Such plan is much less detailed than the one generated by the Time knowledge based system, described in Section 3.5.2. Also, a report accounting all the assumptions made by the system is provided.

Elsie was built using the knowledge based shell Savoir, and runs in IBM PC compatible micro-computers. It was initially developed for

dealing with office blocks only, but its knowledge base has been expanded to handle other types of buildings.

3.5.4 Callisto

Callisto is a knowledge based system for supporting project management of large engineering projects that has been developed at the Robotics Institute, Carnegie-Mellon University, in the USA. The aim of this research project is to apply results of AI research to support project management, through modelling of project environments and managerial and analytical expertise (Sathi et al., 1986). It has included the development of methods for supporting several project management tasks, such as generating, updating, analysing, and evaluating project plans, tracking project events, and providing means of communication and negotiation between different levels of management.

Roth (1987) summarizes the three main areas of research within the Callisto project as follows:

(i) Development of a semantic representation of projects: the main objective has been to develop a knowledge representation scheme rich enough for supporting a variety of scheduling, analysis, and reasoning capabilities, as well as the creation of a detailed historical record of a project;

(ii) Automatic generation of text and graphical explanations: the main objective is concerned with developing an explanation approach for assisting managers in the analysis and search for relevant information across large updated schedules.

(iii) Developing a distributed approach to project management systems: here, the goal has been to investigate ways to support the communication process amongst the several levels of management involved, either by providing a language for managers to communicate about project plans and conflicting constraints, or by providing methods by which some negotiation between managers can be performed.

Callisto has been built using a knowledge engineering programming environment called SRL (which was later upgraded to become the commercial product Knowledgecraft). It uses CPM networks for representing construction plans.

3.5.5 Construction Planex

Construction Planex is a generic knowledge based framework developed at the Carnegie-Mellon University, USA, that can be used as an automated planning assistant (Hendrickson et al., 1987). It attempts to emulate construction planning expertise at a very fine level of detail.

The system takes as input the description of elementary building components, site conditions, and resource availability. During the planning process, the system creates and uses a description of the project that consist of hierarchies of design elements and construction activities. As output, it assists in the selection of appropriate construction technologies, aggregates activity elements into project activities, generates plans using precedence data that is provided in advance rather than deduced, and estimate activity durations and costs.

Construction Planex scope was initially limited to the ground works, foundations and frame erection operations of modular high rise buildings. More recently, the system was generalized for other areas, such as electric wiring harness assembly. It is implemented in the programming environment named Knowledgecraft, and runs in a Texas Instruments' Explorer LISP workstation.

3.5.6 CONSAS

CONSAS (CONstruction Scheduling Analysis System) is a knowledge based system developed by a joint effort of the University of Illinois and the US Army Corps of Engineers. It intends to emulate the reasoning process that experienced project managers use for accessing the correctness and soundness of a contractor's initial project plans, and for evaluating construction progress, both from the point of view of the client (Ibbs & De La Garza, 1988). The overall goal of the research is to develop an intelligent assistant capable of supporting the work of less experienced project managers. The research is limited to a specific type of building: medium to high rise reinforced concrete buildings.

A large emphasis of the research was given to the knowledge acquisition process. Multiple sources of expertise were involved: a

senior project manager from a large building contractor, representatives from the client (US Army Corps of Engineers), a construction planning consultant, and a number of staff from the University of Illinois. Some of those experts were involved in a knowledge elicitation controlled experiment, described by De La Garza et al. (1988).

CONSAS runs in IBM PC micro-computers and compatibles, and involves three different software packages: (i) Personal Consultant Plus, a knowledge based system shell; (ii) Primavera Project Planner, a commercial project control system; and (iii) DBASE III Plus, a database management system. In the long term, this system will be further developed, involving other project management tasks, such as estimating, scheduling, and control. The programming environment ART (Automated Reasoning Tool), running in the Explorer workstation, was chosen as the tool for the future developments (Ibbs & De La Garza, 1988).

3.5.7 Platform

Platform was built at Stanford University, USA, with the aim of investigating whether an AI hybrid environment is able represent and use construction planning knowledge for enhancing the power of traditional project management systems as real time control tools (Levitt & Kunz, 1985). It was developed to the prototype stage, involving a very specific type of project, offshore oil drilling platforms.

Platform's most significant enhancement in relation to conventional CPM based planning systems is to perform automated schedule updating. The system not only corrects the network with actual project data for completed activities, but also looks for significant risks that appear to have impacted their durations. It encapsulates heuristic knowledge for identifying those risk factors that have had some effect in the durations of activities, either positive (called "knights") or negative (called "villains"). The durations of future activities are then revised to a more optimistic or to a more pessimistic value, according to the risk factors that are impacting each of them. Platform II is an enhanced version of the original Platform, which uses interactive graphics for representing construction plans.

Platform was developed in the Intellicorp KEE (Knowledge

Engineering Environment) programming environment, operating on workstations such as XEROX 1100 Series, Symbolics 3600 Series, and Texas Instruments' Explorer. This system has been extended to be used in other project management domains, such as software project management and factory automation (Levitt & Kunz, 1987).

Platform III is another knowledge based system that was built for illustrating the use of the artificial intelligence technique of "multiple worlds" in making project feasibility decisions under uncertainty (Levitt & Kunz, 1987). This technique assists project managers in making decisions under an uncertain environment, by generating worlds that describe all the possible combinations of choices available, as well as the implications and the outcome of those decisions.

3.5.8 Mason

Mason is a knowledge based system prototype, developed at Carnegie-Mellon University, USA, that is able to estimate the duration of bricklaying activities (Hendrickson; Martinelli & Rehak, 1987). Its knowledge base was built using expertise from a professional bricklayer and a labourer, both of them having many years of experience in the field.

The system initially estimates the maximum productivity that can be expected for a particular activity. Then, it reduces this value, according to a number of characteristics of the job, such as work content, gang size, temperature, height, type of operatives (union and non union labour), etc. In addition to the estimating procedures, Mason also makes recommendations concerning appropriate gang compositions and technologies.

The system is implemented in the OPS5 programming language. A probable extension of the system will be to develop it as a general knowledge based system framework for estimating a much wider range of activities.

3.5.9 GHOST

GHOST (Generator of Hierarchical networks for cOnSTRUCTION) is a knowledge based system that is part of a larger integrated knowledge based environment for construction planning, named CONPLAN, currently

being developed at the Massachusetts Institute of Technology (MIT), USA. CONPLAN will take as input: (i) design; (ii) resources available and material delivery times; (iii) availability of trades and project personnel; and (iv) knowledge about past projects. And it will be able to produce: (i) project networks optimized by trade, resources, and cost; (ii) activity durations; and (iii) network analysis (Navinchandra et al., 1988).

GHOST is essentially a programme that defines activities and establishes precedences between them. It does not extract activities from construction drawings, nor does it estimate activity durations. It takes as input a list of objects to be constructed, such as foundations, walls, floor slabs.

GHOST's initial step consists of producing an optimistic, but non feasible CPM network, in which all activities are in parallel. It then modifies the network in order to make it feasible, introducing linearizations wherever activities cannot be done in parallel. The establishment of such precedences is based on a number of construction principles, such as enclosure, support, etc. (Navinchandra et al., 1988).

GHOST is written in IMST, a knowledge engineering programming environment developed at the MIT.

3.5.10 MIRCI

MIRCI (Management Interface for the Construction Industry) is a system developed jointly by the University of Salford and Liverpool Polytechnic, that is aimed to investigate the feasibility of automating the generation of CPM networks, using micro-computer based knowledge based systems. It integrates three distinct software units: (i) a knowledge based system, built using the shell Leonardo Level 3; (ii) Pertmaster Advanced, a commercial CPM based planning tool; and (iii) DBASE III Plus, a database management system (Alshawi et al., 1990).

MIRCE breaks down the project into activities and establishes precedences between them. The information generated is then passed on to Pertmaster Advanced, enabling the activities to be displayed in a variety of ways, including a graphical presentation of the network. DBASE III Plus is used as an interface between the knowledge based

system and Pertmaster Advanced. The user can interact with the system through any of the units, the knowledge based system, the database, or the planning tool.

Like Construction Planex, MIRCI uses a frame-based representation scheme for creating a hierarchical description of the project in terms of design elements and construction activities. Currently, MIRCI is at a prototype stage, being able only to establish precedences between previously known activities.

3.5.11 Ratu-aj

Like Mason, Ratu-aj is a knowledge based system prototype for estimating the duration of construction activities. It is the result of a pilot project, developed at the Technical Research Centre of Finland, for computerizing information that had been available in manuals for construction project planning in that country (Kähkönen, 1989).

The current version of Ratu-aj is limited to estimating the duration of large panel shuttering activities. The user has to input the size of the gangs, their level of experience, the work content, and conditions related to the weather, site, and equipment. Besides estimating a deterministic duration of the activity, the system produces a linked bar chart representing all sub-activities involved.

The development environment consists of a knowledge based system shell NEXPERT, running on a Macintosh II micro-computer. Future developments of Ratu-aj include transferring the system to an IBM PC micro-computer, and linking it to a commercial project planning and control systems.

3.5.12 SIPEC

SIPEC is an AI planning system, developed at Stanford University, USA, which is able to generate a construction plan for fairly simple multi-storey buildings (Kartam & Levitt, 1989). One of the main aims of the study was to investigate the utility of AI planning techniques for construction planning.

SIPEC uses fundamental knowledge to derive precedence relationships between activities, rather than having activity precedences "hard

wired" into the system (Levitt, 1990). However, it does not consider resource requirements and resource limits, being unable to support the calculation of activity durations.

The AI mixed planner SIPE, developed by Wilkins (1984), was used for implementing the system. It has been also been integrated to a CAD system, so that component descriptions for a project and their topology can be read in from a CAD database (Levitt, 1990).

3.5.13 OARPLAN

OARPLAN (Object-Action-Resource Planning System) is an AI planning system which is part of an integrated design and construction environment, currently being developed at Stanford University (Levitt, 1990).

The system takes as input a description of a facility to be constructed, and generates a hierarchical project plan for the construction of such facility. Like GHOST and SIPEC, OARPLAN reasons with knowledge concerned with basic construction principles to derive precedence relationships among activities (Darwiche et al., 1988).

One of the main objectives of the research is to develop a planning shell for construction projects that (i) provides a natural and powerful constraint language for expressing construction planning knowledge, and (ii) produces construction plans by satisfying constraints expressed in this language (Darwiche et al., 1988).

The initial version of OARPLAN was implemented using the BB1 blackboard environment (Hayes-Roth, 1985). More recently, a second version was implemented using two LISP based shells, named Framekit and Rulekit. OARPLAN contains interfaces to CAD systems, and to a commercial CPM based planning tool, named Micro Planner.

3.5.14 PREDICTE

PREDICTE (PROject Early Design-stage Indicative Construction Time Estimate) is a knowledge based system developed by Digital Equipment Corporation (DEC), and Civil & Civic, two private companies from Sydney, Australia.

The system was designed to be used as a decision support system which estimates the construction time of concrete framed multi-storey

buildings, during early design stages, when little information about the project is available. One of the main objectives of this project was to provide a powerful tool for helping to evaluate and improve early design concepts for multi-storey projects, using construction time as criterion (Stetton & Stevens, 1990).

The knowledge encapsulated in the system was elicited from an expert from Civil & Civic, before he retired, in order to avoid the loss of his expertise. Like Elsie, it has also reached the stage of a marketable tool (Stretton & Stevens, 1990).

PREDICTE usually asks between 100 and 140 questions about the location, size, shape, appearance, ground conditions, and surroundings of the project being analysed. Its main output is a list of the main stages of work, which shows the starting day, duration, and completion day. The system was implemented using a representation language named Candle, which was developed by DEC.

3.5.15 Discussion

Brandon et al. (1988) classified knowledge based systems in five different categories, according to their stages of development: skeleton system, demonstration system, working system, usable system, and commercial system. Most systems described above have not succeeded beyond the stage of a working system. Only two of them, Elsie and PREDICTE, have reached the stage of a commercial system.

None of the models developed so far is capable of performing an automated generation of detailed construction programmes, although this seems to be the long term objective of a number of research projects, such as the ones at the MIT (Navinchandra et al., 1988), and Carnegie-Melon University (Hendrickson et al., 1987).

In the UK, several research studies have emerged from demands of the quantity surveying profession. The models of construction planning expertise developed by the Department of Environment (1971), Flanagan (1980), Gray (1986) and Brandon et al. (1988) have been built for providing advice to clients and design teams, in the early stages of the building process.

Like PREDICTE, both Time and Elsie are able to generate fairly simple plans for the production stage of construction projects. However, such plans are not detailed enough for guiding execution,

being rather like estimates of the durations of the main stages of the work. They can be used to forecast the duration of the whole project, and to compare different design alternatives using construction time as criterion. Such models of planning expertise can be seen, after all, as attempts to produce pricing techniques for quantity surveyors that take into consideration both the construction method and construction duration.

In the USA, most studies have developed applications related to the use of CPM techniques for construction planning. They have generally attempted to automate some of the task performed by planners or managers when updating a network (Levitt & Kunz, 1985); criticising a network (De La Garza & Ibbs, 1987); estimating activity durations (Hendrickson; Martinelli & Rehak, 1987); or establishing activity precedences (Navinchandra et al., 1989). Such studies can be criticized for having entirely accepted the concept of CPM as a convenient model for construction planning. They have not considered all the evidences offered by the literature about the incompatibility of network based planning techniques with the essence of the construction process, previously discussed in the Section 2.3.5.1.

While most systems in the UK were built using micro-computer based shells, in the USA a large number of applications were developed in sophisticated knowledge engineering programming environments, running on expensive hardware.

Clearly there are two main areas of research amongst the studies described. Some studies have focused on the knowledge acquisition side of the problem. They have concentrated on the problem of extracting from human experts sound models of construction planning expertise. This is the case of the research carried out at the University of Reading (Gray & Little, 1985b), University of Salford (Brandon et al., 1988), Carnegie-Mellon University (Hendrickson; Martinelli & Rehak, 1987); University of Illinois (De La Garza et al., 1988); and Technical Research Centre of Finland (Kähkönen, 1989).

On the other hand, there are studies that have emphasized the issues of finding an adequate general architecture for construction planning expertise, involving the development of sophisticated knowledge representation schemes, inference control mechanisms, interactive computer graphics, and the application of techniques

developed in general purpose AI planning systems. This is the case of the research at Carnegie-Mellon University (Hendrickson et al., 1987); Stanford University (Levitt et al., 1988); and MIT (Navinchandra et al., 1988). This area of research usually demands the use of powerful programming environments, and expensive hardware.

All research studies described have approached only a very narrow aspect of planning, in order to limit the size of the domain knowledge. The boundaries were established by means of (i) approaching a small number of planning tasks, such as generating plans (e.g. Construction Planex), updating plans (e.g. Platform), criticizing plans (e.g. CONSAS), estimating activity duration (e.g. Mason, Ratu-aj), rather than the whole process; and (ii) dealing only with a specific type of building or a small number of construction technologies, such as office blocks (e.g. Elsie), offshore platforms (e.g. Platform), reinforced concrete framed buildings (e.g. CONSAS, Construction Planex, SIPEC, PREDICTE).

Another common characteristic of all applications described is that none of them is aimed at replacing human experts completely. They have been developed rather like decision support systems, which are able to free planners or managers from time consuming or tedious work.

According to Brandon (1990), knowledge engineering applications have not proved yet to be capable of performing difficult tasks at the level of human experts, except in well structured, very narrowed domains, with clear boundaries. He stated that what most current applications can do is to provide some kind of decision support, by giving a convenient starting point for human decision making, or, in other words, a "sounding board" for human ideas.

This limitation is particularly severe in domains that can be classified as soft, wide, and shallow. Such domains are characterized by a large number of potentially relevant items which are linked by a dense matrix of weak relationships. The knowledge is therefore not very reliable and most decisions often involve empirical associations in the form of heuristics or rules-of-thumb (Basden et al., 1987). Considering the description presented in Chapter 2, construction planning can be included in such category of domains.

Warszawski (1988) pointed out that it is very difficult to develop knowledge based systems which can replace human experts in the field

of construction planning, even if the planning process is broken down into a number of individual tasks in order to limit the scope of the domain knowledge. He stressed that, given the complexity of construction planning, there are interdependences among different planning tasks, which are difficult to eliminate.

3.6 Guidelines for this research

The review of the main domain specific AI systems for construction planning provided some guidelines for establishing the main features of the knowledge engineering application developed in this research.

One of the main restrictions for the development of this application was concerned with the hardware and software available. The limited amount of resources available for the research discarded the use of knowledge engineering programming environments and workstations.

The decision of using a commercial micro-computer based shell, rather than building a system from scratch using a programming language, was made because of limited time available for this study. Such tools are convenient for rapid prototyping (Ortolano & Perman, 1987), and they are usually better designed than would be the case with a knowledge representation formalism designed in-house (Brandon et al., 1988).

The decisions concerned with hardware and software geared the research towards exploring the problem of using knowledge acquisition for extracting models of expertise from people involved in construction planning. Although the aim of devising a convenient architecture for knowledge engineering applications in this field has not been neglected, the author was aware that the potential contribution of a micro-computer based application to issues such as knowledge representation and inference control mechanism for construction planning is very unlikely to be in the forefront of innovation.

Another important decision was concerned with establishing the boundaries of the domain knowledge. Based on previous research work, it seemed convenient to approach only a portion of the planning problem, and to deal with a narrow range of building types and construction technologies.

The choice of the planning tasks to be approached depended to a great extent on the availability of expertise, and could not be precisely specified before the knowledge acquisition process had started. However, the initial proposal was to focus on the production of construction plans.

Considering all the evidences provided by the literature about the limitations of CPM techniques, the initial proposal was to develop a model of construction planning expertise based on the way the construction process really happens on site, rather than simply adopting the CPM concept.

Another important feature chosen for the application was the ability to cope with incomplete information, so that it could be used in the early stages of the building process, such as feasibility, design, and tendering. It was envisaged that such feature would give an interesting contribution towards the use of models of construction planning expertise by the design team.

The range of building types chosen was traditional technology low rise houses. The author has had a specific interest for house building projects for the reasons presented in Section 1.4. Moreover, no other type of building has been more investigated through activity sampling studies in the UK, during the last thirty years, than house building. Most of these studies were carried out by the Building Research Establishment (BRE), and they could be used as an additional source of knowledge for the application by providing a scientifically based description of the construction process, as it really happens on site.

The choice for traditional technologies rather than industrialized ones was made because they seem to be in favour nowadays, both in the public and in the private sector in the UK (Leopold & Bishop, 1983; National House Building Corporation, 1990). In general terms, traditional house building technologies involve the use of the following components: (i) strip, pad, raft or piled foundations; (ii) load bearing cavity wall, brickwork on the outer leaf and concrete blockwork on the inner leaf; (iii) concrete slab or timber joisted floor at ground level; (iv) precast concrete slab or timber joisted floor at upper floor levels; (v) timber staircases; (vi) pitched timber roofs, covered with concrete tiles; and (vii) concrete block or

stud partitions.

The limited time scale of this research restricted the development of the application to the stage of a working system. At that stage of development, a system is reasonably validated and debugged, being able to generate accurate results: it could, in theory, be used in practical situations, but its questions and reports are still clumsy for users not sympathetic towards it (Brandon et al., 1988).

Finally, for the reasons discussed previously in Section 3.5.15, the system had to be designed as a decision making support system for people that possess some construction expertise, rather than as a consultancy type of knowledge based system that stands on its own.

3.7 Summary and conclusions

In the first part of this chapter the current state of AI research on general purpose, domain independent planning systems was discussed. Although research in this field has fulfilled the role of testing ground for some AI planning techniques (Tate, 1985), the applicability of such systems in the field of construction planning so far has shown to be very limited.

On the other hand, several domain specific, knowledge intensive AI models of construction planning expertise, either planning systems or conventional knowledge based systems, have been successfully developed. However, most of them have not succeed beyond the stage of working prototype.

A review of some of the most important applications developed for construction planning revealed the existence of two main areas of research. Some studies have emphasized the development of models of human expertise, while others have focused on the search for an adequate knowledge based architecture for planning systems.

None of the applications described aimed at completely replacing human experts. Instead, they were developed as decision making support systems, tackling a very limited portion of the planning problem. Furthermore, the size of the domain knowledge was generally restricted by dealing with only a narrow range of building types and construction technologies.

Some general guidelines for the development of an application were

established, based on the lessons learnt from other studies, and on the limitations of this research in terms of resources and time. This application was defined as a micro-computer based decision support system, aimed at modelling expertise concerned with traditional house building projects in the UK. It would be built using a commercial knowledge based system shell, and the main issue involved in its development was to devise a sound model of construction planning expertise, rather than searching for an innovative architecture for construction planning AI systems.

The model will not use CPM as a framework, like most other studies in this field. Its structure will reflect the way the construction process really happens on site, according to the literature, coping, at the same time, with the lack of complete information which is typical during the early stages of the building process.

The following chapter consists of a review of the literature about the production process involved in house building, which has supported the knowledge acquisition process involved in the development of the application.

CHAPTER4: A CHARACTERIZATION OF HOUSE BUILDING

4.1 Introduction

In Chapter 2, the difficulties of using CPM as a tool for construction planning were discussed. The main limitation of the CPM concept is concerned with the fact that it makes assumptions about construction activities that have been denied by the experience of some site engineers and by scientific reports: the construction process seems to be much more complex than is usually assumed by several CPM textbooks (Forbes, 1977; Roderick, 1977; McLeish, 1981; Heineck, 1983). For that reason, the development of the system using any of the available CPM based programming techniques as a framework was rejected.

No other kind of building has had its production process studied in the UK as much as low rise house building. Since the end of the Second World War, several productivity studies concerning house building projects have been developed in this country, most of them carried out by the Building Research Establishment (BRE). The main objective of such studies has been to get a better understanding of the actual process of house building. During the Sixties and early Seventies, research in that field reached a peak, but, in recent years, only limited exercises have been carried out, probably because work study techniques have not been in favour any more (Bennett & Ormerod, 1984).

This chapter consists of a description of the production process in low rise house building projects, as it really happens on site, based on several publications that resulted from the studies mentioned in the previous paragraph. The objective of this analysis is to provide qualitative information that can be used in the task of building the model which had its guidelines proposed in Chapter 3.

In Section 4.2, the progress of work in house building is compared to the traditional concept of production line, and the main strategies used by the construction industry for building repetitive projects are discussed. The role played by key resources in traditional house building is analysed in Section 4.3, and the way the pace of work is usually established in house building projects is presented in Section 4.4. Finally, Section 4.5 consists of a discussion about the difficulties of making predictions related to the production process.

4.2 The progress of work in house building

4.2.1 Comparing repetitive building to a production line

A great proportion of building work consists of the construction of a series of similar units. This is found in low rise house building, and also in multi-storey building, where the units may be dwellings, bays, or storeys.

Nuttal (1965) compared the progress of work in repetitive construction projects to the flow of work in a production line, by describing the construction process as a series of queues: the different trades are the servers and each similar work unit is a customer to be served; the service time is equal to the required time to perform an operation on each unit; and the interval between arrivals of customers in the queue is the interval between completions of units in the preceding operation. If the average time to perform an operation is longer than the average interval between completions of the preceding operation, a gradually lengthening queue of units will be formed between the two operations.

In a traditional production line the units to be produced are identical and the uncertainty related to each operation is low. The use of balanced gangs usually avoids that the work of one trade affects the work of others. It means that it is possible to adjust the size of each gang so that all gangs serve the sequence of units at approximately the same rate.

If the construction process was similar to a production line, the only restriction to the perfect balancing of all gangs would be concerned with the physical limits to the size of gangs. For most trades involved in construction, the work is more efficiently performed if small gangs are used, rather than large ones (Pigott, 1972). Also, there is usually an optimum proportion between the number of skilled operatives and the number of unskilled ones for each trade, for instance 2:1 or 3:2 (Forbes, 1971; Clapp, 1978). Since the pace of work is usually established by choosing a number of operatives for each trade that is a multiple of the optimum gang size, the rate of progress of individual activities can only be varied in steps: it is a discrete variable, not a continuous one (Heineck, 1983).

However, the actual construction process is far less uniform than a

production line. Many projects are difficult to break into a number of similar units. Even in repetitive projects it is hardly possible to balance gangs perfectly. The method of balancing is based on assumptions such as the amount of work is approximately the same and the durations are constant for the same operation on different units. Nuttal (1965) presents the reasons why neither of these assumptions are entirely valid in practice: (i) variations in site conditions and design may change the amount of work to be carried out in each unit; (ii) the average duration of each activity normally is different from the estimate used when balancing the gangs; (iii) the times taken to perform the same activity on different construction units are variable due to differences in the performance of distinct gangs or individuals and to the learning effect; and (iv) there are delays caused by external interferences such as materials shortage and inclement weather.

In fact, there may be occasions when there are no units waiting to be tackled, because of variations in the service time, resulting that the men engaged in the following operation will have unproductive time. This is particularly likely to happen at the beginning of the job, before the queue of units to be served has time to grow (Nuttal, 1965).

An additional complexity of the construction process in relation to a traditional production line is concerned to the existence of loops in the flow of work (Nuttal, 1965). A single gang may be involved in more than one activity along the production of one unit. Such situations require a gang to halt before finishing the work in a location, and return to complete it at a later date. For instance, in traditional house building, usually the same gang of bricklayers builds the external wall of a house in separate lifts, since floor joists need to be placed at the first floor level, and scaffolds need to be mounted at each 1500 mm lift.

In summary, the production process involved in building repetitive units looks much more complex and chaotic than a traditional production line. In order to cope with the unavoidable variability and uncertainty related to the production process on site, the construction industry developed a number of strategies, that have been reported by the literature, such as: (i) low intensity of work; (ii) the spreading of work to various construction units; (iii) lack of

continuous flow of work; (iv) the overlapping of theoretically sequential activities; (v) varying rate of deployment of resources to individual activities; and (vi) the lack of compulsory sequence of work. In the following sections of this chapter, each one of these strategies is analysed, and the main difficulties faced by traditional planning techniques, such as CPM and line of balance, are highlighted.

4.2.2 The low intensity of work

One of the tactics adopted by the construction industry for avoiding the interference between the work of different gangs is to build relatively slowly, by creating buffers between the visits of sequential gangs to each work place (Bishop, 1982). This procedure reduces the incidence of non-productive time within gangs but also extends the duration of the project as a whole, since it causes long periods of inactivity during the building of any one house (Eden, 1972).

Obviously, the project duration cannot be increased indefinitely in order to avoid all possible interferences between gangs. Waiting times between operations represent capital tied up in the contract (Nuttal, 1965). Clients' capital costs and contractors' indirect costs tend to increase with the duration of the construction duration. There is a conflict between reducing the men's unproductive time and the unit's waiting time. In actual projects, the parties involved usually have to reach a compromise between the total amount of non-productive time and the whole duration of the project (Nuttal, 1965).

The low intensity of work in house building has been confirmed by average figures provided by the literature for the total duration and man-hour requirements of real projects. The average time taken to build individual traditional houses on sites of a repetitive nature has been reported by Heineck (1983) to be in the range of 23 to 59 weeks. Considering a labour content in the range of 1200 to 1700 man-hours (Lemessany & Clapp, 1978; Fraser & Evans, 1980), the average weekly allocation of labour could be estimated as something between 20 and 50 man-hours per week. Such figures correspond to approximately an average of 0.5 to 1.5 man-weeks throughout the whole construction period. This intensity of work is very low if it is considered that the usual minimum crew is made up of at least two operatives (Heineck, 1983).

4.2.3 The spreading of work to various construction units

If there is no particular necessity of finishing the work in each work place quickly, the complex organizational problems can also be tackled by creating a pipeline of unfinished houses, so that each gang is able to find a job somewhere on the site, if the work is interrupted for any reason (Bishop, 1966).

This strategy is particularly feasible in low rise house building projects, since the site is naturally divided in independent work locations, such as single houses or blocks, which often have independent access. If necessary, it is possible to start working on several houses simultaneously, spreading the work over a wide area. Multi-storey buildings tend to have more restrictions to the progress of work at certain stages of the project than do low rise buildings. For instance, building the reinforced concrete structure of a high rise building has necessarily to follow a sequence of work places, from the lower to the higher floors.

The research studies carried out by Forbes (1977) and Heineck (1983) confirmed that in low rise house building much of the non-productive time within the gangs is avoided by spreading the construction work horizontally, increasing the number of alternative work locations for each gang, but also increasing the time needed to conclude a single unit.

The extent to which the work is spread on site may also be constrained by external factors. For instance, some contractors involved in speculative house building have every incentive to deliver completed houses as soon as possible, since such developments have to meet the demands of a volatile market (Leopold & Bishop, 1983a). The rates of building speculative houses have been reported to be significantly higher than the rates of building local authority houses (Forbes, 1969; Leopold & Bishop, 1983a).

4.2.4 Lack of continuous flow of work

Several site studies have shown that the work on building sites is done discontinuously. It proceeds in small intermittent amounts over most of the project, instead of completion in small neat periods of time (Roderick, 1977). Each trade pays several visits to each work

place, specially those involved in the services and finishing stages (Forbes, 1977; McLeish, 1981). In the study carried out by Heineck (1983), the discontinuity was such that, from the beginning to the end of individual activities, the number of weeks without work exceeded the number of weeks in which work was observed.

Several causes have been identified for the discontinuity on building sites: delays on the work of preceding trades, design demanding several visits of each trade (Bishop, 1966); the way subcontractors undertake their work simultaneously in several different sites (Pigott, 1972); number of variation orders issued by architects; shortage of materials; unavailability of labour resources (Heineck, 1983); inclement weather (Clapp, 1966); theft and vandalism; labour strikes (Bennett & Ormerod, 1984), etc.

In the particular case of house building, there are indications that the high discontinuity of building work is to a great extent caused by the large number of work packages needed to the completion of a traditional house. Forbes (1977) reported that as many as 300 work packages have been identified in activity sampling studies, rather than the 100 theoretically required in a traditional house building site.

Bishop (1972) pointed out that the discontinuity of the work on building sites is a direct consequence of the discontinuity, fragmentation, and lack of commitment in the construction industry at a macro-economic level, caused by uncertain and fluctuating demand.

A significant correlation has been found in several research studies between the total man-hour requirements and the number of separate visits of each gang (Pigott, 1972; McLeish, 1981; Horner & Talhouni, 1990), indicating that interruptions tend to cause a loss of productivity in the work of operatives. Horner & Talhouni (1990) pointed out two main reasons for this loss in productivity: first, the operatives tend to slow down the pace of work when they perceive an impending delay, in order to minimize the chance of a complete stoppage; second, the shorter the uninterrupted time available for carrying out a task, the greater the proportion of time consumed in preparatory tasks (e.g. mixing mortar for bricklaying), and in completion tasks (e.g. cleaning up and protection).

A considerable effort has been devoted to the task of increasing

the continuity of building work in order to improve the productivity of the industry. In general terms, most strategies proposed have either tackled the problem by improving the buildability of design or by concentrating the management effort on reducing the impact of unavoidable external interferences (Bennett & Ormerod, 1974).

Buildability is a word of relatively recent origin, focusing on the idea of designing for ease of construction, but considering the overall requirements of the completed building (CIRIA, 1983). It emphasizes the rationalization of design elements in order to improve on-site productivity, encouraging the type of design that enables as much work as possible to be completed by a gang without interruptions from the work of other men (Leopold & Bishop, 1983a).

However, there has been no indications from the literature that the pattern of work in construction has changed significantly. Heineck (1983), for instance, reported on the progress of work on three house building sites, in which the electrical installation had been specially designed in order to be executed during a single visit. Although the majority of work was carried out in the 2 or 3 initial weeks, several visits by the gang of electricians were still required to each work place, resulting in a total duration in the region of 15 weeks.

Some components largely used in house building nowadays involve several work packages of very low work content, causing interferences between gangs. Porch roof, for instance, is a design element that requires the work of a number of gangs: plumbers, joiners, roof tilers, decorators, and sometimes bricklayers and electricians. Installing kitchen units, on the other hand, involves the work of only two trades, but usually requires more than one visit by each of them, characterizing the situation named by Nuttal (1965) as looped operation.

Both the low intensity of work and the lack of continuous flow of work lead to construction activities of relatively large durations, if compared to the time needed to perform all the work in each work place and to the total project duration (Roderick, 1977; Heineck, 1983).

4.2.5 The overlapping of theoretically sequential activities

Several studies have indicated that the rigid precedence between activities of a head and tail type is the exception rather than the rule on building sites (Roderick, 1977; Birrel, 1980; Heineck, 1983). Most activities tend to overlap with other activities, in order to accommodate the relatively long durations, previously referred in Section 4.2.4.

Roderick (1977) described a research study carried out at the BRE, involving a large office block and a central store warehouse, in which the actual sequence and timing of activities were compared to the CPM network prepared by a contractor. He concluded that the pattern of work was very different from the logic of the network: several activities were carried out simultaneously, implying a much larger number of ladder type relationships than established in the contractor's network.

Heineck (1983), in his study of three house building sites, concluded that the technical precedence between stages of work does not necessarily require the completion of a supposedly preceding activity to allow the succeeding one to start. According to that author, most construction activities tend to overlap, instead of being in sequence, and the sharp separation between the work of the various trades, as assumed by traditional network techniques, does not occur.

Moreover, there are indications that the concept of logic link between construction activities should also involve some degree of flexibility. Birrel (1980) pointed out that the work of different gangs can be related to each other by absolute logic, or by preferential logic. Absolute logic means that the precedence between two activities is mandatory: roof tiling, for instance, must be carried out necessarily after roof carcassing.

Preferential logic, on the other hand, is concerned with the fact that, although there is a preferable sequence of carrying out groups of activities, the order in which they are performed can be changed to a certain extent. For example, services and finishing work is advisable to start only after the house is water tight and safe. However, if the work of glaziers is delayed for any reason, the services and finishing activities are likely to start before external

glazing is carried out. It is possible that the flexibility introduced by preferential logic causes a further increase on the degree of overlapping between activities.

Some alternative approaches have been proposed to represent relationships between activities. Roderick (1977) suggested that the timing of related activities should be established not only by start and finish relationships but also by rates of development. The proposition of Heineck (1983) consists of not establishing the sequence of work as a rigid chain of tasks, but defining precedences through the proportions of work that need to be accomplished in preceding activities. This concept of precedence could be applied not only to different activities carried out in the same work place, but also to similar activities performed in sequential units.

4.2.6 Varying rate of deployment of resources

Considering the site as a whole, the typical pattern of employment of resources follows an "S" curve, consisting of a slow build-up of the number of operatives employed at the beginning, reaching a peak about the middle and tapering off towards the end of the contract (Shippam, 1968). Obviously, such pattern is to some extent a consequence of the small number of work places available at the beginning and at the end of the job. The smaller the contract, the greater the starting and finishing effects, and less remains of the middle period when the number of work places is at its maximum (Nuttal, 1965).

Fleming (1967) observed that the "S" curve pattern is only an approximation of what really happens on site: there is not a gradual build up of labour, but a number of minor peaks spread over a good part of the contract period.

The allocation of resources to each activity also seems to follow a pattern similar to an "S" curve (Roderick, 1977): high intensity of work occurs only during part of the duration of activities, their start and finishing being undertaken with small allocations of resources. In the research carried out by Heineck (1983), the allocation of work was not constant throughout the duration of the activities: some particular weeks were responsible for the major use of resources, the major effort taking only a small number of weeks of the total duration.

An irregular pattern of allocation of resources to activities is also confirmed by the study of McLeish (1981), in which a stable gang structure was found only for the bricklayer trade. The trades that usually have the least regular pattern of allocation are those for which there is not enough work to occupy one man continuously during a relatively long period. Such trades do not carry out their work in a smooth flow, but intermittently. They leave the site if there is no work, and come back only when there is a clear run of work available (Bishop, 1972). This type of work is usually suitable for sub-contracting (Fleming, 1967).

4.2.7 Lack of compulsory sequence of work

Several authors have reported a lack of rigid sequence of work for most construction activities in house building sites.

Pigott (1972) studied the progress of work in three sites in the Republic of Ireland, and concluded that the operatives moved from block to block without any apparent logic. In the three sites analysed by Heineck (1983), no two stages of work followed the same order of start from unit to unit: wherever work was made available, operatives moved in, without being restricted by the sequence of house blocks that the work was supposed to followed.

Eden (1972) pointed out that the flow of work should not be established in terms of the best sequence of work from unit to unit, but by considering the group of units that can be better dealt with simultaneously at each point in time. Heineck (1983) suggested that the sequencing of work should be seen as the creation of pools of work which can be tackled simultaneously by a number of trades, rather than an orderly arrangement of consecutive activities and units.

The difficulty of following a unique sequence of work from unit to unit imposes serious problems to the practical application of line of balance programming techniques (Heineck, 1983).

4.3 The role of key resources

In construction planning, the activity that controls the pace of work within a stage is traditionally called the key activity. The key activity may be the one that takes the longest time (Building Research

Station, 1956), or one that involves a leading resource (Duff, 1980), i.e. a resource that is critical by its cost or availability. In labour intensive construction, such as traditional house building, the number of operatives available for manning each key activity establishes the rate of production for each stage of work.

In the particular case of traditional house building in the UK, most activities have their rate of progress usually established by the work of skilled operatives, rather than by the pace of work imposed by some mechanical equipment (one of the few exceptions is the excavation of foundations).

Traditionally, the activities carried out by bricklayers play a key role in the construction of traditional houses. Bricklayers are skilled operatives, and in most regions in the UK they have been in shortage (Law et al., 1987). The construction of the shell of a house not only represents a significant part of its labour content (Forbes, 1971; Pigott, 1972; Lemessany & Clapp, 1978; Fraser & Evans, 1980), but it also makes available a work place for several other trades, including those which create a work place protected from the weather.

Bricklayers usually have the lowest non-productive man-hours element among all trades (Forbes & Stjernstedt, 1972). Historically, bricklaying has been organised into relatively large, independent operations, producing an apparent improved productivity in comparison to other trades (McLeish, 1981). The percentage of unproductive time in the work of bricklayers tend to be significantly smaller than for most other trades (Forbes, 1971).

Bennett & Ormerod (1984) pointed out that brickwork is a sort of dominant activity in house building: the progress of work of other activities is usually organized in such a way that continuity of work is given to the bricklaying trade at a constant gang size. This is confirmed by the research work developed by McLeish (1981) in which bricklayers were the only trade with a clear and stable structure.

Compared to the brickwork activities, the services and finishes activities tend to have a more chaotic pattern of work, involving shorter, less continuous working periods (McLeish, 1981). Many activities are carried out in parallel at these stages, and there is a high incidence of interferences between the work of different gangs (Forbes & Stjernstedt, 1972).

Once the building shell is completed, the plastering activities assume a key role in the progress of work. They are dependent for starting upon the completion of the work of several other trades (e.g. joiners, plumbers, electricians), being the last kind of wet work to be executed in each work place. Consequently, plastering holds up all other work in the building that needs a dry environment to be executed (Eden, 1972).

Some stages of work might not have their pace established by a key activity. For instance, the sub-structure stage (including foundations and ground floor) usually can proceed at a much faster rate than the rest of the work (Nuttal, 1965; Forbes & Stjernstedt, 1972; Heineck, 1983). However, if the rate of progress of sub-structure is much higher than the ones chosen for the following stages, a lock up of capital may be created on site. For that reason, the substructure stage is sometimes slowed down or interrupted, in order to let the other stages catch up (Heineck, 1983).

4.4 The natural rhythm

The concept of natural rhythm is often used in connection to the line of balance technique, corresponding to the theoretical optimum rate of output that a crew of optimum size is able to produce: any rate of output that differs from a multiple of the natural rhythm is bound to yield some idle time for labour or equipment (Arditi & Albulak, 1986). Such meaning of natural rhythm seems to be more applicable to a production line type of problem than to repetitive construction.

Lumsden (1968) interpreted the concept of natural rhythm in a more practical way, as the time taken to complete an activity if it is performed by a single, "natural" crew, and just allowed to happen under natural conditions prevailing in the construction industry. Heineck (1983) pointed out that the reason behind this concept is that durations tend to converge to specific values, given present technology, methods of construction, rates of progress normally accepted, and the expectations of those involved: increases in the speed of construction demands a multitude of new requirements different from the ones the parties involved are acquainted with, while decreases in the speed of construction may affect wage standards and contractors' turnover. In other words, the durations of activities

are not necessarily a direct function of single variables, such as labour content, amount of resources allocated, output of these resources, or targets established by the management. Instead, they result from the combination of a large number of factors.

Natural rhythm can also be interpreted as a convenient pace of work that has been established by the construction industry in an evolutionary way, since the complexity and uncertainty involved in construction undermines the application of operational research techniques for choosing an optimum rate of progress (Levitt, 1986). Such convenient pace of work is probably the result of a compromise between the usually conflicting interests of the several participants of a project, such as client, contractor, designers, sub-contractors, suppliers, unions, etc.

Since the rate of progress bears an important relationship to the organization capabilities of each company, different contractors may have distinct natural rhythms for certain activities. In fact, some studies of house building sites indicated that different types of contractors built at different rates of progress. In the studies of Fleming (1967) and Fraser & Evans (1980), larger contracts tended to build faster than smaller ones, while in several studies carried out by the BRE, contractors specialized in house building were usually faster than the ones that were not specialized in this type of project (Bishop, 1965).

The concept of natural rhythm can also be expanded to a construction project as a whole: the existence of natural rhythms for individual activities probably leads to a natural rhythm for the site as a whole. However, considering the degree of flexibility that exist in the inter-relationships between activities, as discussed in Section 4.2.5, it seems reasonable to accept that there is a range of durations for each project that is compatible with the natural rhythms of individual activities.

4.5 Predicting the production process

4.5.1 The chaotic nature of construction

In Chapter 2, anticipation of future events was described as one of the two basic mechanisms of planning. In the context of construction, planning involves making predictions about several aspects of the

production process, based on previously acquired information.

In factory environments, the production times are usually controlled by the speed of machinery, or by well established social practices of the work force (Fine, 1977). Such a production process tends to have a deterministic nature, and its main variables are relatively predictable.

In contrast, the environment in which construction is carried out is plagued with randomness and uncertainty. Generally, construction projects are complex and non-repetitive. There is a multitude of controllable and non-controllable factors that affect the outcome of each decision (Warszawski, 1988). It is widely accepted that there is a very high variability in the work of building operatives: ranges of 3:1 between man-hour requirements of different houses, in the same site, and 4:1 between the productivity of different gangs performing the same activity are fairly typical (Walker, 1971; McLeish, 1981).

A traditional view of uncertainty assumes that the incorporation of uncertainty in predictive models is merely an artificial method of performing even more lengthy calculations (Fine, 1982a). In this sense, using uncertainty is simply a shortcut, in order to avoid time consuming or expensive calculations. Such a view of uncertainty accepts that it is possible to eliminate randomness by gradually increasing the understanding on the reasons for the existing variability (Duff, 1980).

An alternative view of uncertainty is to assume that uncertainty is not ignorance or inadequacy, but an essential content of a system (Fine, 1987). This second approach has been often applied to systems that present some kind of chaotic behaviour, as it is often the case in the field of sub-atomic Physics. According to Fine (1987), this is the kind of uncertainty that exists in the construction field.

Fine (1987) also pointed out that one of the main differences between the production of an artefact and the production of a building is the fact that the latter cause social changes which eliminate the chance of predictability. He argued that construction projects are the infrastructure of the society: "We are changing society as we build. This is a dynamic process and the changes are non-linear" (Fine, 1982b).

4.5.2 The use of mathematical and statistical models

A considerable amount of effort has been devoted to the task of developing mathematical and statistical models for predicting variables such as labour productivity, activity durations, rates of deployment of resources, and total project duration.

However, very few of these models have had, in practice, any impact in the task of construction planning. The main difficulties of applying such techniques are related to the chaotic nature of the construction process, and also to the lack of systematic collection of data from construction sites (Duff, 1980). The adversities that exist in the task of estimating the productivity of building operatives provide some good examples of such problems.

The number of factors that affect the productivity of labour on site is known to be huge (Duff, 1979), and several exhaustive listings and classifications have been produced by the literature (Shaddad & Pilcher, 1984; Thomas & Yiakoumis, 1987; Herbsman & Ellis, 1990).

Several studies have approached the problem of modelling the individual effect of some productivity factors on site, such as repetition (United Nations, 1965; Gates & Scarpa, 1972; Verschuren, 1984; Thomas et al., 1986; Duff et al., 1987), weather (Clapp, 1966; Thomas & Yiakoumis, 1987), building type, gross floor area, and region (Clapp, 1978). However, the effect of each one of the factors has not been easy to isolate, since the interdependencies between them are complex (Horner & Talhouni, 1990).

Some other studies have focused on the application of regression analysis techniques, aiming at identifying a multitude of factors that, for a given level of significance, have a correlation with labour productivity (Fraser & Evans, 1980; Herbsman & Ellis, 1990). One of the main limitations of employing such techniques is the huge amount of data that is needed for establishing relationships which are valid for a wide range of situations.

Despite of all those efforts, very little is yet known about the quantitative effects of the productivity factors (Duff, 1980). According to Bishop (1965), it is unlikely that any study about productivity can possibly distinguish cause-and-effect relationships between measurable factors and achievement which could be applied to

the industry at large. He pointed out that the best that can be done is to demonstrate associations between certain factors and the level of labour requirements, and to infer from the conditions that are likely to lead to an improvement in performance.

An additional limitation of regression analysis techniques is that they have also all the disadvantages of black box models. They only reflect the collective influence of several different factors, and obviously do not consider any unusual condition not included in the data (Christian & Kallouris, 1990). Since the identified relationships are not necessarily causal, regression analysis techniques may not be reliable for sensitivity analysis, and they do not explain the behaviour of the model (Beeston, 1987).

Despite of the limitations of regression analysis techniques, they have been successfully employed as prediction tools in a limited number of cases. They have been used, for instance, for predicting cost-time curves which model the consumption of resources in construction projects. The most common type of cost-time curve is the "S" curve, which is a very useful tool for controlling the cash flow of construction projects.

Another major application of regression analysis to the prediction of variables related to the construction process is the model developed by Bromilow (1987) in Australia for predicting the duration of constructions projects carried out by the Commonwealth Department of Housing Construction. Bromilow (1987) proposed in the early Seventies a formula for predicting the duration of construction projects, using the estimated cost as an independent variable. Such formula was based of data from a large sample of past projects, and its parameters have been recently updated in order to incorporate long term changes in the construction industry.

Although it is theoretically possible to establish the project duration using traditional programming techniques, final handover dates are generally set at a higher level of management, often through a direct negotiation between the client and the contractor (Birrel, 1980; Heineck, 1983). Therefore, models such as the one developed by Bromilow (1987) could provide a rough estimate of the natural or normal duration of construction projects, which would be useful as a starting point for the establishment of a negotiated duration for a specific project.

4.5.3 The application of knowledge based models

Incorporating human expertise in predictive models for construction seems to be a very attractive way to overcome some of the difficulties confronted by mathematical and statistical modelling. The way in which information in the human brain is stored and manipulated results in an extraordinary capacity to cope with chaotic situations (Gleick, 1987). Human beings are very good at solving complex problems that require pattern recognition capabilities, and wide ranging knowledge (Brandon et al., 1988).

In fact, several attempts have been recently made for developing knowledge based systems that make predictions about the construction process. Knowledge based systems have been devised for estimating labour productivity (Boussabaine & Duff, 1990), activity durations (Hendrickson, Martinelli & Rehak, 1987; Kähkönen, 1989), total project durations (Gray, 1986; Brandon et al., 1988; Stretton & Stevens, 1990), etc. Some of those systems have been developed for performing tasks similar to the ones that have been traditionally been tackled by using mathematical or statistical techniques.

In relation to regression models, most knowledge based systems have the advantage of relying on causal relationships, which makes them suitable for sensitivity analysis, as well as capable of explaining their own behaviour. Obviously, knowledge engineering cannot be seen as a general solution for all predictions that have to be made in the construction planning process, since they have their own limitations, which have already been discussed in Chapter 1.

A compromising approach would be to develop knowledge based and regression based models in a complementary way, exploring the strong points of each of them. Christian & Kallouris (1990), for instance, suggested a predictive model for "S" curves, in which regression analysis is used for getting some kind of first opinion about future building costs, while a knowledge based system would be able to refine such predictions, based on the experience and knowledge of domain experts.

4.6 Summary and conclusions

In the first part of this chapter, the progress of work in low rise repetitive house building was analysed, based on the extensive literature available. The production process involved in building repetitive units was characterized as much more complex and chaotic than what usually happens in a production line. In summary, the strategy adopted by the construction industry for building such projects involve: low intensity of work, the spreading of work to various construction units, lack of continuous flow of work, the overlapping of theoretically sequential activities, varying rate of deployment of resources to individual activities, and the lack of compulsory sequence of work.

The role of key resources in the progress of house building was discussed in the Section 4.3, with particular emphasis on the dominant role performed by the bricklaying trade. The concept of natural rhythm, which has a major importance in the construction planning process, was reviewed in the Section 4.4.

Making predictions about production related variables, such as labour requirements, activity durations, and rates of deployment of resources, is a major difficulty in the construction planning process. Some of the mathematical and statistical predictive models developed so far in this field were referred and their main weakness pointed out in the Section 4.5.

The qualitative description of the construction process presented in this chapter was one of the sources of domain knowledge used for the knowledge engineering application developed in this research. The next three chapters consist of a description of the process of building such model and of the model itself.

CHAPTER 5: THE DEVELOPMENT OF THE APPLICATION

5.1 Introduction

The development of the application can be divided in three main phases: (i) conceptual stage; (ii) model building; and (iii) model validation. Although these three stages are described as sequential in this thesis, some overlapping between them occurred in practice.

The objective of the conceptual stage was to identify the role that the application could play in the problem environment, and to outline the boundaries of the domain knowledge needed to devise the model. At the end of the conceptual stage, the basic structure of the problem domain was identified. This made possible to expand the previously proposed guidelines into a more detailed system specification, and to choose an adequate knowledge based system shell for developing the full version of the application.

The second phase consisted of performing a detailed elicitation of knowledge and its implementation as a computer application. Two main sources of knowledge were used: expertise from a number of experienced construction planners from the industry, and information extracted from the literature.

The model validation consisted of performing a formal validation of the proposed model at the end of its development. The main objective of this stage was to check whether the system has reached a reasonable level of quality, and to identify a number of possible limitations of the model.

This chapter is divided in five main parts. Section 5.2 discusses the design methodology chosen for this study. The first phase of development is described in Section 5.3. Section 5.4 presents a more detailed specification of the system, which was established at the end of the conceptual stage. Section 5.5 describes the process of choosing the software tool that was used for developing the full system. Finally, Section 5.6 discusses, in general terms, the second stage of the system development. The stage of model validation will be discussed in Chapter 8.

5.2 Choice of a design methodology

5.2.1 Lack of an adequate methodology

Although knowledge based systems have been produced since the mid Seventies, no comprehensive methodology for modelling the knowledge of human experts and representing it into the machine has yet proved to be effective (Stockley, 1987; De La Garza et al., 1988). It seems that such a methodology will be able to emerge only after more advances are made in the fields of cognitive psychology and knowledge engineering (Slatter, 1987; Gaines, 1987).

The absence of adequate methodologies has resulted in most knowledge based systems being designed through an ad hoc process known as a rapid prototyping: knowledge is elicited from experts and implemented into a prototype, which is subsequently reviewed by domain experts and reformulated by the developers in iterative cycles (Buchanan et al., 1983).

Born (1989) pointed out that early prototyping is so widely used in knowledge engineering projects for the following reasons: (i) some significant system requirements are unknown at the beginning of the development stages; (ii) a highly effective way of eliciting knowledge from experts seems to be showing them the effects of implementing their rules; (iii) finding an appropriate way of representing and structuring knowledge sometimes requires experimentation through prototyping; and (iv) it is very difficult to determine requirements for the user interface when development commences.

On the other hand, the prototyping approach has been criticized for being too informal. As elicited knowledge is often translated directly into code, there is no complete and explicit statement of the knowledge encapsulated in the system (Watson, 1989). This can make both re-implementation and updating cumbersome, and seriously distort the elicitation process, since the development tools usually imposes a pre-determined format which the elicited knowledge must fit in (Slatter, 1987).

For this reason, a number of more formal approaches have been proposed for the process of analysing the knowledge elicited from experts. These can be divided into two main groups. The first one consists of analysing the elicited knowledge on paper before it is implemented, using a representation formalism that is independent from

the implementation language. Such formalism is usually known as intermediate representation, because it can be situated between the form in which the expert's knowledge is expressed and the implemented code. The second group involves the use of automated tools specifically designed for the analysis of the elicited knowledge.

The practice of using paper models has been strongly recommended by the literature (Alexander et al., 1986; Wielinga & Breuker, 1986; Slatter, 1987; Young, 1989; Davies & Hakiel, 1988). However, this approach has also been criticized for not providing rigorous methodologies, and for still having inadequate representational formalisms (Watson, 1989).

The development of automated knowledge analysis tools emerged because of the intricacy of constructing an intermediate representation of domain knowledge, and the subsequent problems in implementing the model. KADS (Breuker & Wielinga, 1989) and KEATS (Motta et al., 1989) are among such tools. This approach has also a number of limitations, since each of the tools available has at least one of the following drawbacks: (i) it is limited to a single knowledge elicitation technique; (ii) it does not produce implementation; (iii) it imposes a problem solving strategy onto the model; or (iv) it is not fully independent of the resulting implementation (Watson, 1989). Neither of these tools are commercially available at the present moment.

5.2.2 Proposed methodology

The development of this knowledge engineering project had an exploratory character. At the beginning of the study, the availability of expertise in the industry was not known, neither existed any experts committed to providing expertise. Furthermore, the development of the application had to start without having a formal system specification. The only guidelines available at that stage of the research were those established in Chapter 3.

This suggested that developing an early prototype was appropriate, since it could be used for assessing whether the system was feasible, and, at the same time, be employed as an instrument for communicating the objectives of this study.

However, considering the limitations of the early prototyping

approach, the decision was made to proceed the analysis of the elicited knowledge using an intermediate representation paper model, simultaneously to the development of the prototype. The intention was not to construct a formal and complete paper model of the expertise, but, instead, to use a variety of schemes that could be useful for storing, structuring, and analysing subsets of the domain knowledge.

The general structure of the knowledge acquisition process proposed for this research is presented in Figure 5.1. Knowledge elicitation results in transcripts that are analysed and represented using an intermediate representation formalism, which is independent from the implementation language. The resulting paper model is further refined during the interviews. The prototype is implemented in an iterative way: it is submitted directly to the criticism of the expert a few times before its completion.

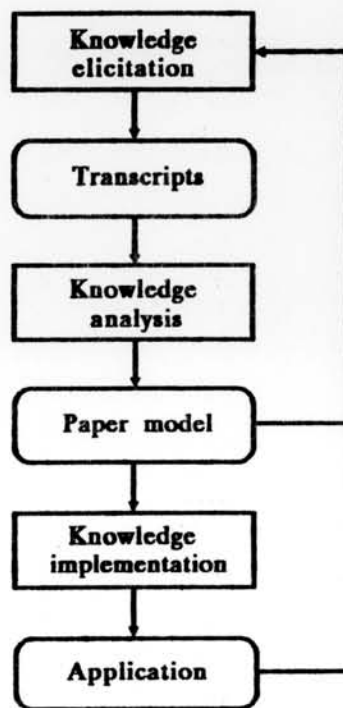


Figure 5.1: The knowledge acquisition process

5.3 Conceptual stage

5.3.1 Investigating the availability of expertise

The first step of the conceptual stage was to investigate the availability of expertise in the construction industry, and to identify a number of experts willing to contribute in this research

project.

Research in the field of knowledge engineering has indicated that, in certain cases, eliciting knowledge from a diverse collection of human experts is more adequate than modelling the expertise from a single expert. Mittal & Dym (1985) and Basden (1990) pointed out for the fact that, in complex and varied domains, experts are often knowledgeable only about a small subset of tasks in the domain, and that many different kinds of expertise may co-exist in what appears to be a single domain of expertise. At a more theoretical level, the operational model on the notion of human expertise proposed by Gaines (1987) corroborated the importance of considering groups of experts in the development of knowledge based systems. He claimed that the basic cognitive system that should be considered in knowledge engineering is the social organization, rather than the individual.

Using a multiple expert approach to knowledge engineering is based on the assumption that a common body of knowledge exists in the domain. One of the limitations of such an approach is that it is not feasible in domains where there is very little agreement amongst experts. Obviously, some kind of disagreement is bound to occur in most domains. According to De La Garza et al. (1988) and Basden (1990), the contradictions and conflicts that may turn up when eliciting knowledge from multiple experts are, in fact, beneficial to the process of modelling expertise, since such difficulties indicate areas for further research.

Construction planning seems to be one of such complex and varied domains, which are more suitable to a multiple expert approach. Construction projects tend to be very complex, the number of alternative components and techniques is very large, and each single project is usually affected by unique design solutions and site conditions. Each expert is bound to have experienced only a limited range of project conditions and construction technologies. Even for a specific type of project, knowledge about construction planning is likely to be found diffusely spread amongst several different experts (De La Garza et al., 1988).

The existence of a common body of knowledge in the construction industry has been accepted by several authors, and, more recently, confirmed by some knowledge engineering controlled experiments.

Construction was described by Birrel (1980) as a process made up of a finite set of tasks, chosen from an existing feasible set of tasks carried out by the industry as whole. Beeston (1987) claimed that there is an intense exchange of staff and ideas among contractors which tends to lead to a common, economical method of planning and execution for any given design.

The experiment carried out by Gray & Little (1985b) in the UK indicated that, given no artificial constraints of market or risk, construction planners generate plans for the production stage in a very similar way: "they choose a similar number of activities which are linked together in accordance with a similar logic to produce a duration which is also similar". One of the main conclusions from the knowledge engineering experiment carried out by De La Garza et al. (1988) in the USA was that a common body of knowledge in the construction field exists, and it can be meaningfully categorized, structured, and applied within a knowledge based system.

In this particular research, the development of an application that could encapsulate some of that common body of knowledge seemed to be a very attractive alternative, since the model to be developed could be widely used throughout the industry, rather than by an individual user.

A large number of house building contractors were contacted at the beginning of the conceptual stage, ranging from small companies to major house building contractors in the UK. Most small and medium size companies were not able to provide the expertise needed for this study because they did not employ any expert in construction planning at that moment in time. In such companies, planning was usually carried out in a very informal way by people that had only general knowledge on the field of construction planning. This initial difficulty in finding experts confirmed to a certain extent the existence of a knowledge bottleneck in the field of construction planning, previously referred in Section 1.4.

From the companies that had experts in construction planning available, most were reluctant to participate in this study due to pressures of work. A few of them also were worried about disclosing information that was considered as confidential.

Giving the initial difficulty of forming a panel of experts, the

decision was made to develop a working prototype of the system in a short period, using the expertise of a single expert. This approach was expected to give better means to communicate the objective of the research and to show the potential of expert systems in the field of construction planning to other possible contributors, who could get involved in the stage of model building.

5.3.2 Knowledge elicitation techniques

Before the knowledge acquisition exercise started for the development of the prototype, a review was made on techniques available for eliciting knowledge from human experts.

Several authors have agreed that the task of eliciting knowledge from experts is both difficult and time consuming (Buchanan et al., 1983; Kidd & Welbank, 1984; Burton et al., 1989; De La Garza et al., 1988). Knowledge elicitation is often claimed to be a major bottleneck in the process of building knowledge based systems (Slatter, 1987). The main difficulties usually found in the knowledge elicitation task can be summarized as follows:

(i) No scientific framework for knowledge engineering has been established yet, and present techniques are usually based on intuition, experience and empirical results, rather than on deep foundations (Gaines, 1987). They are not particularly robust and often have limited applicability (Welbank, 1983);

(ii) Experts are usually very busy people, in high demand within their organizations. They may have other duties that prevent them of spending an adequate amount of time with the knowledge engineer (Trimble, 1986);

(iii) Experts may be unenthusiastic towards the development of a knowledge based system, if they feel threaten by the purpose of the project (Slatter, 1987);

(iv) It is difficult for an expert to describe knowledge in terms that are precise, complete and consistent enough for use in a computer program (Buchanan et al., 1983);

(v) Some knowledge may not be accessible through human experts, not only because they cannot express it, but also they may not be aware of its significance to their activity (Gaines, 1987); and

Several different knowledge elicitation techniques have been used in knowledge engineering projects, some of them being adapted from the field of clinical psychology (Gaines, 1987). Since they have already been widely discussed by the literature (Welbank, 1983; Slatter, 1987; Stockley, 1987), only a summarized description of the most commonly used techniques is presented in this thesis, as follows:

(i) Interviews: it is the most familiar, and widely used technique. Although time consuming, it is relatively easy to perform, and is able to elicit quickly much of the knowledge that is explicit to the expert (Slatter, 1987). It is reckoned to be very useful early on for eliciting the basic structure of a domain (Welbank, 1983). Its main disadvantage is that it relies heavily on uncued recalls, something at which humans are notoriously bad (Welbank, 1983). Consequently, it may be inefficient for eliciting detailed or inaccessible domain knowledge (Slatter, 1983);

(ii) Verbal protocols: The expert is required to give a verbal commentary on what he/she is thinking about whilst working through a problem. It is more natural to the task situation than interviews, and permits the inference of knowledge the expert cannot directly verbalize (Slatter, 1987). One of the main disadvantages of this technique is the fact that giving a protocol can interfere with the work of an expert, causing him/her to adopt a more systematic approach than normal (Stockley, 1987). Moreover, there are indications that this technique can also be time consuming, and that it retrieves a substantially smaller amount of information than comparable techniques (Burton et al., 1989);

(iii) Machine induction: it consists of inputting a large database of documented examples from the task domain into a system and applying an inductive algorithm to discover the simplest set of rules which will generate those examples (Kidd & Welbank, 1984). Its main advantages include a reduction in the need for a knowledge engineer and the fact that it accounts for all cases available (Slatter, 1987). However, extensive trials of such algorithms have revealed some disconcerting problems, such as: similarly to regression analysis (see Section 4.5.2), the identified relationships does not necessarily reflect causal connections (Trimble, 1986); the rules generated may be unstable, since a single added example can sometimes change some of the induced rules (Slatter, 1987); rule induction programs still need

considerable knowledge engineering work, since humans need to supply constraints (Stockley, 1987);

(iv) Observational studies: similar to verbal protocols, except that the knowledge elicitation activity does not interfere in the expert's normal task performance. It can take such forms as videoing or recording. It helps to overcome preconceived ideas, being useful for finding out the actual role of the domain experts, and for drawing attention to the user's contribution (Slatter, 1987). It is only effective if the expert makes explicit most decision making steps, for example, through a conversation with the user, or by drawing sketches;

(v) Conceptual sorting: this technique basically consists of obtaining a set of concepts that roughly covers a domain; transferring each concept to a card; asking the expert to sort cards into several different groups; and combining these groups to form a hierarchy in an iterative way. It is suitable for establishing the global structure of the domain knowledge when a large amount of information has to be organized in a hierarchical way (Slatter, 1987);

(vi) Goal decomposition: the problem space is represented as a hierarchy of goals - terminating in the solutions to the problem. The elicitation exercise is started by randomly entering into the space, and then moving around it with prepared probes to explore up, down, and across the hierarchy. The space is drawn gradually on a piece of paper, in front of the expert (Burton et al, 1989). This technique seems to be suitable for what Fenves (1987) described as a derivation or interpretative kind of problem, in which a number of possible solutions and the conditions under which they are acceptable are previously established;

(vii) Introspection: the expert gives an account of how he/she would solve an imaginary, but typical case (Wielinga & Breuker, 1985). It can be performed considering a number of constraints, such as limited information available, or limited time (De La Garza et al., 1988); or focusing on only one small aspect of the job at a time, rather than considering the full analysis of a situation (Stockley, 1987); and

(viii) Step listing: the expert is asked to list in a piece of paper all the steps that are relevant for performing a task, not

necessarily in the order they are executed (Cooke & McDonald, 1986). This technique is very useful for eliciting typical sequences of events.

This list is not exhaustive and some of the techniques have variations. They differ in their effectiveness at eliciting different types of knowledge (Slatter, 1987; Cooke & McDonald, 1986), and at eliciting knowledge from different types of experts (Burton et al., 1989). Kidd & Welbank (1984) and Stockley (1987) suggested that the most adequate approach can be obtained by using as many of the different techniques available as possible in a carefully tuned combination.

In this particular research, interviewing was the only technique chosen for the conceptual stage, because the aim of this phase was simply to identify the general structure of the domain knowledge, on which the development of the prototype could be based. The application of other elicitation techniques was left to the stage of model building, when more information about the characteristics of the domain knowledge, and about the experts involved in the study could be obtained.

5.3.3 The development of the prototype

5.3.3.1 Knowledge elicitation

The company involved in the development of the prototype (named Contractor A in this study) was a major contractor in the UK, which had carried out several different kinds of building and civil engineering projects in most parts of the country. The expert who provided the expertise was the chief planning engineer of this company in the North West Region. He had planned several house building projects in recent years, all of them carried out on a contract basis, either for local authorities or for housing associations.

One of the main constraints of the knowledge elicitation process was the limited amount of time that the expert could devote to the study. The literature on knowledge elicitation has suggested that working through examples is a very useful strategy for improving the effectiveness of interviews, since it provides cues for the expert to remember all the relevant information (Kidd & Welbank, 1984).

For that reason, the expert was asked to provide some information related to a number of past projects, which could provide beforehand some information about the way the planning task was carried out, and also be used as a basis for the discussions.

Information about nine historical cases was supplied by the contractor. It included the construction plan, some architectural plans, a description of the site, and the main contract conditions, for each project. This information was used for pre-establishing some structure in the elicitation interviews, which made possible to use the expert's time in a relatively efficient way,

Simultaneously to the knowledge elicitation process, a literature review on the field of low rise house building technology, and productivity studies (which has been summarized in Chapter 4) was carried out. The objective of such review was to clarify some of the concepts used in the model as well as to consider some of the findings of scientific studies up to date in its development.

The interviews initially indicated that the expert relied heavily on a small number of rules-of-thumb for planning house building projects. He was able to produce a number of simple rules-of-thumb very quickly, such as: "after carrying out a lot of jobs, we know that the time to the first handover from the start of foundations is within a week or two more or less than twenty six weeks ...".

Such heuristic rules were not considered suitable for the model. The aim was to elicit knowledge beyond shallow rules-of-thumb, uncovering the underlying knowledge that is summarized by those rules. Attarwala & Basden (1985) and Berry & Broadbent (1986) identified several benefits that this approach can bring to knowledge engineering projects: (i) agreement amongst experts about the causality of a domain is more likely than about rules-of-thumb; (ii) explanations tend to be more useful; (iii) knowledge from the domain literature can be incorporated into the system; and (iv) the completeness of the knowledge base can be more easily checked.

Using a causal approach does not imply that the knowledge has to be elicited up to a very elemental level, such as to the level of Physics and Chemistry principles. According to Attarwala & Basden (1985), that would not be possible in most domains, because the detailed causality is not known. Those authors pointed out that the level of detail to be

reached in the elicitation process is usually limited by the knowledge available, by the purpose of the system, and by the kind of explanation demanded by the user.

Following the recommendation of Attarwala & Basden (1985), the practice of posing the questions "Why?", "What else?", and "When not?" to the expert was systematically adopted during the interviews. Such questions were useful for identifying cause-effect relationships between concepts, as well as to separate out different categories of knowledge (this will be discussed later in this chapter).

Five interviews proved to be enough for eliciting the knowledge needed for building a simple working prototype, each of them lasting for approximately one and a half hour. The interviews were all tape recorded, and later transcribed.

5.3.3.2 Software tool used

The choice of an adequate shell for implementing the prototype could not be based on detailed attributes of the domain knowledge, since very little knowledge had been elicited up to that time. For that reason, such decision was made considering a number of more general criteria. These were:

(i) Low cost: the shell could not be expensive, because it would not necessarily be the tool used for implementing the full system;

(ii) Easy to use: the time necessary to learn how to use it had to be relatively short, due to the time scale of the research;

(iii) good facilities for handling numerical information: this feature was required, because the task of construction planning usually involves a considerable amount of calculations (e.g. areas, gang sizes, activity durations, etc.);

(iv) Good interface capabilities: this was necessary for developing an attractive interface to the user; and

(v) Interfaces to external files: it could be useful to be able to use and update information handled by widely used conventional software packages, such as databases and spreadsheets.

Crystal was the shell chosen for developing the prototype, because it generally satisfied the above criteria. This shell can be briefly

described as a deterministic, backward chaining rule based tool, which employs propositional logic as the basic knowledge representation scheme. The main advantages and limitations of this shell will be discussed in more detailed in Sections 5.5.1 and 5.5.2.

5.3.3.3 Knowledge analysis and implementation

The knowledge contained in the transcripts from the interviews was analysed and represented as a paper model, using a wide range of formalisms. Inference nets, tables, lists of steps, precedence diagrams, English written rules were the main intermediate representation schemes employed. Some examples of such schemes will be used in Chapter 6 for describing the model of construction planner's expertise.

The prototype was implemented in stages, rather than after the completion of the paper model, because of the limited time scale of this study. Generally, implementation took place whenever a coherent subset of knowledge was identified.

The paper model worked as a record of the elicited knowledge, which was independent of Crystal's knowledge representation scheme, acting as a quick way of communicating the knowledge elicited so far to the expert, so that he could check it before it was implemented into the machine.

During the conceptual stage, the paper model was kept relatively complete and updated. The aim was to use it as a source for re-implementing the application into another software tool at a later stage, if that was necessary, without having to repeat much of the elicitation procedure.

At the end of the conceptual stage, a general idea about the way in which the knowledge is structured in this domain was obtained. This led to the establishment of a more detailed specification for the development of the application, which is presented in Section 5.4. Also, it made possible to establish some more detailed criteria for selecting the shell used in the implementation of the full system. The choice of the shell is discussed in Section 5.5.

5.4 A more detailed specification of the system

5.4.1 Task model

The first requirement for defining a knowledge engineering application is to model the task that the system will have to perform (Breuker & Wielinga, 1989).

The role of construction planning in the organizational structure of the company was coherent with the description of planning as a multi-stage process, presented in Section 2.3.3. For most projects, planning the construction stage was performed at two distinct levels, as it is shown in Figure 5.2.

At a higher level, a general plan of methods which integrates the entire project is produced by specialist construction planners, who are based in the main office of the company. The plans produced are normally used for establishing a number of key dates related to the production stage as well as for checking the content of a number of critical resources. These plans are not very detailed, being mainly used for feasibility studies, tendering purposes, and as a contractual instrument. They are also employed by planning experts for monitoring the construction process in a broad basis. Such feedback consists of monitoring only a small number of variables that are considered to be of crucial importance for the progress on site.

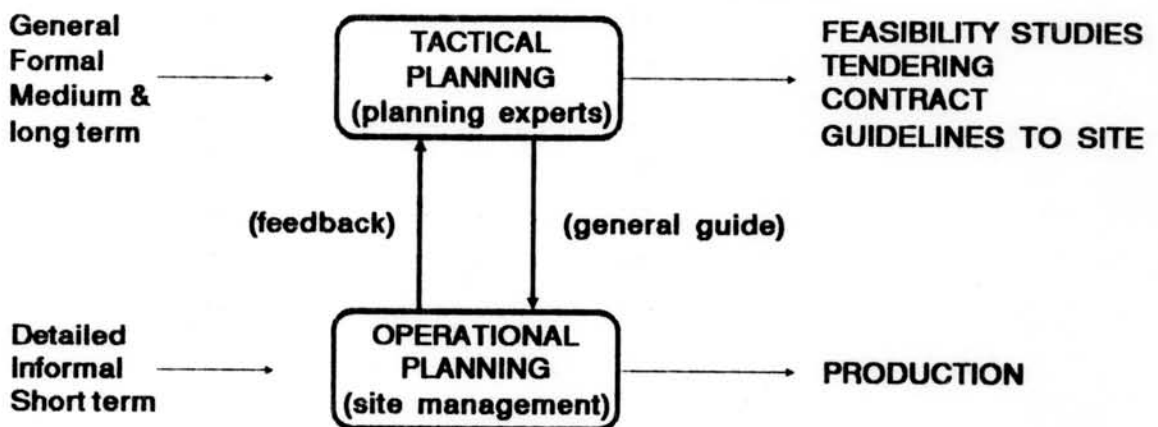


Figure 5.2: Levels of construction planning

At a lower level, very informal plans are produced by personal involved in the site management on a short term basis, usually daily or weekly. Generally, site managers and sub-contractors use the general plan produced in the main office as a framework in which they have to fit their short term decisions.

The lower level was named operational level, since it is closely related to the execution of the job. The higher level plans were designated tactical plans, since they are situated between the operational and the strategic planning level, which is generally related to top level management.

The task chosen to be investigated was to plan construction at a tactical level. Modelling the expertise of construction planning at an operational level would imply eliciting a huge amount of very detailed knowledge from a much larger number of people, such as site managers, foremen, sub-contractors, etc., which could not be performed within the resources and time scale available for this study.

The task of planning construction at a tactical level can be divided in two main groups of sub-tasks: establishing default data, and generating a plan. The need for default data occurs because the expert usually has to generate plans without having a complete set of information about the project: the design is often incomplete, and there is usually a lot of uncertainty related to the site conditions and availability of resources. In extreme situations, such as in feasibility studies, only a general description of the job is available. In that case, the expert has to assume typical values for several aspects of the job, which have been learnt through the experience of planning a large number of similar jobs.

The strategy adopted by the expert for generating plans was consistent with some research studies that have analysed planning procedures in construction companies, previously referred in Chapter 2 (Birrel, 1980; Laufer & Tucker, 1987). Although some elements of CPM were found in the experts' decision making process, his planning strategy was not characterized by the bottom-up approach that is the essence of network techniques. The experts' crucial decisions were not primarily concerned with accurate duration estimates and resource allocations for individual tasks. They involved rather more aggregate aspects of the job, such as defining a breakdown of locations, sequencing the work through these locations, establishing the pace of

work, and estimating the maximum amount of a number of key resources for the whole job. This confirmed that it was not convenient to use CPM based planning techniques as a starting point for constructing the model.

The main sub-tasks involved in the generation a construction plan are: (i) to choose a sequence of work places; (ii) to divide the job into activities; (iii) to establish the pace of work for the main construction stages; (iv) to define a profile of activity starts; and (v) to make final adjustments in the plan, such as to adapt the plan to a calendar, to establish stage buffers, and to eliminate minor inconsistencies in the plan. Each one of them can be further divided into a number of more detailed operations (see Chapter 6). For most real projects, these major sub-tasks are not performed sequentially: they usually overlap, and a number of loops may occur.

5.4.2 Role of the application

Another important aspect of the application that must be included into a general specification is the way in which the user and the system will co-operate, i.e. the definition of the sub-tasks that will be assigned to the system and the ones which will be left to the user (Breuker & Wielinga, 1989).

The reasons for constructing a decision support system rather than an autonomous problem solver type of system have already been discussed in Section 3.5.15. The aim is to develop an application that encapsulates the expertise necessary to perform a number of planning sub-tasks, specially those that are repetitive or time-consuming. Then, the role of the experts in the task can be reduced to the sub-tasks which essentially require human decisions.

The interviews conducted during the conceptual stage indicated that the expert often does not have enough time to generate plans as detailed and as consistent as he would like them to be. Therefore, there is scope not only for automating some of the work that is performed by the expert manually, but also for increasing the consistency and completeness of the planning process, by improving the way in which some of the sub-tasks are performed.

One requirement that seems to be essential is to make the system flexible enough in terms of coping with different levels of expertise,

otherwise it cannot be employed by a wide range of users in the industry. The way chosen to create this flexibility was to design a system capable of proposing solutions for most aspects of a construction plan, even if such decisions are not founded in very deep reasoning, giving an adequate justification for each proposition. The user will then bring his/her own reasoning to the problem by being given the option to alter or confirm the values proposed by the system.

From the five major sub-tasks listed in Section 5.4.1, only the first one - the choice of the sequence of work places - was considered to be entirely unsuitable to be performed by the system. In order to carry out such sub-task, the system would have to be interfaced to a CAD system, through which a good description of the site, and the location of the houses could be input, and transformed into a numeric form. The development of such a sophisticated facility was not considered feasible in this research, due to the limited resources available. In this particular sub-task, the role of the system had to be restricted to providing some guidelines to the user on how to establish a convenient sequence of work.

5.4.3 Types of knowledge

The division of the domain knowledge into different categories have been recognized as beneficial to the process of knowledge elicitation, because it increases the possibility of re-using domain knowledge, and of identifying problem solving strategies that are common to certain types of problems (Wielinga & Breuker, 1986). Most methodologies for knowledge analysis have been based on some kind of classification of knowledge.

Several different classifications for types of knowledge have been proposed in the literature, but no agreement about terminology has emerged yet (Wielinga & Schreiber, 1989). In fact, there are indications that the distinctions between categories of knowledge are far from rigid (Alexander et al., 1986).

The most common distinction is between declarative knowledge and procedural knowledge (Hoc, 1988, Watson et al., 1989). Declarative knowledge bears on facts, is static, consisting of domain concepts, their attributes, and relationships (Hoc, 1988), while procedural

knowledge refers to the execution of operations involving those concepts (Watson et al., 1989).

Another common distinction is between knowledge that define operations to be performed, and knowledge that guide the selection of those operations. Alexander et al. (1986) called the first as dynamic knowledge and the second as epistemic knowledge. A similar differentiation was used by Breuker & Wielinga (1989).

Considering that no rigorous intermediate representation formalism was used in this research for constructing the paper model, there was no need to define categories of knowledge up to a very fine level of detail. For this reason, the knowledge elicited from the expert was simply divided in three categories: declarative knowledge, inferential knowledge, and task knowledge.

Declarative knowledge corresponds to the physical objects of the domain, and their inherent properties and relationships. Inferential knowledge includes all operations that manipulate those objects directly. Task knowledge also involves operations, but at a more strategic level, being concerned with the problem solving strategies adopted by the expert.

5.4.4 Context knowledge

The development of the prototype indicated that it was also convenient to identify that knowledge which is likely to change quickly and that which remains fairly stable.

The reason for this distinction was that a number of rules and parameters used by the expert were only valid if applied under a certain context. They were affected by a combination of intangible factors, such as company policy, market situation, site location, or personal preferences of people involved in construction planning. The deep reasoning behind the combined influence of such factors did not seem to be worthwhile to investigate, since it involved a great deal of wide ranging information.

From the practical point of view, the main objective of such division was to develop a facility in the system where context related rules and parameters can be easily checked and updated. Such facility aimed at allowing the system to be fine tuned, according to the context in which the user is currently operating. A similar approach

was taken in the development of the knowledge based system Elsie (Brandon et al., 1988).

5.4.5 Outputs of the system

The aim was to design a system that is able to produce a set outputs similar to the ones generated by the expert. The most common kinds of outputs generated by the expert were: a general programme for the whole construction stage, schedules of a number of key resources, and a site plan where the sequence of construction is indicated.

The general construction programme produced by the expert for one of the historical cases analysed during the development of the prototype is presented in Figure 5.3. It consists of a matrix of numbers complemented by a Gantt bar chart. The job is usually divided into six stages. Gantt bar charts were used for describing the first and the sixth stages, named "site preparation" and "landscaping" respectively. These stages involved activities that cannot usually be associated to individual houses. In the stages two to six, named "foundations", "shell/roofing", "first fix/plaster", and "second fix/finals", each activity was scheduled by allocating the number of houses handed over each week.

The expert does not use any kind of probabilistic calculation for generating plans. The way in which he copes with the uncertainty consists of keeping the plans at a low level of detail, which gives a high degree of flexibility for the short term decisions that have to be made by site management. For instance, the contract duration is usually divided in weeks, despite of the fact that several activities have a duration much shorter than such a period. Also, many activities are not depicted up to the level of work package, as defined in Section 2.3.3, but consist of highly aggregate groups of tasks, sometimes involving more than one trade.

Therefore, there seemed to be no need for significantly increasing the level of detail adopted for the general construction programme, since such level is a consequence of the uncertainty involved, as well as it is intended to give some degree of flexibility to the site management.

WEEK No. 1111111112222222222333333333444444444555555
 1234567890123456789012345678901234567890123456789012345

ITEM	DESCRIPTION		
SITE PREPARATION			
1	Set up site/hoarding		
2	Out & fill preparation for vibro		
3	Vibro-compaction		
4	Main drainage		
5	Excavate roads		
6	Road gullies		
7	Stone to sub-base		
8	Kerb race & channels		
9	Road base & base course		
FOUNDATIONS			
10	Excavate & concrete footings	22	22222333333333222222
11	Brickwork to foundations		22222233333333222222
12	Internal drainage & services		22222233333333222222
13	Concrete slabs		22222233333333222222
14	House drainage		22222233333333222222
SHELL/ROOFING			
15	Brickwork 1st lift		22222223333333222222
16	Erect scaffold		22222223333333222222
17	1st floor joists		22222223333333222222
18	Brickwork 2nd lift		22222223333333222222
19	Roof carcassing		22222223333333222222
20	SVP & RWP gutters & flashings		22222223333333222222
21	Felt batten & flashing		22222223333333222222
22	Strip scaffold		22222223333333222222
23	Fix windows		22222223333333222222
24	Glazing externals		22222223333333222222
FIRST FIX/PLASTER			
25	Plumbing & heating 1st fix		22222223333333222222
26	Joiner 1st fix		22222223333333222222
27	Electrician & TV 1st fix		22222223333333222222
28	Plate ceiling		22222223333333222222
29	Paramount & stud partitions		22222223333333222222
30	Plaster backing coat		22222223333333222222
SECOND FIX/FINALS			
31	Joiner 2nd fix		22222223333333222222
32	Plaster skim		22222223333333222222
33	Front & back doors		22222223333333222222
34	Electric & gas cupboards		22222223333333222222
35	Plumber 2nd fix		22222223333333222222
36	Electrician 2nd fix		22222223333333222222
37	Gas services		22222223333333222222
38	Electric services		22222223333333222222
39	Water services		22222223333333222222
40	Gas meters		22222223333333222222
41	Electric meters		22222223333333222222
42	Kitchen units		22222223333333222222
43	Heating test & comission		22222223333333222222
44	Loft insulation		22222223333333222222
45	Porch roof		22222223333333222222
46	Artex		22222223333333222222
47	Joiner final fix		22222223333333222222
48	Wall tiler		22222223333333222222
49	Prepare for painter		22222223333333222222
50	Painter		22222223333333222222
51	Floor tiler		22222223333333222222
52	Ironmongery		22222223333333222222
53	Clean out & C.O.W. notes		22222223333333222222
54	Handover		22222223333333222222
LANDSCAPE			
55	Water mains		
56	Gas mains		
57	Electric mains		
58	British Telecom		
59	Street lighting & TV		
60	Top soil		
61	Fencing & boundary		
62	Kerbs		
63	Paving to footpaths		
64	Brick paving		
65	Wearing course		

Figure 5.3: Example of construction programme generated by the expert

5.4.6 Inputs of the system

The house building projects that were object of this study consist of housing estates with between 20 and 150 residential units. These units are usually detached, semi-detached, and terraced houses, or, more rarely, flats and maisonettes. The job includes not only the construction of houses, but also site preparation (demolitions, excavation to reduced level, drainage, road construction, etc.), construction of service mains, and landscaping.

The knowledge acquisition process indicated that the expert is capable of generating construction plans even at the early stages of the project, when very little information about the job is available. This confirms to some extent the results of the study carried out by Gray & Little (1985b), in which experts in construction planning were reported to generate plans using only a small number of basic characteristics of the job.

In general terms, the information that an expert needs about each project consists of: (i) some general contract conditions; (ii) the availability of a number of critical resources for the job; (iii) the main design dimensions; (iv) a general description of the site; and (v) the specification of a number of key components.

The main requirement of the system in terms of input is the ability to cope with missing information, so that it can be used in the early stages of a construction project. Also, the system must be able to use detailed information about the design and the site, if that is available. On the other hand, there must be a limit in the amount of questions that the user is required to answer: the expert that is using the system must not be asked to collect more information than he/she is used to do. Otherwise, he/she may loose interest in using the system.

5.4.7 Man-machine interface

Several authors have pointed out that a good man-machine interface is an essential requirement for the effectiveness and acceptability of a knowledge based system (Kidd & Cooper, 1985; Cleal & Heaton, 1988). A study carried out by Berry & Broadbent (1986) suggested that poor man-machine interface is one of the most common reasons behind the fact that very few knowledge based systems have actually made it to

everyday field use.

In this particular research, a good man-machine interface was an important requirement not only for the final form of the application, but also during the development stage, since early versions of the system were often submitted to the criticism of the experts, as part of the knowledge acquisition process.

Considering the evident importance of the human-computer interaction for the success of the research, a number of guidelines were established for the development of the system's man-machine interface, as presented below:

(i) Jones (1978) recommended that man-computer dialogue should be preferably modelled on concepts that the user has already experienced. This implies that problems must be divided into components which bear some resemblance to the users' understanding of the task, and the technical language used must be as familiar as possible to the user;

(ii) Some concepts may have different meanings according to the context in which they are inserted. Consequently, the meaning of all model variables must be very clearly explained to the user, specially when there are imprecise concepts involved;

(iii) The user cannot be expected to use the system without making typing mistakes. The system must have some safeguards which prevent the user from paying an excessive penalty for making a mistake;

(iv) It is desirable to develop a man-machine interface in which the user is able to have some control over the interaction to the system, rather than being submitted to a rigid consultation with an exhaustive set of yes/no or menu style questions initiated by the system. This tends to make a system usable for a wider range of users (Berry & Broadbent, 1986). While the less experienced users usually prefer to be led by the machine, and to make the most of the explanation facilities, the more experienced ones are likely to prefer a more flexible interaction with the system;

(v) There is an almost unanimous agreement among several authors that it is very important for knowledge based systems to have good explanation facilities (Kidd & Cooper, 1985; Berry & Broadbent, 1986; Cleal & Heaton, 1988). Such facilities assure the more expert users that the system's knowledge and reasoning process are appropriate, and

instruct the less expert users by uncovering some knowledge encapsulated in the system.

(vi) The user must feel visually motivated while using the system. This can be achieved by several different means, such as by designing screens that look attractive, by not imposing a very long time between the system's responses, or by keeping the user informed about what the system is presently doing (Jones, 1978).

Such guidelines were actually regarded as some ideal targets to be aimed at, since the extent to which they could be applied was obviously restricted by the software and hardware employed, as well as by the limited resources available for this research study.

5.5 Choice of the shell

5.5.1 Crystal

The main advantages of using Crystal for developing the prototype can be summarized as follows:

(i) Crystal is very easy to use. Learning how to use it takes a very short time, since there is a very good documentation and no knowledge of computing or formal training is required. It is entirely menu driven, and the knowledge base can be quite readable if the application is of a small scale;

(ii) Unlike most other commercial shells available at that time, Crystal has a wide range of commands and functions for handling numeric variables;

(iii) Crystal has very powerful interfaces with other software packages, such as Lotus 123 and DBASE III. This feature gives the possibility of using the facilities provided by such packages for storing and accessing some of the information used in the knowledge base; and

(iv) The facilities available for generating screens are relatively good, which makes possible to develop a good interface to the user.

5.5.2 Selection criteria

Once the general structure of knowledge was identified, it became possible to assess the requirements of the system in terms of software

tool. The very simplicity that made Crystal so attractive for developing the prototype in a short period, also restricted its utility for developing the full system. The main limitations of Crystal for the implementation of this particular application were:

(i) The only form of knowledge representation available in Crystal are production rules, which are inadequate for defining terms and describing objects and static relationships (Fikes & Kehler, 1985). Much of the domain knowledge elicited so far turned out to be essentially declarative. For instance, it was necessary to describe a building in a hierarchical way, dividing them into a number of elements at several different levels of detail. Also, it was necessary to create a library of activities, in which each one of them had to be linked to several attributes, such as durations, man-hour requirements, dependencies, etc. Frame based systems have much more expressive power for structuring this category of knowledge. Production rules tend to become excessively verbose in the absence of classes of objects and sets of attribute descriptions;

(ii) Some sub-tasks involved a large number of calculations. Crystal does not provide any facility for writing any conventional sub-routines separately from the production rules, and the interface for writing external programs is relatively difficult to use. During the development of the prototype, such calculations had to be mixed with statements in production rules, which reduced the clarity of the knowledge base;

(iii) The development of the prototype indicated that a very large number of rules would be needed for the full system. In rule based systems, as the knowledge based grows, it becomes more difficult to understand the interactions among the rules, to debug them, and to control their behaviour (Fikes & Kehler, 1985). Crystal does not provide any formalism that enables the rules from a very large knowledge base to be organized into small, manageable modules;

(iv) The rule language available in Crystal uses propositional logic, rather than predicate logic, which means that it is not possible to reason about items within propositions (Allwood et al., 1985). This may lead to a large number of rules having to be written for relatively simple steps of reasoning;

(v) The control strategy in Crystal is established by a rigid

decision tree, in which a static list of goals has to be pre-established by the knowledge engineer. It means that decisions about knowledge representation and control strategy have to be made simultaneously. Other shells provide separate facilities for establishing a number of alternative control structures, which makes easier the task of knowledge implementation. More importantly, there is a possibility, in such shells, of devising very flexible ways of using the knowledge base during consultation, making the system appear more intelligent to the user (Allwood et al., 1985);

(vi) Crystal's inference control mechanism does not provide real opportunistic forward chaining, which makes the use of rules relatively inefficient;

(vii) Crystal does not provide any powerful facility for approximate reasoning. Although reasoning under uncertainty was not considered to be an essential feature of the application at that stage, the availability of facilities for handling uncertainty seemed to be an attractive option, since it could provide a valuable upgrading route for the system;

(viii) The runtime facilities provided by Crystal are relatively limited. There are not any built-in facilities that give the user the opportunity of volunteering information, stepping back a question or making what-if questions;

(ix) The size of a knowledge base in Crystal is limited by the amount of memory available. Consequently, any large application has to be divided into several independent knowledge bases;

The subsequent upgrades of Crystal indicated that the policy adopted by its developers has not been to increase the expressive power of its knowledge representation structure, or the flexibility of its inference control mechanism. The emphasis has been to improve it as a general purpose tool, which could be used as an alternative to conventional programming languages.

Giving the limitations of Crystal, other commercial shells available in the market were considered for the development of the application. A set of criteria was established for comparing a number of such tools, including the following items: adequacy of the knowledge representation structures, flexibility of the inference

control mechanism, availability of facilities for writing procedural routines, availability of facilities for handling uncertainty, readability of the knowledge base, quality of the development environment, availability of run-time facilities, quality of the interface to other software packages, speed, hardware requirements, and cost.

Four shells were considered for the development of the application: Xi Plus, Savoir, Leonardo, and Goldworks. Each one roughly represents a different category of shells available for micro-computers at that time, in the British market. Shells not marketed in this country were not considered, because of the possible lack of technical support.

5.5.3 General description of shells

5.5.3.1 Xi Plus

Xi Plus represents a category of rule based shells, written in PROLOG, which are suitable for small to medium size knowledge engineering projects. A large emphasis is given to the readability of the knowledge base: the rules usually have an English-like syntax. The rule language is based on predicate logic, either using the default predicates provided by the shell - "is" and "includes" - or using a limited range of predicates that can be defined by the knowledge engineer. A small number of more sophisticated knowledge structures, such as "is-a" hierarchies is also provided to supplement the rules.

The inference control mechanism is relatively flexible, using demons for introducing forward chaining, and an agenda for establishing the order of sub-goals. Unlike the other three shells, no mechanism for approximate reasoning is provided in Xi Plus.

5.5.3.2 Savoir

Savoir is a rule based shell, written in PASCAL, which encourages the developer of the application to regard the knowledge base as a network. Besides rules, Savoir also uses templates that can be considered as primitive types of frames: each variable or question used in the knowledge base has an associated number of qualifications, such as standard messages, format, range of allowed values, formulae for calculation, etc.

One of the main strengths of this shell is the variety of

facilities available for approximate reasoning: Bayesian operators, extended Boolean logic, and fuzzy logic operators. Also, very flexible inference control strategies can be built in *Savoir*: there is no default inference strategy, and the inference is controlled by a mechanism called "action", which instructs the system to investigate distinct goals at different times.

Knowledge bases have to be prepared in a text file using a conventional word processor and have to pass through two stages of compilation, which makes very time-consuming the task of debugging a system. On the other hand, the shell provides a considerable large number of useful runtime facilities, such as volunteering information, amplifying questions, stepping back to previous questions, etc.

5.5.3.3 Leonardo

Leonardo is a hybrid shell, written in FORTRAN. The knowledge base is structured in an object-oriented fashion, using rules and frames simultaneously as knowledge representation structures. The rule language is based on predicate logic, using a number of predicates provided by the shell, such as "is", "includes", "excludes", "overlaps", and "equiv".

Each object in Leonardo is given a frame, which contains several slots. Such slots can be used for displaying messages, generating screens, controlling inference, or for storing information about some object attributes. Moreover, frames can be organized hierarchically using special objects, named class objects, which are able to support property inheritance.

One of the outstanding features of Leonardo is that it provides a very powerful programming language, similar to FORTRAN, which can be used for writing procedural routines. The use of such routines does not affect the readability of the knowledge base, since there is a fine mechanism for integrating them to the rules.

5.5.2.4 Goldworks

Goldworks is the most sophisticated of the four shells examined. It is written in LISP, and contains several facilities that are usually found only in workstation based knowledge engineering environments.

Like Leonardo, this shell is also object-oriented, using a rule/frame hybrid knowledge representation scheme. However, Goldworks allow frames to be hierarchically organized by establishing parent-child relationships between any objects, rather than using class type objects. Also, the message passing mechanism available is considerable more sophisticated than in Leonardo: the slots in which messages are passed can also be associated to a number of attributes, called facets, which hold some additional information, such as functional behaviour, and restrictions on the type of value that the slot is allowed to accept.

A very flexible inference control is provided in Goldworks: the order of rule firing can be entirely established by the knowledge engineer through facilities named multiple agendas and priority values.

Unlike the other three shells, Goldworks does not run in any standard PC. Its minimum hardware configuration is an IBM PC AT or 100% compatibles (i.e. 80282 chip based micro-computers), with 512 kilobytes of base memory, 5 megabytes of extended memory, and 10 megabytes of free space in the hard disk.

5.5.4 Final decision

Table 5.1 presents a summary of the properties of the tools investigated, based on the eleven criteria established in Section 5.5.2. All four shells considered seem to have several advantages in relation to Crystal, in this particular study.

Obviously, the most critical item was the extent to which the domain knowledge could fit the knowledge representation structures available in each shell. Previous experience in the development of other knowledge engineering projects in the field of construction planning and control had indicated that pure rule based systems cannot usually cope with the complexity of the knowledge in this domain (Logcher, 1987). In this respect, both Leonardo and Goldworks had the advantage of having a hybrid object-oriented knowledge representation structure.

Table 5.1 indicates that the only advantages of choosing Xi Plus were its low cost and the readability of the knowledge base. None of them seemed to compensate the lack of hybrid knowledge representation.

CRITERION	Xi Plus	Savoir	Leonardo	Goldworks
Knowledge representation	Rules	Rules	Rules & Frames	Rules & Frames
Procedural language available	External routines in C or ASSEMBLER	External routines in PASCAL	FORTRAN, external routines in any language	LISP, external routines in C
Flexibility of the inference mechanism	Good	Good	Fair	Very good
Mechanisms for handling uncertainty	none	Bayesian operators, certainty factors, and fuzzy logic	Bayesian operators, and certainty factors	Certainty factors
Readability of the knowledge base	Very good	Poor	Good	Poor
Quality of the development environment	Fair	Poor	Good	Good
Availability of run-time facilities	Fair	Very good	Good	Good
Interfaces to other software packages	Good	Poor	Good	Good
Speed	Poor	Fair	Fair	Poor
Hardware requirements	Standard PC	Standard PC	Standard PC	Standard PC + mem. extension
Cost (educational)	£ 275	£ 1,500	£ 1,000	£ 2,000

Table 5.1: Comparison of four shells

The main advantage of Savoir in relation to Leonardo and Goldworks was its powerful mechanisms for handling uncertainty. Since approximate reasoning was not one of the main features of the application, this alternative was eliminated.

The final decision was between Leonardo and Goldworks. Goldworks had the advantages of having a richer knowledge representation structure, and a more flexible inference control mechanism. On the other hand, Leonardo had a very efficient way to integrate procedural routines and rules, and had a relatively readable rule language.

The factor that eventually discarded the alternative of choosing Goldworks was its minimum hardware requirements. The cost of buying this shell and the five megabytes of memory extension required was beyond the resources available for this research project. Also, such hardware requirements might create difficulties for running the system in the main office of construction companies. This could affect the knowledge acquisition process, since the experts would not be able to directly criticize interim versions of the system.

5.6 Model building

5.6.1 Participation of more experts

At the beginning of the building model phase, the search for contractors willing to provide expertise for the application resumed. At this stage, however, a prototype of the system was available for demonstrating the objectives of the study.

This prototype played a key role in getting the participation of other contractors in this study. In general, construction planners seemed to get much more interested in the development of the system once they could see something running in the computer.

Two construction companies eventually agreed in providing the expertise for developing a full working version of the system. Each of them had two experts in construction planning working in the North West Region who were able to devote some time to this research. One of the companies was a medium-size contractor (named Contractor B in this study), which had carried out a large number of house building projects in the Region. The other one (called Contractor C) was, like Contractor A, a major national contractor in the UK. Both Contractors B and C had a large experience in carrying out house building projects in a contract basis, for either local authorities or housing associations.

Some contribution was also obtained from one of the biggest housing associations in the UK, based on the North East Region. Although that organization did not have any expert in construction planning available, it was able to provide some information about a number of past projects, which could be used in the knowledge acquisition process as historical cases.

5.6.2 The development of the working system

5.6.2.1 Knowledge acquisition

The knowledge acquisition process during the model building phase essentially followed the same procedure adopted during the conceptual stage, described in Section 5.3, and diagrammatically presented in Figure 5.1. The only differences at this stage were the diversity of knowledge elicitation techniques employed (this topic will be discussed in Section 5.6.2.2), and the fact that there was a panel of five experts involved, rather than a single one.

A number of additional historical cases were provided both by the contractors and by the housing association. On the whole, there were information about twenty three house building projects: ten from Contractor A, six from Contractor B, four from Contractor C, and three from the housing association. Two of the housing association projects had been carried out by a large national contractor, named Contractor D, and one of them by a small regional contractor, named Contractor E.

The amount of information available for each project was variable. Some projects had a very complete documentation, including all architectural plans and the bill of quantities, while others had only a summarized description of the job, accompanied by a general construction programme.

The level of detail of the programmes generated by Contractors B and D was very similar to the ones produced by Contractor A (see Figure 5.3). The programmes produced by Contractors C and E were less detailed. However, the role of construction planning in the organizational structure of the three companies that provided experts for the knowledge elicitation process (A, B, and C) was, in general terms, very similar: there were two main levels of planning, one at a tactical level, performed by experts, and another at an operational level, executed by the site management, as described in Section 5.4.1.

During the building model stage, it was not possible to maintain the paper model updated up to a very fine degree of detail. No special purpose automated tool was used for representing the elicited knowledge, and adding every single new piece of detailed knowledge to the model turned out to be a very time consuming task. Consequently, the role of the paper model as a way of interacting with the experts during the elicitation of very detailed knowledge was considerably

reduced.

This problem was partially surmounted by increasing the role of the interim versions of the system during the elicitation of some subsets of knowledge. The experts were encouraged to criticize the implemented model before its completion, using two main validation techniques, named sub-system validation and static validation.

The first one consists of running separate sub-systems of the knowledge base for a number of test cases, and asking the experts to check the soundness of the results (O'Keefe et al., 1987). In the second technique the experts are asked to check directly frames and rules implemented in the system (Hollnagel, 1989). The latter kind of interaction was only possible in this particular research because Leonardo has a relatively readable rule language.

The issue of validating knowledge based systems, during development and after completion, will be discussed in more detail in Chapter 8.

No formal method of approximate reasoning was incorporated in the model. The main reason for such decision was the fact that the experts felt unease about expressing their expertise in terms of precisely quantified probabilities. This problem has also been reported in several other studies (Welbank, 1983; Allwood et al., 1985; Schutzer, 1987; and Slatter, 1987)

5.6.2.2 Elicitation techniques

From the techniques presented in Section 5.3.2, four of them - observational studies, conceptual sorting, goal decomposition, and machine induction - were considered to be unsuitable for this particular knowledge engineering project.

Observational studies was not selected because it seemed to be disadvantageous in relation to verbal protocols, since it was not possible to get much verbal or written information from the experts while they were performing the task, without interrupting them.

Conceptual sorting was not considered to be very relevant because the amount of declarative knowledge that had to be organized in a hierarchical way in this study was relatively limited.

Goal decomposition was not selected because of the nature of the

construction planning task. Planning is essentially a generative type of problem, rather than an interpretative one. In a generative problem, the possible solutions are not previously known (there is usually an infinite number of solutions), and conditions are given in the form of constraints, which have to be satisfied by a chosen solution (Fenves, 1987). As mentioned earlier in this chapter, goal decomposition is a technique more suitable for interpretative problems, in which all possible goal states are previously established.

Finally, machine induction was discarded because of all its limitations, already reported in Section 5.3.2. Moreover, considering the multitude of factors that affect the construction process, the number of historical cases available did not seem to be large enough to provide valid results from an induction algorithm.

The usage of the remaining elicitation techniques was to a great extent restricted by the limited amount of time that the experts were able to allocate to this study. Unfortunately, it was not possible to carry out any kind of controlled experiment in which cognitive aspects of the construction planning task could be investigated.

Another practical restriction in this study was the fact that this knowledge elicitation phase coincided with a period of very low amount of work in the house building sector. For that reason, it was not possible to apply the technique of protocol analysis.

Both the techniques of introspection and step listing turned out to be very natural to the experts. Step listing was a very efficient way of eliciting the sequence of work that experts follow when performing a sub-task that is considered to be normal or typical, e.g. accounts of typical sequences of work on site.

On the other hand, introspection was very useful for making the experts to analyse some exceptional or unusual situations, for which no historical cases were available. Both techniques were employed in a relatively informal way, being usually intermingled with the interviews.

On the whole, seventeen knowledge elicitation sessions were carried out during the model building phase, corresponding to approximately forty five hours of expert's time. Besides the verbal data, some of the experts also provided some written material that they are used to

employ as planning aids, such as checklists, lists of activities, activity sub-networks, compilations of output rates, etc.

5.6.2.3 Issues related to the involvement of multiple experts

The experts involved in the study distinguished from each other not only in terms of types of projects and technologies that they had experienced, as it was expected, but also in terms of level of experience.

The most clear difference in terms of level of expertise was between the two experts from Contractor B. One had many years of experience as a planner, while the other one had been working only for a few years in this task. This difference turned out to be very beneficial to the knowledge elicitation process. The more experienced expert had some difficulty in accessing the causal relationships that were behind his heuristic knowledge, and was invariably busy. The less experienced expert was more able to articulate his knowledge in an orderly way, and had more time available to devote to the study. This relationship between the level of expertise and the capability of articulating deep knowledge has already been reported by the literature (Slatter, 1987).

The strategy adopted during knowledge elicitation was to elicit as much knowledge as possible from the less experienced expert, taking advantage of the time he had available, and of his capability for explaining his own thinking. The relatively short time available from the more experienced planner was then used for focusing on some difficult aspects of the task, about which the less experienced expert did not have a lot of knowledge.

The experts were usually interviewed in an individual basis. However, if two experts from the same company were available at the time, both of them were invited to participate of the discussion. The sessions that had contributions from two experts generally resulted in a more productive elicitation exercise: more cases were brought to the discussion, and the experts tended to search more for causal relationships, rather than just giving shallow rules-of-thumb, in order to reach an agreement between themselves.

In spite of the causal approach adopted in the knowledge acquisition process, a number of disagreements existed among the

experts involved. Some of these disagreements will be discussed in Chapter 6.

Two main criteria were employed for selecting an approach amongst the ones followed by different experts. The first criterion consisted of choosing the alternative that was used by the majority of experts. If that did not exist, the alternative chosen was the one that, from the point of view of the author, was the most coherent in relation to other aspects of the model.

5.4 Summary and conclusions

The most important steps taken during the first and second phases of the development of the application have been described in this chapter. A pragmatic strategy for knowledge acquisition was adopted in the study, because of a number of existing practical restrictions.

The first stage involved the development of an early prototype of the system, based on the expertise provided by only one construction planner, and using a very simple software tool. At the end of this stage, it was possible to produce a more detailed specification of the system, and to select an adequate software environment.

In the second stage, a panel of experts was formed, involving five practitioners from the industry. Three different knowledge elicitation techniques were employed: interviews, introspection, and step listing. The main constraint to the knowledge acquisition process at this stage was the limited availability of time from the experts. Consequently, knowledge elicitation was performed in a relatively informal way, without carrying out any kind of controlled experiment.

A number of lessons were learnt during these two stages. They can be summarized as follows:

(i) The development of an early prototype played a key role in forming a panel of multiple experts. The experts were able to understand more clearly the objectives of the research when they were shown the prototype. In general, they felt much more motivated by the study once they were able to see something running in the computer;

(ii) Working through the several historical cases available seemed to be a very useful strategy for using efficiently the limited time available from the experts. Such cases were used by the author as a

source of information about the task, prior to the elicitation sessions, providing a number of cues which were used for focusing the elicitation process into a narrow aspect of the problem;

(iii) The use of a paper model enabled the experts to check some of the knowledge analysed before it was implemented in the knowledge base, specially during the early stages of knowledge elicitation. Such documentation was also useful when the application had to be transferred from one shell, where the prototype had been implemented, to the environment where the full working system was developed.

The role of the paper model was considerably reduced during the elicitation of detailed knowledge, due to the excessive manual work required. As a result, the documentation of the model was not carried out to a very fine level of detail.

It seems that this problem can be overcome in future knowledge engineering projects, once some affordable knowledge analysis automated tools can be used for constructing paper models. The use of such tools will probably result in a much more organized and complete system documentation, compared to the one that resulted from the development of the paper model in this study;

(iv) Two of the knowledge elicitation techniques employed - step listing and introspection - were relatively successful because they were very natural to the experts. It seems to be worthwhile to further investigate the applicability of both techniques for studying cognitive aspects of the construction planning task, through the development of some controlled experiments in this field.

(v) The interim versions of the system played an important role in the task of extracting detailed knowledge, by running the system in the presence of experts, and asking them to check directly some of the pieces of knowledge implemented in the system.

(vi) Building a model of expertise using knowledge elicited from multiple experts was confirmed to be an interesting approach. The elicitation sessions in which two experts were simultaneously involved were generally more productive than the ones that had the participation of only one expert. As expected, the experts had experience in slightly different types of projects and technologies. Each one of them was encouraged to focus his contribution in those

particular aspects that he was more specialized in. The fact that there were experts with distinct levels of expertise also turned out to be beneficial to the study: while the most experienced planners were able to find solutions for the most difficult situations, the less experienced ones were able to explain causal relationships in a more orderly way.

The next chapter consists of a description of the model of expertise extracted from the experts, in which some sections of the paper model that resulted from the knowledge analysis are presented. The main features of the implemented system will be discussed in Chapter 7.

CHAPTER 6: AN ANALYSIS OF THE EXPERTS' APPROACH

6.1 Introduction

This chapter consists of a general description of the model of construction planning expertise that was constructed in this study. This model encapsulates knowledge provided by a panel of five practitioners from the industry, as well as information extracted from literature.

The description presented along this chapter is relatively independent from the formalism available in the software tool used for implementing the model. It is essentially based on the paper model that was developed during the knowledge acquisition process. Several of the intermediate representation schemes employed in the paper model are used to illustrate this description.

The approach described in this chapter is a distillation of the strategies employed by different experts. Although some reference is made to their disagreements, no formal comparison between these is reported.

Such comparison was not worthwhile to carry out because of the lack of comparability between the knowledge elicited from different experts. This was a result from the fact that the elicitation sessions were relatively informal. Each expert expressed his own expertise in a different way, although similar sets of questions were posed to all of them at the beginning of the elicitation process. Furthermore, each expert tended to talk in more depth about the aspects of house building which he was more experienced in.

6.2 Main planning sub-tasks

In the previous chapter, the planning task was divided into two main groups of sub-tasks. The first one consisted of forming a description of the job, while the second group was more specifically concerned with producing construction plans.

Figure 6.1 presents the main planning sub-tasks, and their position in the decision making process. The planning process starts by the collection of information from a number of project documents, such as

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architectural plans, specification, bill of quantities, contract, site report, etc. When there is any information missing, some default data is used by the expert, so that a complete, though not necessarily detailed description of the job can be formed.

Once a thorough description of the job is available, the main parameters of the construction plan can be established through four separate sub-tasks performed by the expert. They are: choosing the sequence of work places, dividing the work into activities, establishing the pace of work, and defining a profile of activity starts. The sequence in which such sub-tasks are carried out does not follow a fixed pattern among different experts. These sub-tasks are usually performed simultaneously, since a number of interactions may occur between some of them.

After establishing the main parameters of the construction plan, the experts start to assemble it. At this stage, a number of more detailed decisions related to the plan are made, such as adjusting the plan to a real calendar, introducing buffers between stages, deciding whether to build temporary roads, etc. There may be situations in which the expert has to make some minor adjustments in some of the parameters established during the four previous sub-tasks.

If the plan is aimed at providing guidelines to the site management, it is usually checked against a number of general requirements for the particular project, and sometimes submitted to the criticism of a higher level manager. If any of these requirements is not satisfied, other alternative plans will have to be generated, until an acceptable solution is found.

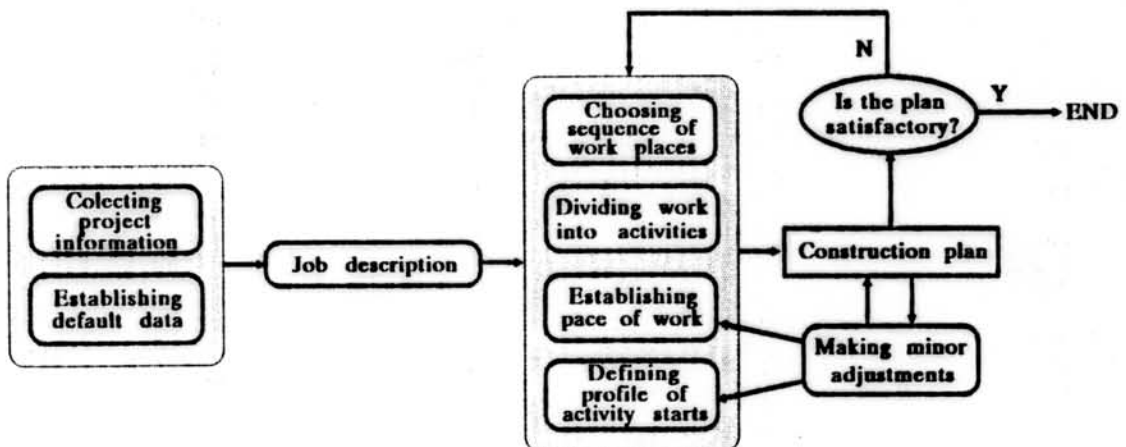


Figure 6.1: Main planning sub-tasks

In the following sections, each of the main planning sub-tasks will be discussed in some detail.

6.3 Forming description of the job

6.3.1 Organizing the relevant variables

The elicitation of knowledge related to the first group of sub-tasks initially focused on identifying and organizing all the project variables that the experts considered to be relevant for generating a construction plan. The aim was to form an abstract representation of house building projects, which could be used for describing the main aspects of the work to be done.

The project representation elicited from the experts turned out to be a very simplified model of real projects, since the experts employed only a relatively small amount of information for generating fairly detailed plans, as previously discussed in Section 5.4.6. Employing a much more detailed representation than the experts' was not considered to be advantageous in this study, because this would require the user of the system to input a very large amount of data. This further development could be considered in the future, if the system is adequately interfaced to a CAD package, which would free the user from inputting the project geometric description.

The variables selected for describing the job were organized in an object oriented form. This approach was the first step towards organizing the static knowledge related to construction elements into a lattice of frames, allowing a number of different types of relationships to be established between such elements.

The main construction elements involved in the description of the project were hierarchically organized, as shown in Figure 6.2, using a "part of" type of relationship. This figure indicates that the construction elements differ from each other in terms of the level of detail in which they are described. The elements related to the operations carried out by bricklayers are detailed up to a relatively fine level, since the work of this trade needs to be carefully planned by the experts. On the other hand, very few elements related to the finishings and services are included in the description, despite the large variety of materials and trades involved in such operations.

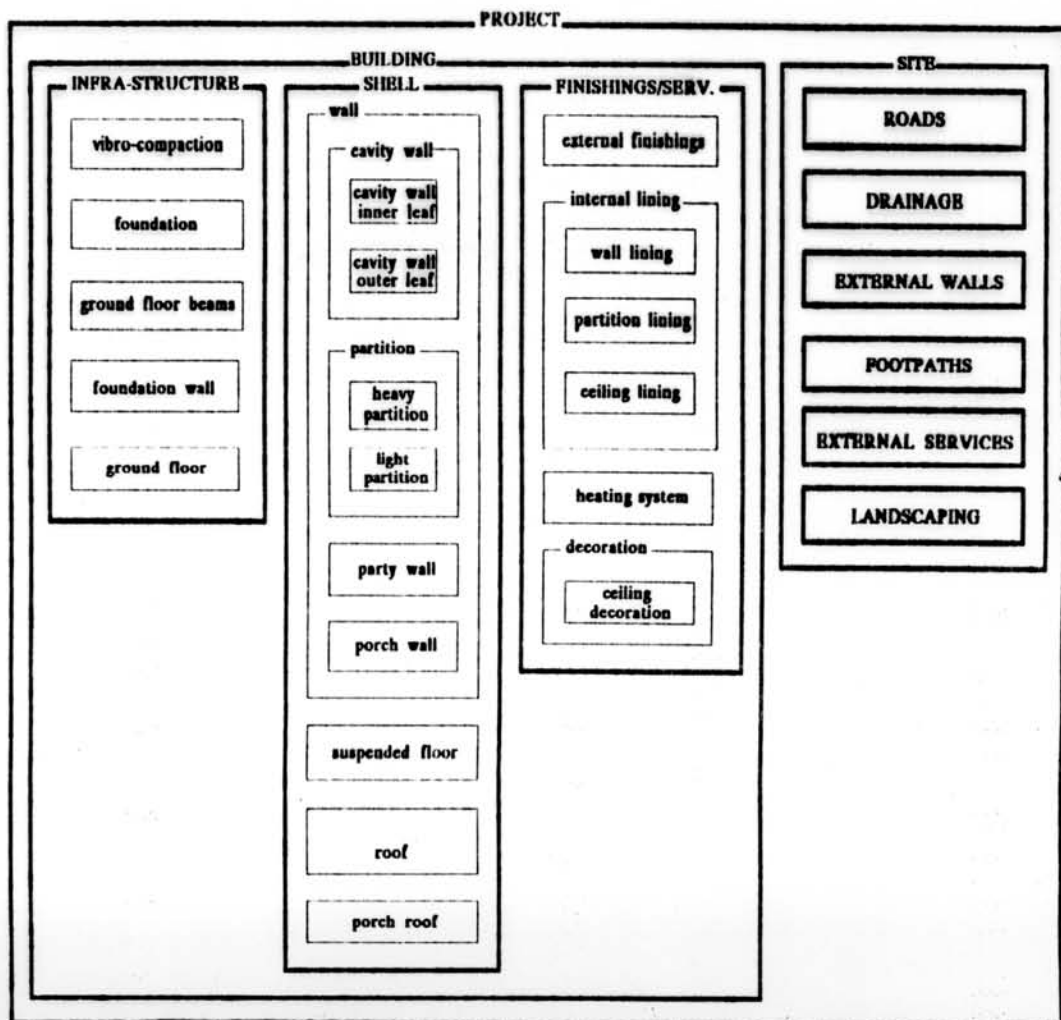


Figure 6.2: Hierarchy of main construction elements

Most construction elements were also involved in another type of hierarchical tree in which the objects were related to each other by a "kind of" type of relationship. Figure 6.3, for instance, presents the trees which contain all the possible alternatives considered for each of the elements from the infra-structure.

The variables employed in the geometric description of the building and the site were also organized in hierarchical trees, by employing three different types of links. Firstly, some of the variables that expressed volumes or areas were linked to the variables that expressed the elemental dimensions, such as width, length, and thickness. Figure 6.4, for instance, presents all the elemental dimensions related to the variable "road excavation volume". In the second type of link, the geometric variables were also related to the more aggregated variables: for example, all the variables related to concrete volume were linked to a global variable named total concrete volume, as shown in Figure 6.5. The third kind of link concerned with the geometrical variables connected them to the construction element that each one of them was related to, as presented in both Figures 6.4 and 6.5.

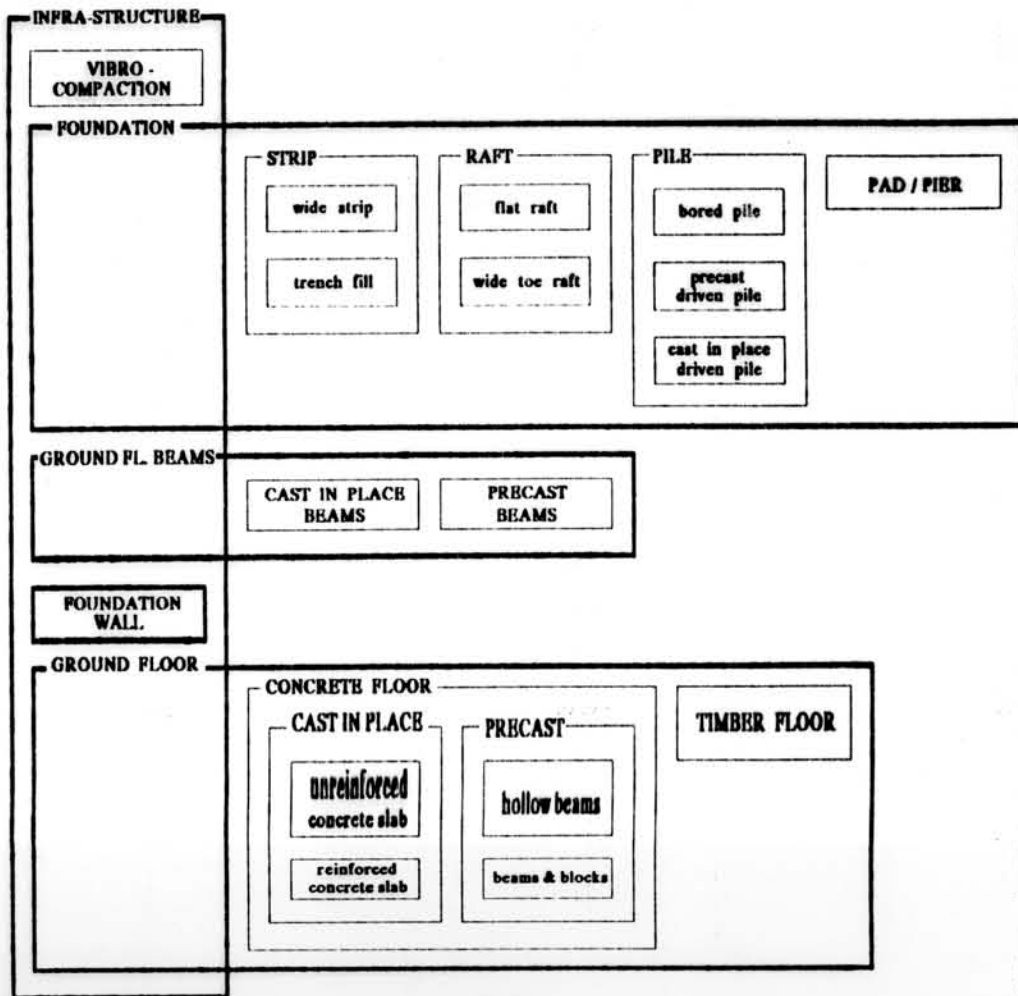


Figure 6.3: Hierarchy of alternative infra-structure elements

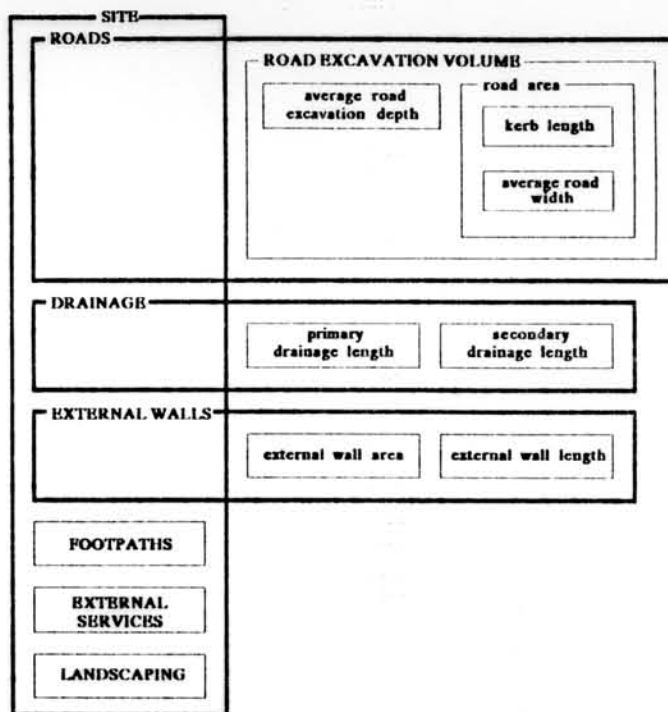


Figure 6.4: Hierarchy of site elements geometric variables

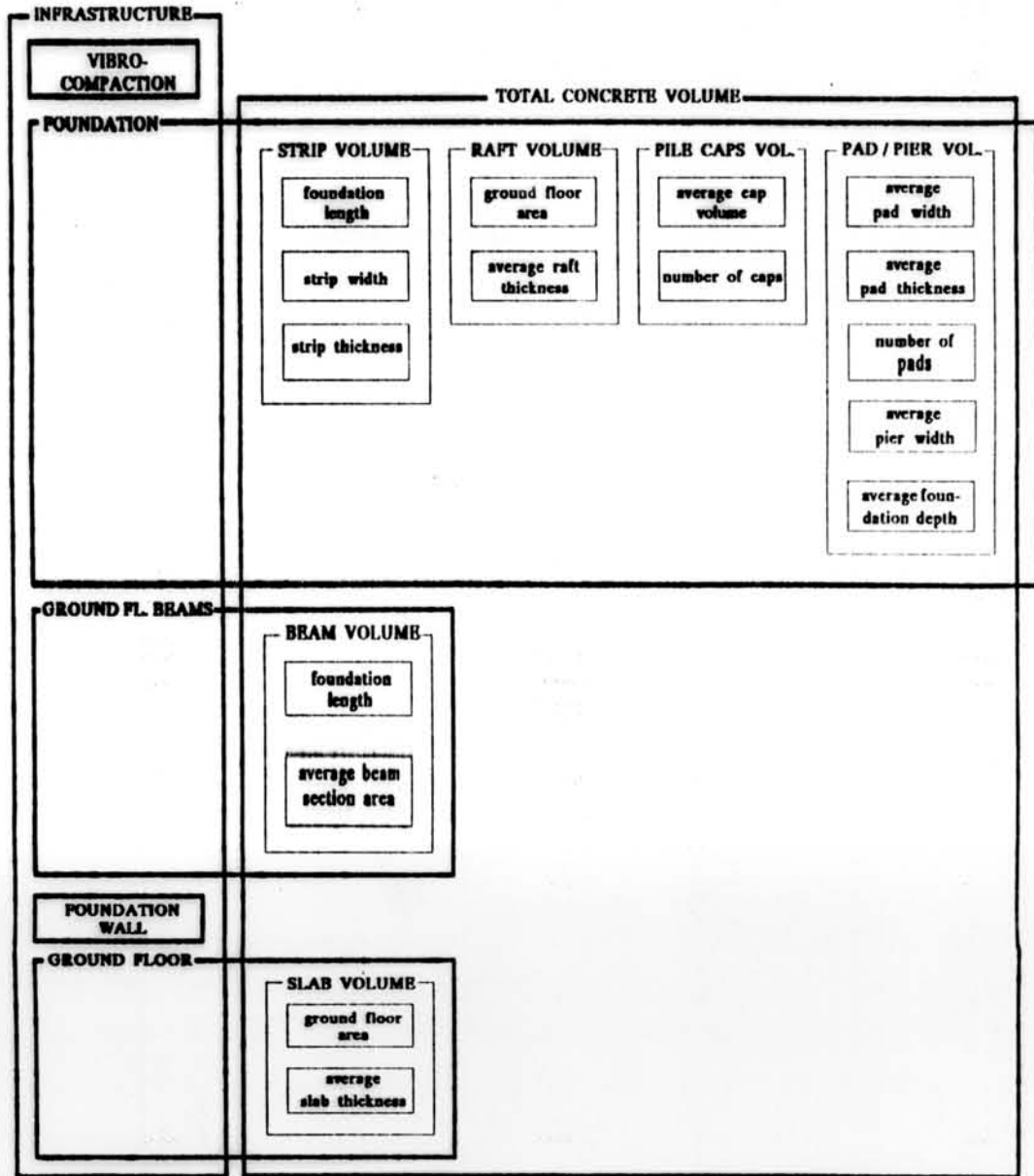


Figure 6.5: Hierarchy of concrete geometric variables

In order to limit the number of geometric variables included in the project description, most of the geometric variables were expressed in terms of its approximate or average value. The dimensions of houses, for example, were expressed by axis to axis distances, without considering the thickness of each wall, while most foundation elemental dimensions were expressed by average values, e.g. "average foundation depth", "average pile depth", etc..

Besides variables related to construction elements and their dimensions, the experts also include in the job representation some variables concerned with other aspects of house building projects, as follows:

(i) Contractual conditions: date in which the construction stage is due to start, maximum duration of the construction stage, required strategy for delivering the houses, etc.;

(ii) Availability of a number of potentially critical resources;
and

(iii) General description of the site: type of urban area in which the site is located, average slope, initial site preparation needed, etc.

6.3.2 Default data

In order to make the system able to cope with missing information, the experts were asked to provide some default data for most of the variables involved in the description of the job. The experts did not find much difficulty in providing default data, because they are used to generating such information while performing the planning task manually.

The experts were able to provide a straight forward fixed default value for several of the variables involved in the model. They all agreed that certain geometric dimensions, and material specifications can be considered as standard in traditional house building projects. For instance, when the value of the floor-ceiling height is not available, they all assume that it is 2400 mm.

On the other hand, there are a number of geometric variables which do not have such straight forward default values, because they tend to vary considerably. These variables usually have their values derived from other variables, using either one of the following procedures:

(i) Some variables that express areas or volumes can be calculated from the default values of elemental dimensions, which the experts are able to establish more easily. For example, when the experts need to provide a default value for the total concrete volume of strip foundations, they can calculate it from the default values of the average width, average depth, and length of strip dimensions; or

(ii) The geometric values which cannot be calculated from elemental dimensions are roughly estimated from a correlated variable. For instance, if the kerb length is not known, some experts estimate its value based on the number of houses available, and the average width of each piece of land.

The most complex set of default data required for the model was the dimensions of the houses. The experts sometimes have to generate

construction plans without having the architectural drawings of each house type. In such cases, the only kind of information available about the design consists of a general description of each unit, expressed in terms of number of floors, type of house (detached, semi-detached, or terraced), number of bedrooms, number of people, etc.

Such default data was organized by creating a database of building stereotype descriptions. The design types included in this database were chosen from a wide range of design types available, which were provided by the experts, or obtained from a number of studies concerned with the design of low rise house building projects in the UK (National Building Agency, 1969; Leopold & Bishop, 1983b).

The procedure adopted for selecting the house stereotypes consisted of defining several categories of houses, expressed by the shape of the house, number of floors, number of bedrooms, number of people, and frontage type (wide, medium, or narrow). The house type that had the gross floor area nearest to the average among those in each group was chosen as the representative. The database of building stereotypes is presented in Appendix 1.

6.4 Establishing the sequence of construction

6.4.1 Dividing the job into work places

Low rise house building projects are naturally divided into a number of discrete work places, such as individual houses, or blocks of houses. The way a project is sectioned into work places in a construction plan depends on the personal preference of the expert, on the amount of data available, and on the particular trades that are considered.

Sometimes the planner does not have enough information for establishing the sequence of work places, or it is the practice in his/her company to leave this decision for the site management. In such cases, the most adequate way of sectioning a project is to consider each individual house as a work place, so that the construction plan can be expressed in terms of generic houses.

If the planner wants to specify the sequence of work at a very detailed level, more than one type of sectioning may be used simultaneously in the same project. The main reason for this is the fact that the work of some trades can be naturally sectioned in terms

of individual houses, while the work of other trades can only be segmented using blocks of houses as units. The trades involved in finishing activities, such as plasterers, decorators, glaziers, etc. usually belong to the first group: the work in each house often is independent from the work in the rest. On the other hand, trades involved in activities such as brickwork, and roof tiling usually see their work as divided in house blocks, since there is continuity of work along houses from the same block.

Some construction planners also divide house building projects into larger sections, named pools of work, each one containing a number of blocks. This is usually made in order to organize the way the houses will be tackled by the gangs on site, and subsequently handed over to the client. Each pool of work corresponds to a group of blocks that will be tackled simultaneously by a number of gangs. This practice is consistent with the description of the construction process presented in Chapter 4, which contradicts the assumption that repetitive house building projects are carried out in a sequential and orderly way.

The number of houses in each pool of work depends on the extent to which the contractor wants to spread out the work on site. It may also be affected by the way the client requires the houses to be handed over: blocks of houses may have to be delivered one by one, in groups, or all at the end. In the first two cases, the contractor is encouraged to finish each block, or group of blocks, as early as possible, rather than spreading the work on a large number of work places. The size of each pool of work among the contractors involved in this study ranged from 5 to 18 houses.

The following guidelines were used by the experts for dividing the job into pools of work:

(i) It is preferable to join in the same section blocks of houses that are relatively near to each other, and not separated by any natural division, such as roads, deep drains, or service mains. This facilitates the movement of gangs, and the transportation of materials within each section.

(ii) In most house building projects there is a variety of house types, and blocks in which the houses are arranged. Also, houses in the same site may require different types of foundations, or have distinct specifications of components. The houses included in the same

pool should be as similar as possible, in order to limit the number of different trades involved, as well as to create conditions for the learning effect to occur.

6.4.2 Sequence of work places

In general, the sequence of work places is left to the contractor's choice. Very rarely, the client requires the houses to be delivered according to a pre-established order. Only one exception was reported by the experts involved in this research. It occurred in a particular site, where there was a number of occupied buildings to be demolished, and the work carried out by the contractor had to follow the order in which such buildings were to be vacated.

In the absence of a pre-established sequence, the main factors considered by the experts for establishing the sequence of work are the following:

(i) Access of houses by road: contractors usually prefer to start the job by houses that already have road access, or by the ones for which the necessary access can be quickly constructed, so that they can start to build houses earlier.

(ii) Avoiding excessive movement: an excessive movement of gangs and equipment around the site obviously should be avoided. Therefore, sequential work places should be located as near as possible to each other.

(iii) Position of the compound: the compound should be put in a position where there is an easy road access throughout the whole project. The section of the site where the compound is located should preferably be one of the last ones to be concluded, so that the traffic concerned with the movement of the operatives, and the transportation of materials does not have to cross sections where the work has already been concluded.

(iv) Housing estates in the neighbourhood: in areas where vandalism is very likely, the newly completed houses can be used, after being delivered, as a barrier between the construction site and other housing estates in the neighbourhood. It means that the project should start by those work places that are adjacent to existing housing estates.

(v) Requirements of individual gangs: if a plan is generated up to the level of individual gangs, it may be necessary to define a sequence of work places, based on the requirements of individual gangs. Such requirements can include the maximization of the learning effect, and fair distribution of work among several gangs.

None of the experts use any kind of objective criteria for comparing the effect of alternative sequences of work in the cost and duration of the project. They usually make their decisions based on subjective considerations, and the relative importance given to each of those factors mentioned above often varies from one expert to another.

The deep knowledge that is used by the experts for making such decisions was not investigated in this study, because of the limited role of the application in this particular sub-task. For the reasons presented in Section 5.4.2, the system will provide only some general guidelines on how to perform this task, as well as a facility for inputting the chosen sequence.

6.5 Dividing the work into activities

6.5.1 General approach

The study of this sub-task was divided into two main stages. The first stage consisted of creating a library of construction activities that could be used by the system. The second one involved the elicitation of the knowledge that the experts would use for selecting the activities necessary to carry out a particular project, from the library of activities created.

The development of a library of activities within the system seemed to be an important step towards improving the consistency and completeness of construction plans. Providing such a facility for the work of a construction planner may encourage him/her to use the same work breakdown criteria in several different projects, as well as may act as a check-list during the planning task, so that none of the activities necessary for carrying out the job is forgotten.

The elicitation of knowledge related to this sub-task initially focused on the identification of a coherent set of general criteria for breaking down the job into activities. This strategy was adopted

because there was a need for a common basis which could be used for amalgamating knowledge elicited from different experts. There were several differences between the level of detail of work breakdown employed by the experts involved, and it would be very difficult to reach an agreement among them about the most convenient way of dividing the job into activities, without investigating the deep knowledge behind their choice.

Breaking down all the work into activities as detailed as the level of work package was considered to be unsuitable for this particular application. Such a measure would lead to an excessive number of activities, probably several hundred of them, which is much larger than the number that the experts are used to deal with in the task of planning at a tactical level. They usually divide the work into higher level activities, most of them aggregating a number of work packages. This approach inherently assumes some kind of interference between the work of gangs involved in different activities.

The most detailed plans amongst the historical cases available were the ones produced by Contractors A, B, and D, in which the number of activities ranged from 50 to 70. The level of detail found in those plans was used as a basis for creating the library of activities, since the aim was to design a system capable of producing a set of outputs similar to the plans manually generated by the experts.

6.5.2 Work breakdown criteria

The establishment of the set of criteria for activity breakdown was mainly based on the functions that construction plans are expected to perform in project management, already described in Section 2.3.2. On the whole, five main criteria were identified:

(i) **Single trade:** each activity must include work of a single trade, and each trade must be represented by at least one separate activity. This measure makes construction plans more efficient and complete tools for guiding execution and co-ordinating the work of interacting gangs. In the historical cases, most activities defined by the experts followed a very clear operational concept, consisting of the work carried out by a single trade at a specific work place. Generally, there were only a few activities which involved the work of more than one trade. These were defined by design elements, and had to be further broken down.

(ii) Starting and finishing activities: it is usual practice among construction planners to employ two standard activities for pointing out the beginning and the conclusion of the construction stage. Each one of them usually contains a large number of small tasks. Although they may include the work of more than one trade, the experts find it convenient not to split them up because they vary considerably. They are the only exceptions to the single trade criteria. This criterion was also identified by the research of Gray & Little (1985b).

(iii) Work performed by key trades: the role of key trades in construction have already been discussed in Section 4.3. The project management tends to impose a tighter control over such trades than over less critical trades. For that reason, the work carried out by trades considered to be of key importance must be broken down to a finer level of detail than the work performed by non key trades. In some companies, there is also less need for detailing the work of non key trades because they are sub-contracted.

The most detailed activities found in the construction plans available were the ones related to the construction of foundations, brick walls, and plastering. For instance, the construction of brick walls was usually divided into several bricklaying lifts, in order to consider the interruptions caused by other trades. On the other hand, those plans also contained several activities that aggregated several tasks, and had a relatively high work content. That was the case of activities related to site preparation, landscaping, and the finishings of houses.

(iv) Important events: a number of important events on site must be pointed out in the plan in order to make explicit important project targets, as well as to facilitate the control of the project at a strategic level. This can be done by including a number of very detailed activities related to such events, each one defining a milestone in the project, such as conclusion of foundations, house closure, end of wet trades, and house handover.

(v) Familiarity to the experts: as discussed in Section 5.4.7, the names used for defining activities must be as familiar as possible to experts in construction planning. For instance, all experts agree in dividing the work of a number of trades into first fix, and second fix, each one of them grouping a large number of different tasks. Some

of these widely accepted criteria for grouping tasks have been originated on the way bills of quantities are usually broken down (Gray & Little, 1985b).

Based on the five criteria above, a library of approximately 130 activities was created. Appendix 2 presents a complete list of all activities contained in the library, grouped according to the stage of work which they belong to. Obviously this library of activities does not cover all possible types of house building projects, but is able to handle a relatively wide range of situations, which the experts involved in this study have been through.

6.5.3 Selection of activities

The strategy followed by the experts for selecting activities from the library available consisted of organizing the activities into groups and associating each group to a segment of the project. Such segments corresponded to sub-divisions of the stages of work, and a number of alternative groups of activities can be found for most of these sub-stages.

The selection of a group of activities for each sub-stage is made by the expert according to the value of some variables from the job description. Once the activities were conveniently organized into groups, it was relatively straight forward to extract from the experts the rules that they use for such selection.

Table 6.1 presents the main factors that affect the choice of activities for each sub-stage. No factor is mentioned for a number of sub-stages in this table because only one option exists. This is the case of the first and the last sub-stages, which contain respectively the starting and the finishing activity, and of the sub-stages named "house closure" and "first fix". Although there may exist a wide variation in the construction tasks involved in work content of these sub-stages, their activity content remains constant, due to the level of generality in which the activities are defined. For instance, the sub-stage "first fix" always consists of the following activities: "joinery 1st fix", "plumbing 1st fix", "heating 1st fix", and "electricity 1st fix". Each one of them is made up of several smaller construction tasks, which may vary considerably from project to project.

STAGE	SUB-STAGE	FACTOR
Site preparation	Set up site Demolitions Ground preparation Deep foundations Road construction	None Site conditions Site conditions, external work required Foundation type Roads required
Infra-structure	Shallow foundations Ground floor	Foundation type Ground floor type
Shell/roofing	Shell Roof House closure	Number of floors, suspended floor type Roof type None
First fix/plaster	First fix Plaster	None Specification of wall lining,
Second fix/finals	Second fix Finals	Porch type Specification of finishings
Landscaping	Landscaping External walls/garages Service mains Clear away	External work required Garages and external walls required Existence of service mains None

Table 6.1: Main factors that affect the selection of activities

The first and the last stages of work contain sub-stages that have their activities chosen according to the current conditions of the site, such as the availability of road access, and the existence of service mains, as well as to the external work that is required (e.g. landscaping, road construction, footpaths, etc.). On the other hand, the activity content of the sub-stages concerned with the construction of houses is mostly affected by the geometric shape of the buildings, and by the specification of components.

Each group of activities in reality corresponds to an ordered list of activities, which roughly reflects the sequence of tasks in which the job will be carried out on site. Consequently, the organization of activities into groups had to be performed simultaneously to the elicitation of knowledge related to the establishment of dependencies between those activities. The precise definition of activity precedences will be discussed later in this chapter.

6.6 Establishing the pace of work

6.6.1 Types of activities

The method employed by the experts for establishing the pace of work varies according to the type of activity. Two main categories of activities were initially identified in this study: bar-chart, and repetitive. Each one of them was further divided into two sub-categories, named continuous and stretched.

Repetitive activities are those that have to be repeatedly performed, once for each house or block of houses. They were usually represented in the plans from the historical cases by the number of houses completed in each particular week, as shown in Section 5.4.5.

Bar-chart activities are those which cannot usually be directly related to the construction of houses, such as, for example, the activities related to site preparation, road construction, and service mains. They were given this name because the experts usually represent them as a bar-chart in the construction plans.

The concepts of continuous activity and stretched activity were introduced in order to differentiate between the activities performed by gangs that stay continuously on the site, and those which are carried out by gangs that come and leave the site several times during the project. Therefore, the term continuous activity in this context

does not mean that this type of activity is necessarily performed with no interruptions.

The gangs involved in stretched activities are usually subcontracted, and tend to start their work only when a clear run of work is available. Such activities normally have a duration much shorter than the period available for their execution.

6.6.2 General approach

The rate in which each repetitive activity is carried out, expressed in terms of houses per week, varies along the job. It usually starts at a low value, grows to a peak that is kept for a while, and then goes down in the last few units. This pattern is fairly compatible with the traditional view that resources in construction are consumed according to a "S" curve, which has been discussed in Section 4.2.6.

If the construction plans from the historical cases were represented by a line of balance, they would look like the example presented in Figure 6.6, rather than the typical line of balance shapes found in some text books, such as the one shown in Figure 6.7.

The experts usually adopt the same profile of building rates for all the repetitive activities, either continuous or stretched, from the same stage of work. Obviously, the profiles of stretched activities in practice can be expected to be less smooth than the ones from continuous activities.

Differences in the rate profile usually occur at the level of stages of work. In general, the earlier the stage, the higher is the peak rate employed, such as in the example shown in Figure 6.6. This strategy leads to a gradual increase in the float between stages of work, as the gangs move from one house to another.

Three different rate profiles for the activities related to the construction of houses are usually established by the experts. The first one is for the foundation stage, the second for the shell/roofing stage, and the third for all finishing activities, which includes both the first fix/plaster and second fix/finals stages.

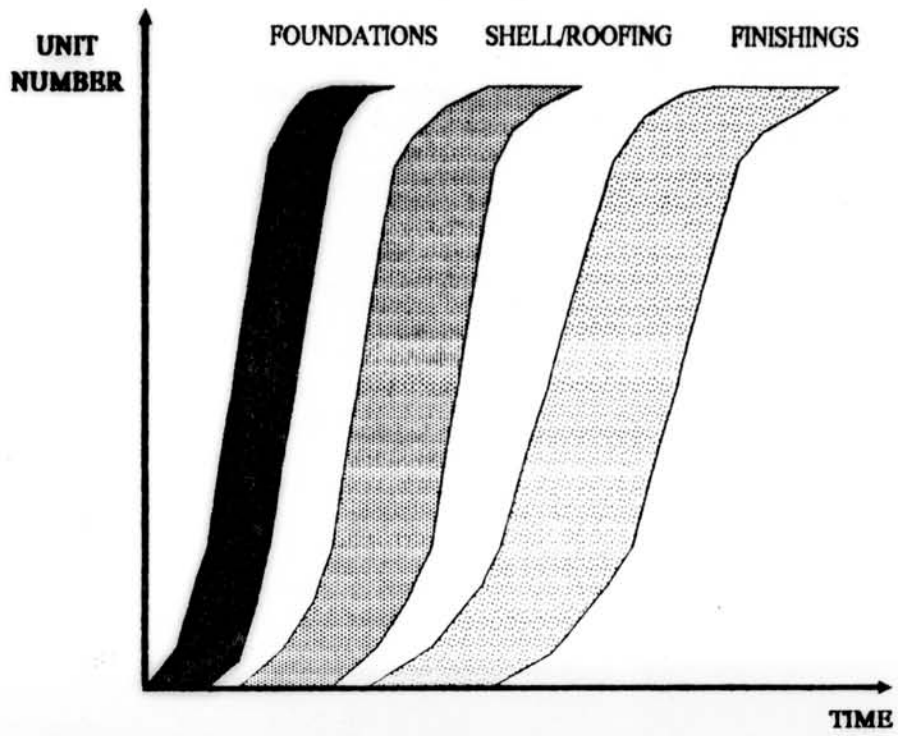


Figure 6.6: Line of balance typically found in the historical cases

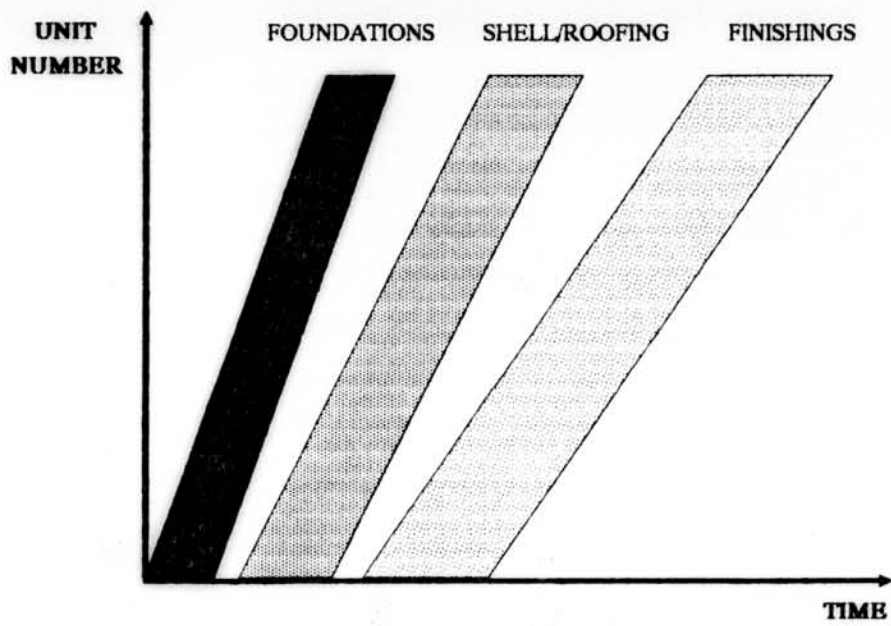


Figure 6.7: Line of balance shape usually found in text books

The experts initially produce a peak building rate for each one of the rate profiles, according to what they assume to be their natural rhythm. This decision is based on the availability of the leading resources, or on the rate of deployment that is considered to be the most economic one. In other words, the peak rate of each profile is initially calculated according to the rate of progress chosen for the activities that involve leading resources, and all the other activities in the same stage are supposed to follow the same pace of work.

The final decision about those three building rates is made jointly, since the experts find convenient to keep certain ratios between them. Once the peak rates have been finally chosen, the experts are able to draw the rate profiles, based on "S" curves that are considered typical in their companies.

Several distinct criteria are used for establishing the pace of work for the activities from the site preparation and landscape stages. Some have their durations individually estimated in the traditional way, by calculating the quantities of work needed and choosing a convenient intensity of deployment of resources. Others have their pace related to the rate in which some of the activities concerned with the construction of houses are carried out.

In the following sections, each of the steps taken by the experts for establishing the pace of work is discussed in more detail. Section 6.6.3 to 6.6.6 describe the way in which the experts establish the peak rates for the stages concerned with the construction of the houses. Section 6.6.7 discusses how the rate profiles are drawn. Finally, Section 6.6.8 examines the strategy employed by the experts for establishing the pace of work for the site preparation and landscape activities.

6.6.3 Shell peak rate

6.6.3.1 The experts' approach

The key role played by the work of bricklayers in low rise traditional house building projects has already been discussed in Section 4.3. Bricklayers are the leading resource in the shell/roofing stage, and are often the leading resource for the whole project. In fact, the availability of bricklayers can effectively impose a limit

to the pace of work: the experts reported several projects in which the whole job had to be slowed down because of the shortage of bricklayers in the region.

The fact that bricklayers are in general the leading resource in traditional house building implies that the experts tend to examine the pace of work of the activities carried out by this trade in much more detail than for any other kind of speciality.

The main factors that the experts consider for establishing the peak shell rate are: the number of bricklayers that are likely to be available for a particular project, the estimated productivity of bricklayers, and the quantities of work that have to be carried out by this trade.

The number of bricklayers available is predicted by the experts according to knowledge they have about the supply of labour in the construction industry, or by consulting somebody from the company that has this kind of information.

Getting the quantities of brickwork and blockwork that have to be built is a relatively straight forward task. They can be obtained from the bill of quantities, when there is one available, or by directly measuring architectural plans.

On the other hand, estimating the productivity of building operatives is a very complex task that demands a considerable amount of expertise. In fact, there is a number of fairly complex knowledge engineering applications that have been devised with the specific objective of modelling the expertise related to estimating the productivity of a single building trade, and the duration of a few construction activities. Two of them, Mason and Ratu-aj, have been described in Chapter 3.

The knowledge elicitation process indicated that the experts used a relatively unstructured approach for estimating the productivity of bricklayers. The only kind of productivity data that was systematically collected in their companies consisted of a list of average output rates related to a variety of bricklayers' tasks. The experts usually estimated the output of bricklayers for a particular task by adding or deducting a heuristic allowance, expressed in percentage terms, from each average figure, according to the general

impression that they had about the job.

Although it is widely recognized that there is a very large number of factors that affect the productivity of building trades, the experts involved in this study considered only a few of them for estimating the bricklayers' output rates for a particular job. There are two main reasons for this simplification.

Firstly, the experts assume that some of those factors are relatively stable within a given context, and that their effect is already incorporated in the productivity data available. This is the case, for instance, of the quality of site management in the company, and the quality of the workmanship available. Secondly, there are several factors that normally are not under the control of the company's management, and the experts find it very difficult to predict their effect in the productivity of a specific gang early in the project, such as when tactical plans have to be generated. The effect of strikes, shortage of materials, and inclement weather are among these factors.

On the whole, there are five project characteristics that the experts normally take into account for estimating the bricklayers' output rates. They can be described as follows:

(i) Design simplicity: the simpler is the geometric shape of the houses and the layout of the site the shorter is the time needed to complete the work, for the same number of operatives;

(ii) Number of repetitive units: the larger is the number of work places in which different gangs have to carry out similar work the greater is the improvement in the productivity by the learning effect;

(iii) Design repetitiveness: the more repetitive is the design of houses the greater is the possibility of increasing labour productivity by the learning effect;

(iv) Work concentration: the larger is the amount of work in each work location the shorter is the time that the operatives have to spend in non-productive tasks, such as moving, carrying materials and tools and preparing the work place; and

(v) Geographical continuity: if the project is spread in more than one site, the productivity of operatives is likely to be reduced, for two main reasons. Firstly, the interruption in the work sequence that

happens when a gang finishes the work in one site and starts in another tends to increase the non-productive time. Secondly, the larger the number of sites the more difficult the site management tends to be.

From the five productivity factors listed above, only design repetitiveness and the number of repetitive units, both related to the learning effect, have had their influence in the productivity of building trades investigated for a wide range of situations. The effect of such factors have been isolated in several research studies, such as United Nations (1965), Gates & Scarpa (1972), Piggot (1972), Verschuren (1984), Thomas et al. (1986), and Duff et al. (1987), by introducing the concept of learning curves. The incorporation of a learning curve in the model was considered to be an attractive idea, since this concept was well accepted by the experts, and such a measure would allow some of the results obtained in research studies on the field of labour productivity to be used in the model.

In the following section, a very brief literature review on the learning effect is presented, in which a learning curve suitable for the model is chosen.

6.6.3.2 Choice of a learning curve

The learning effect in repetitive operations is the combined effect of several factors, such as increased work familiarization, improved equipment and gang co-ordination, improved job organization, better engineering support, better day-to-day management and supervision, development of more efficient techniques and methods, development of more efficient material supply systems, and stabilized design leading to fewer modifications (Thomas et al., 1986). As not all these factors are directly related to the content of the operation, the learning effect can occur even when the units are not completely repetitive (Piggot, 1972; Verschuren, 1984).

The learning effect is usually expressed by a learning rate, which expresses the percentage of increase in the productivity of a gang that occurs when the number of units carried out is doubled. In general, the learning rate varies according to the nature of the operation: operations that involve reading drawings, making adjustments and dimensional setting out, or verification tend to have

a learning curve higher than operations in which these procedures are virtually absent (Verschuren, 1984).

The learning rate can also vary within a single operation. Indeed, the learning effect can be divided in four main phases:

(i) Operation learning phase: the learning rate is usually very high in the first few units, as the operatives acquire sufficient knowledge on the task to be performed;

(ii) Routine-acquiring phase: after the operation learning phase, the learning rate tends to decrease, as a more gradual improvement is achieved through a growing familiarity with the job and through refinements in organization (Thomas et al., 1986);

(iii) Stable productivity phase: a stable operational time is eventually attained if the number of repetitive units is very large (Thomas et al., 1986); and

(iv) End-effect phase: this is normally a very short period in which the productivity is decreased due to relaxation of supervision and disorganization of the site, as well as the fear among the workers that they may be unable to obtain a new job when the present one is finished (United Nations, 1965).

Several mathematical models for the learning curve have been suggested in the literature. The most widely used one is the straight-line model, in which the learning rate is assumed to be constant throughout the execution of the operation. Thomas et al. (1986) recommended the use of non-linear models which are able to consider variations in the learning rate. Duff et al. (1987), on the other hand, pointed out for the fact that the non-linear models need parameters which are very difficult to estimate in practice, and that the precision achieved by a constant rate model in its cumulative version is fairly acceptable for the construction industry. Studies in Sweden and Finland (United Nations, 1965) and in Holland (Verschuren, 1984) have also confirmed the reasonable accuracy of the straight-line model for a number of cases.

The cumulative constant rate model was the learning curve adopted in this study. The main advantage of this curve is its simplicity: it is easy to use, and its parameters can be easily monitored in practice. Moreover, the assumption of a constant learning rate does

not seem to be very inaccurate for the specific case of bricklaying. As the work pace of bricklaying is established by skilled operatives, the learning rate in the operation-learning phase does not tend to be much higher than in the routine-acquiring phase. Also, the stable productivity phase may not be reached in projects as small as those studied in this research project.

Some of the research studies developed so far have indicated that bricklaying is among those operations that normally have a low learning rate. In well organized sites, the non cumulative learning rate of building trades usually ranges from 2 to 20%, while in the specific case of bricklayers this rate has been reported to vary between 6.5 and 10% (United Nations, 1965; Verschuren, 1984; Thomas et al., 1986; Duff et al., 1987).

6.6.3.3 A model for estimating the productivity of bricklayers

The model for estimating the productivity of bricklayers that was developed in this study is restricted to the task of predicting the output rates of bricklayers in a particular operation, named "building half brick wall". This is one of the most frequent operation performed by bricklayers, being present in virtually all traditional house building projects. All the experts had much experience on this operation, and they found it easier to estimate the man-hour requirements of a project in terms of an equivalent amount of half brick wall, instead of estimating the output rates related to each operation individually.

Once the productivity of bricklayers is estimated for that particular operation, the output rates for all other operations can be calculated by using coefficients of conversion. This approach is supported by the study of Clapp (1978), in which a significant correlation was found between the output rates achieved by bricklayers in several different operations.

A diagrammatic representation of the model is presented in Figure 6.8. The starting point of the process is a range of output rates, provided by the experts, which express the usual range of bonus scheme targets set for the work of bricklayers. Such range is used for estimating the initial output of bricklayers, i.e. the rate achieved in the first few units, before the learning effect starts to occur. This output rate is calculated as follows:

$$\begin{aligned} \text{initial_output} &= \text{min_output} + (\text{max_output} - \text{min_output}) && (6.1) \\ & * ((\text{DS_weight} * \text{DS_index}) + (\text{WC_weight} * \text{WC_index}) \\ & + (\text{GC_weight} * \text{GC_index})) \end{aligned}$$

In the above formula, min_output and max_output are the extreme values of the range of output rates; DS_index, WC_index, and GC_index are productivity indices related to design simplicity, work concentration, and geographical continuity, respectively, for a particular job; and DS_weight, WC_weight, and GC_weight are the weights related to each of these factors.

The indices are objective measures of each of the productivity factors, obtained from a number of characteristics of the job. Their values range from 0 to 1, and their methods of calculation are summarized below:

(i) Design simplicity index: it is the average of the design simplicity indices of individual houses. The index of each house depends on its shape. The simplest possible house is a rectangular detached house, while the most complex one is an irregular terraced house, in a block with steps and staggers;

(ii) Work concentration index: this index is calculated by comparing the average man-hour content of bricklayers per house with the man-hour content of this trade in two arbitrarily chosen blocks of houses, one very small and the other very large; and

(iii) Geographical continuity index: the lower extreme corresponds to the situation where there are as many plots as blocks of houses, and the upper extreme to the situation in which there is only one plot.

The weights related to each productivity factor were provided by the experts, and they reflect the relative importance of each factor in the initial output rates achieved by bricklayers. The experts were asked to provide the percentage of variation that they expected to happen in the output rates when each of the productivity indices varied from its minimum to its maximum value (i.e. from 0 to 1), while keeping the other factors unchanged. Based on such percentages, it was possible to calculate the relative weight of each factor.

The average output rate for the whole job is obtained by entering in a learning curve the initial output of bricklayers, and the average number of repetitive units carried out by each gang. The learning rate used in this curve is calculated from a range of learning rates provided by the experts, using another productivity index, related to the repetitiveness of design. This index also ranges from 0 to 1, the higher extreme corresponding to the situation in which the houses have all the same design, and the lower extreme when each house has a unique design. The methods used for all four productivity indices are described in more detail in Appendix 3.

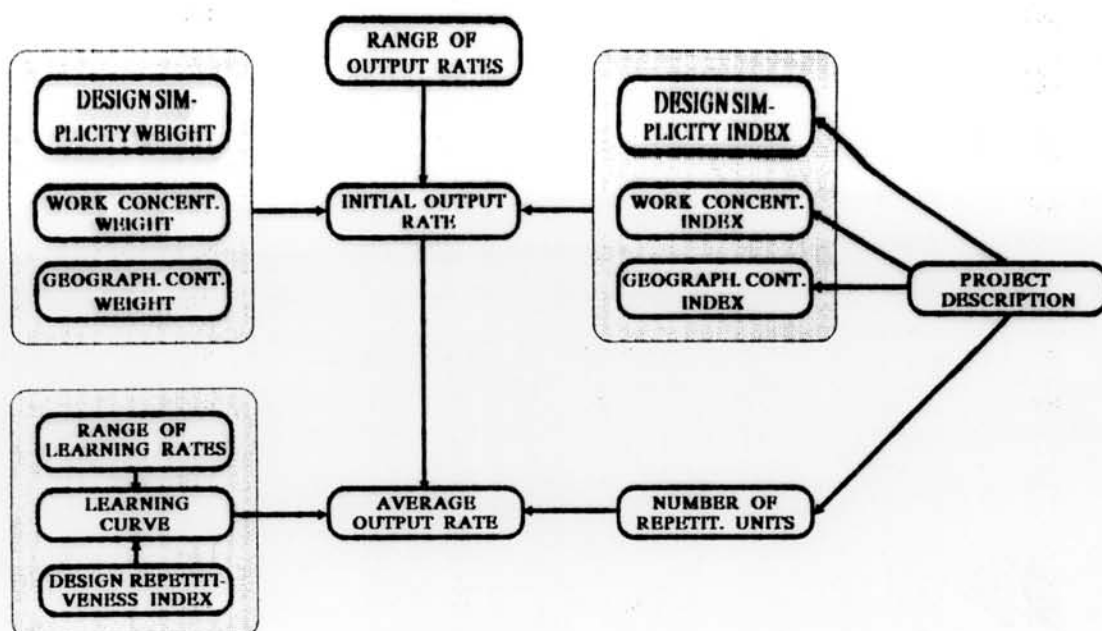


Figure 6.8: A model for estimating the productivity of bricklayers

It is evident that this predictive model is very much based on heuristic assumptions which have not been validated by any scientific study. However, the causal relationships that it encapsulates are consistent with the decision making process followed by the experts. Also, despite the uncertain accuracy of the model, the objective consideration of some productivity factors in the process of estimating output rates seems to represent an advance in comparison to models based on single average figures.

6.6.4 Finishing peak rate

As mentioned in Section 4.3, the finishing activities tend to have a much more chaotic pattern of work, if compared to the activities from the foundation and shell/roofing stages. During the finishing stages,

there is usually a number of activities carried out concurrently in each work place, and there is a high incidence of interference between the work of different gangs (Forbes & Stjernstedt, 1972). For this reason, the experts considered that the effectiveness of site management has a much more decisive influence in the pace of work of finishing activities than in any other stage of work.

The experts employed the concept of availability of management for referring to the effectiveness of site management, rather than expressing it as quality of management. Availability of management denotes the amount of attention that the managers of a company can allocate to a specific project, in relation to its average productive capacity. This concept assumes that everyone in the company is competent, given the necessary time to perform a task.

Based on the current availability of management, the experts are able to predict a maximum peak finishing rate, beyond which the site management is likely to have difficulties in co-ordinating the several gangs involved in the finishing stages. This rate is obviously affected by the complexity of the finishings and services specified: the more complex they are the lower the peak finishing rate that the site management is able to cope with.

Based on these two factors, a range of maximum peak finishing rates was elicited from the experts, in which all possible combinations of availability of management, and complexity of finishings and services were considered.

From the several gangs involved in finishing activities, the plasterers' were the only one systematically checked by the experts. As discussed in Section 4.3, the plastering activities usually assumes a key role in the progress of work of the finishing stages, because they hold up the work of several other trades.

Although the experts reported that very rarely a short supply of plasterers can impose limitations in the pace of work, they preferred to keep the number of plastering gangs below a certain limit. The main reason for this strategy is the fact that, unlike other trades such as joiners, the work performed by plasterers is concentrated in a short period of house construction, the end of the first fix/plaster stage. The experts fear that, in the case of unexpected delays in the preceding activities, it may be difficult to find alternative work

places for a large number of plastering gangs. The maximum limit considered by the experts involved in this research was around five to six gangs of two plasterers each.

The number of plasterers for a particular project is calculated from the amount of work that has to be carried out by this trade, as measured from the design. The output rates of plasterers are obtained in a much more expedited way than the bricklayers': the experts simply use average figures available in their companies, without adding or reducing any kind of allowance.

The decision making process performed by the experts for establishing the maximum finishing rate is summarized in Figure 6.9. The peak rate chosen is the least among the maximum rates established by the availability of management and the maximum number of plasterers.

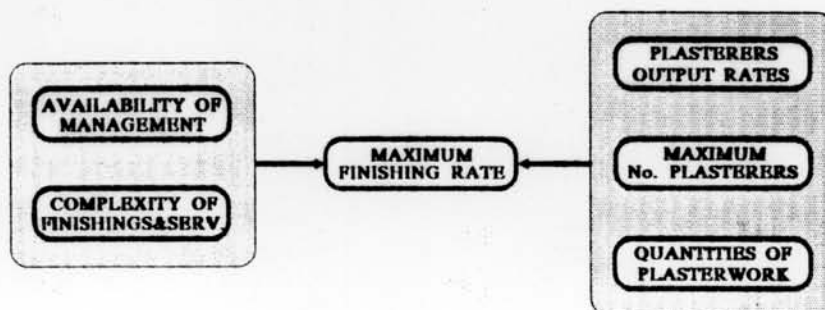


Figure 6.9: Strategy adopted for establishing maximum finishing rate

6.6.5 Foundation peak rate

As discussed in Section 4.3, the foundation stage can usually be carried out at a much faster pace than the following stages. However, the experts usually avoided employing a foundation rate much higher than the shell rate, in order to reduce the lock up of capital between these two stages. This strategy frequently results in a rate of deployment of resources much lower than the optimum. Indeed, the experts reported that the mechanical equipment used for excavating foundations and concrete pouring are often under-utilized in house building projects.

The only resource whose shortage might impose some limitation to the peak foundation rate is the bricklaying trade, in case there is

brickwork or blockwork to be built below the damp proof course (DPC) level. However, the availability of bricklayers is much less likely to restrict the pace of work in the foundation rate than in the shell/roofing stage, since the quantities of work in the former are usually much smaller than in the latter.

In the absence of a concrete limitation to the pace of work of the foundation stage, most experts establish the peak foundation rate according to what they consider to be the rate of deployment of resources that the site management and the work force involved in house building projects are used to. For instance, one of the experts mentioned that, although his company was used to carrying out building projects in which several hundred cubic meters of concrete were poured a week, he preferred to keep a limit of around 150 to 160 cubic meters a week in most low rise house building projects. Such pace of work can be interpreted as the natural rhythm for this activity in this particular type of project.

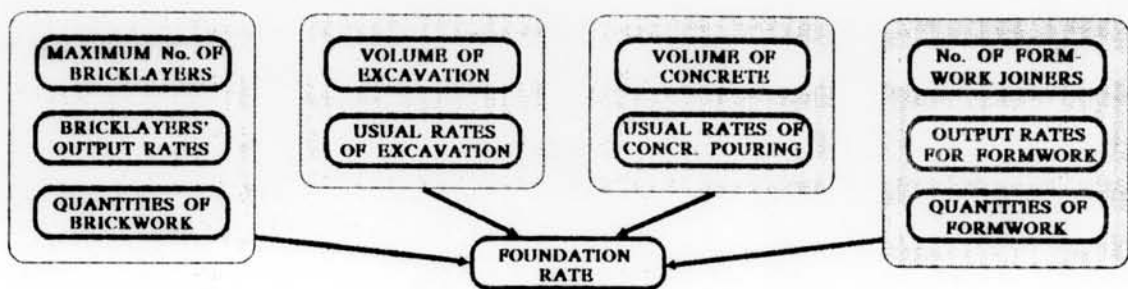


Figure 6.10: Resources considered for choosing the foundation rate

On the whole, four main resources have their rate of deployment checked by the experts. They are: bricklayers, concrete, mechanical excavation equipment, and formwork joiners. Figure 6.10 summarizes the strategy employed by the experts for establishing the peak foundation rate.

6.6.6 Relationships between peak rates

Although the leading resource defines the most convenient peak rate for each individual stage, the resulting combination of such rates may not be the most adequate for the project as a whole. The experts usually make some adjustments in the building rates in order to keep a

certain ratio between them.

From one side, either the client or the contractor wants to avoid an undesirable lock up of capital in the project, by keeping a small ratio between the building rates of consecutive stages. On the other hand, the contractor may find desirable to use a distinct pace of work for each stage, so as to create buffers between the conclusion of one stage, and the beginning of the following one.

The solution adopted is usually some kind of compromise between these two situations. The choice of the most adequate solution is affected by a number of factors, such as the contract conditions, contractor's aversion to risk, and site management's efficiency

The experts involved in this research were able to identify three main types of situations, which are diagrammatically presented in Figure 6.11.

In the majority of projects carried out in a contracting basis, the foundation rate is higher than the shell rate, and the shell rate is higher than the finishing rate, as shown in Figure 6.11a. This strategy allows the first few units to be delivered relatively early in the project, and, at the same time, creates an increasing float between the end of one stage and the beginning of the following one, along the subsequent units. In the experts' opinion, both the ratios between the foundation rate and the shell rate, and between the shell rate and the finishing rate should be around 1.2 in such cases.

There may be situations in which the contractor wants to avoid any lock up of capital, and prefers to employ very similar building rates in all stages, in spite of the risk of delays caused by interferences between the work of gangs from different stages. This strategy is shown in Figure 6.11b. It usually occurs when the contractor is not gradually paid by the work done on site, such as in speculative developments.

Another exception to the standard case occurs when the contractor performs the finishing activities at a higher rate than the activities from the shell/roofing stage, in order to minimize the costs of preventing vandalism (see Figure 6.11c). This situation usually happens when all houses are due to be handed over to the client at the end of the project, and the risk of vandalism in the area is very high.

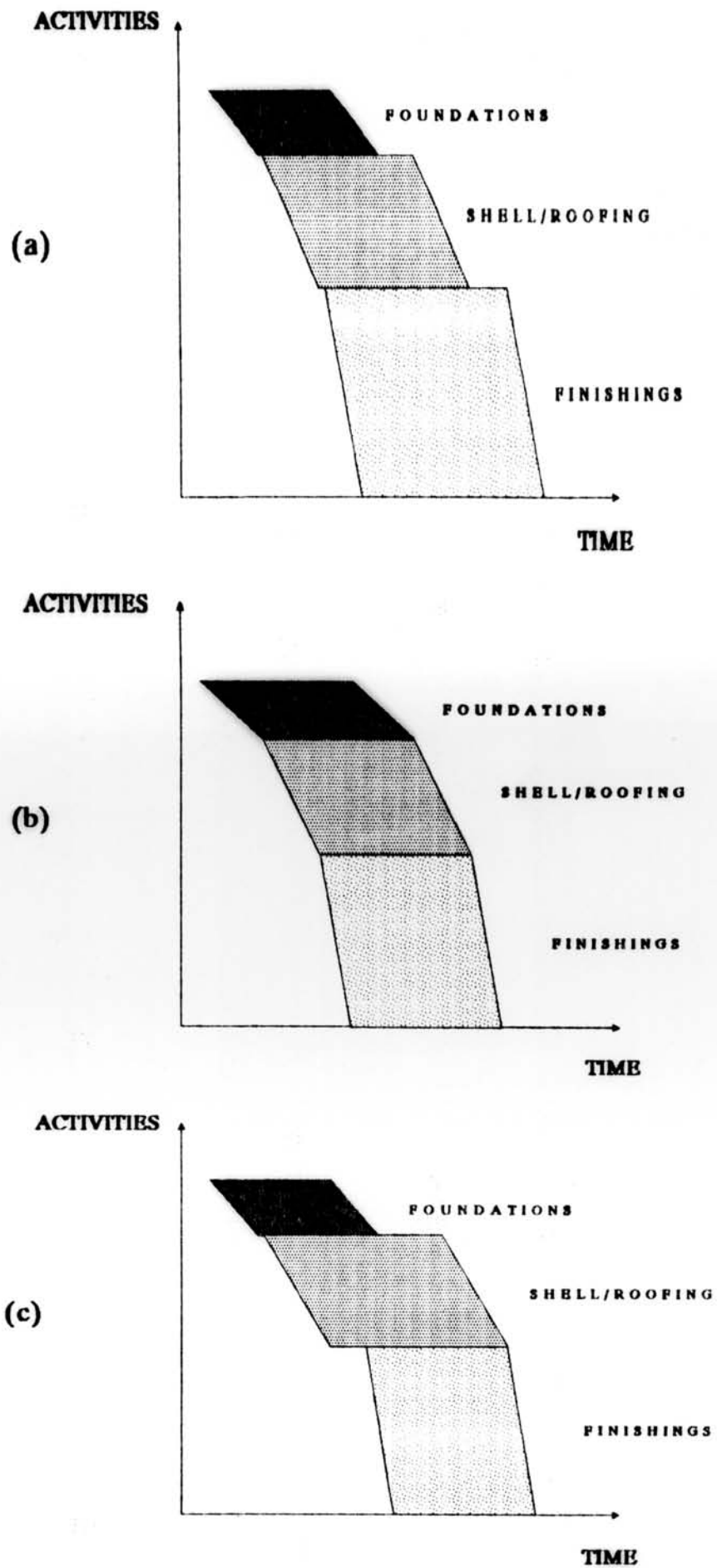


Figure 6.11: Typical shapes of construction programmes
 (a) Standard solution
 (b) Avoiding lock up of capital
 (c) Minimizing the costs of preventing vandalism

Unfortunately, it was not possible to elicit knowledge related to this aspect of the planning task to a deeper level for two main reasons. Firstly, none of the experts was experienced in a wider range of contract conditions, which could affect the ratio between peak rates to a greater extent. Secondly, deep reasoning about this aspect of the job would necessarily involve estimating construction costs, which is outside the scope of this research.

6.6.7 Rate profiles

After establishing the three main building rates for the stages related to the construction of houses, the experts have to define a strategy for accelerating and decelerating the pace of work, in each of these stages. This strategy can be usually represented by an "S" curve.

The "S" curve is a concept that has been intensively investigated by researchers in the field of construction management, mainly as a tool for financial control. A number of typical curves concerned with the value of the work done for a project as a whole have been produced in the literature, for several different types of construction projects (Stallworthy, 1979). However, very little has been published about usual "S" curves at the level of stages of work. Heineck (1983) and Christian & Kallouris (1990) pointed out for the necessity of studying further the shape of "S" curves related to individual activities in order to increase the applicability of such models to the task of construction planning.

On the other hand, the knowledge elicitation process indicated that the experts established the profiles of building rates in a pure ad hoc basis. No consistency was found among the several "S" curves employed in the historical cases, and in none of the companies involved there was a collection of information about typical patterns of allocation of resources.

It seems that there is a gap in the knowledge available about this particular aspect of the planning task: neither the research community nor the practitioners have developed models for the "S" curve that could be readily employed for establishing the rate profiles in this study.

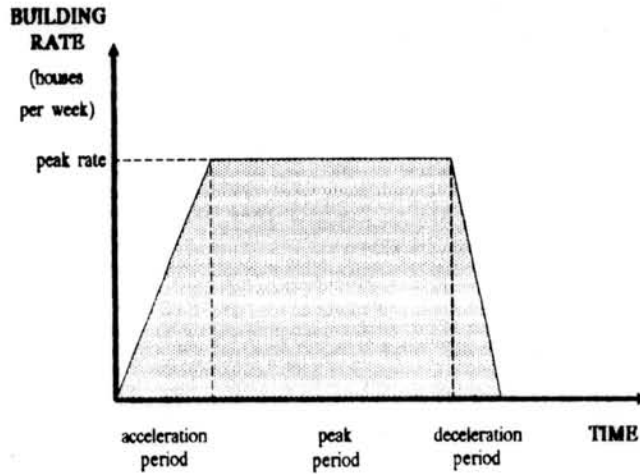


Figure 6.12: Non cumulative "S" curve adopted for the application

Consequently, the choice of an "S" curve for drawing the rate profiles had to be made on an arbitrary basis. The model chosen was an "S" curve which has, in its non-cumulative version, the shape of a trapezoid, as shown in Figure 6.12. This model was chosen because of its simplicity: the shape of the profile is defined by only two parameters, the ratio between the peak and the average rate and the ratio between the acceleration and the deceleration period, both having a very clear meaning to the experts.

All the experts agreed about some basic characteristics of the profiles. For instance, they considered that the acceleration period is usually longer than the deceleration period. Also, they all confirmed that the acceleration period in the foundation stage should be proportionally longer than in the other stages, since the foundation stage starts in the first few weeks of the project, when the site is still being organized.

However, no agreement about the actual parameters of the model was achieved among the experts. Table 6.2 presents the range of values elicited from the experts for each of the parameters. Such disagreement might be a consequence of the distinct strategies that each of the companies involved employ for accelerating and decelerating the pace of work in house building.

STAGE	Peak/average rate ratio	Acc/decelerat. period ratio
Foundation	1.20 to 1.40	1.50 to 3.00
Shell	1.05 to 1.20	1.50 to 3.00
Finishing	1.05 to 1.20	1.50 to 3.00

Table 6.2: Ranges of parameters for the rate profiles

6.6.8 Pace of site preparation and landscape activities

As mentioned in Section 6.6.2, the experts used a number of different criteria for establishing the pace of work of the activities from the site preparation and landscape stages. Both bar-chart and repetitive activities can be found in the landscape stage, while all activities from the site preparation stage are usually assumed to be bar-chart activities.

A number of categories of activities were identified within these two stages of work, based on the criteria employed by the experts for establishing the pace of work. These are described below:

(i) Starting and finishing activities: the need for such activities has already been discussed in Section 6.5.2. Both of them have fixed durations assigned, independently of the work content of the job to be carried out;

(ii) Site shaping, deep foundation, and road construction activities: these have their durations usually established in an individual basis, by calculating the quantities of work needed, and choosing a convenient rate of allocation for a leading resource. Such durations are normally predicted in a relatively expedite way, in order to avoid the need for a large collection of information;

(iii) Activities concerned with external walls and detached garages: the pace of work of these activities is defined by the site management in a short term basis, since both external walls and detached garages may be used as spare work places for some of the gangs involved in the construction of houses (e.g. bricklayers, roof tilers, joiners). In the case any of these gangs is run out of work places, they can work temporarily in such activities. Otherwise this work is carried out after the completion of the houses. At the tactical level of planning, the experts are only able to define the starting and completion time of the activities, but not their actual pace of work;

(iv) Activities concerned with external work around the houses: this is the only category that contains repetitive activities. These activities follow the pace of work in which the houses are handed over, and, therefore, their profile of building rates is the same as for the finishing activities; and

(v) Activities carried out by external boards: there are a number of activities related to service mains and connections that are carried out by gangs that are not under the control of the contractor. Like the third category of activities, these activities cannot have their pace of work defined in advance. The planners are only able to establish the likely dates when they must be started and completed.

Some of the site preparation and landscape activities have critical links to activities related to the construction of the houses. For instance, the foundation stage cannot start before some site preparation activities have been carried out to a certain extent. For this reason, some of the decisions related to the pace of work described in this section are likely to be affected by decisions related to the profile of activity starts, which are discussed in the following section.

6.7 Defining a profile of activity starts

6.7.1 General approach

The profile of activity starts is an essential element of the construction plans studied in this research project. It defines the time necessary for the completion of the first unit, and plays an important part in the establishment of the total duration of the construction stage.

The experts establish the profile of activity starts by assigning precedence relationships between activities, or between an activity and a site event. Such precedence relationships define the week in which each particular activity will start.

The process of assigning precedences can be divided into two phases. In the first phase, the expert establishes precedence relationships between activities following the order in which they start, beginning from the first activity in the project, up to the last activity in the second fix/finals stage, named "handover". At this point, the total duration of the project can be established. Then the second phase starts, in which the remaining activities, all from the landscape stage, are scheduled from the completion date backwards. This strategy is employed because most landscape activities are left for the latest possible time, in order to minimize the possibility of damages caused the work of other trades.

In most CPM based computerized planning systems, the activity precedence relationships are expressed as constraints (e.g. activity A will start one week after the beginning of activity B). This approach has been highly criticized as being a very shallow form of representing construction planning expertise (Levitt & Kunz, 1985; Kähkönen & Atkin, 1990; Waugh & Froese, 1990). Plans generated in that way do not contain any information about the reasons and assumptions underlying the inclusion of each constraint into the network. This has important implications in terms of failing to convey critical details of the plan for other members of the project team, involved in the execution of the job (Waugh & Froese, 1990), and in the project control (Levitt & Kunz, 1985).

Another disadvantage of this approach, experienced in the present study during the early stages of knowledge acquisition, is concerned with the fact that it is difficult to get an agreement among experts about every single constraint. This was consistently observed in the historical cases available: several differences were found in the plans, both in terms of the sequence of work, and the extent in which the activities overlapped, even for projects that had a very similar activity content.

Based on these two facts, the decision was made to investigate the expertise related to activity precedences beyond the level of constraints. The aim was to elicit a body of knowledge that contained some more general principles about the sequencing of work, rather than simply hard coding constraints provided by the experts into the system.

Such body of knowledge resulted in the development of a conceptual model for establishing activity precedence relationships, which acted as a framework for the knowledge elicitation process related to this particular sub-task. This model is presented in the following section.

6.7.2 A model for establishing activity precedence relationships

6.7.2.1 Main elements of the model

The model is diagrammatically presented in Figure 6.13. As in the study carried out by Kähkönen & Atkin (1990), each precedence relationship can be represented in this model by three different

levels of abstraction.

At the higher level, precedence relationships are expressed by a number of factors, which denote the construction principles that make an activity to be dependent on another activity or on a particular event. Below that level, each precedence relationship is depicted into four basic elements, named dependency, link type, float, and overlapping extent. Finally, at the lower level precedence relationships are expressed by constraints, such as the ones discussed in Section 6.7.1.

Constraints in this model are regarded only as the final expression of precedence relationships that is incorporated in the plan. The elements involved in the two upper levels of abstraction were used as a focus for eliciting the causal knowledge behind each constraint.

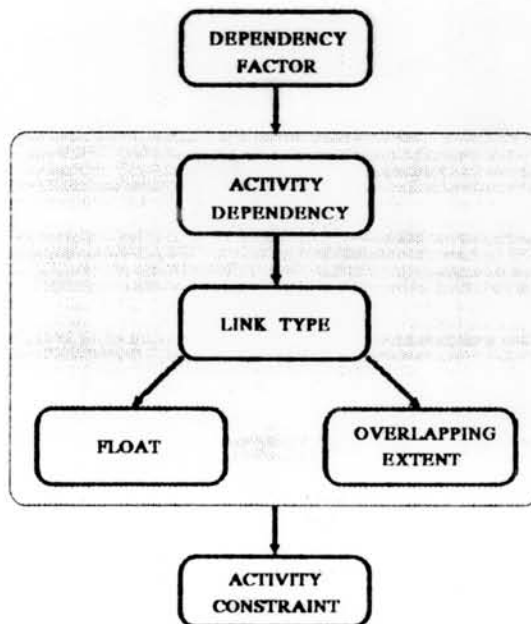


Figure 6.13: Activity precedence model

6.7.2.2 Activity dependencies

Each construction activity usually has precedence relationships with a large number of other activities. However, only a few of such dependencies are relevant for generating a construction plan, because the great majority of them are redundant.

The experts involved in the knowledge acquisition process were able to provide a list of all possible non-redundant dependencies for each

activity from the library. They were also asked to define the conditions in which each of them occurs, and the dependency factor that is behind each precedence relationship.

The number of alternative dependencies for each activity ranged from one to five. This number is fairly small because of the relatively low level of detail of the work breakdown adopted in this particular study.

Most disagreements about activity dependencies among the experts can be explained by the nature of the dependency factors. Some of these factors lead to a mandatory dependency between activities, while others usually admit a number of feasible alternative sequences of work. The following dependency factors have been identified as relevant in the types of projects considered in this study:

(i) Structural: this occurs when an activity produces an element which provides a fixing base for another element, which is subsequently produced by another activity;

(ii) Covering: when there is a multi-layer sequence of materials to be placed, the activity that involves the material to be hidden obviously must come before the activity concerned with the material that provides covering. Alternatively, if there is a sequence of materials to be removed, the activity that involves the more external materials have to precede the activity concerned with the removal of the more internal ones;

(iii) Avoid damaging: it may happen that an activity has to precede another in order to avoid that the execution of the first one damages the result of the second;

(iv) Providing a service: some activities provide a service without which the following activities cannot be carried out. For instance, each stage of scaffolding provides a working platform for carrying out the correspondent lift of brickwork;

(v) Protected environment: some activities provide a protected environment for the execution of other activities;

(vi) Flexibility: when several activities are concentrated in one particular area, the fixing order should be the least flexible followed by the more flexible;

(vii) Safety: some activities must come before others in order to guarantee the safety of operatives or outsiders;

(viii) Resource: some activities are required to be carried out in a certain sequence, so as to keep the continuous usage of certain resources;

(xix) Work area: if there is a restricted working area, a limit must be set to the number of activities that can be performed simultaneously; and

(x) Delivery time: some materials have a long delivery time, which may imply a restriction to the beginning of some activities.

The structural factor, for instance, defines a mandatory type of link: in no circumstance can "brickwork 2nd lift" be carried out before "brickwork 1st lift", due to their structural relationship. The other factors that do not admit alternative sequences of work are: covering, providing a service, safety and delivery time.

All the remaining factors are less restrictive in relation to the sequence of work. For example, some experts placed the activity "house drainage" soon after "service entries", in order to keep continuity in the work of drain layers; while other experts preferred to schedule "house drainage" later in the sequence of work, after the completion of floor screed, so as to minimize the possibility of damaging the drainage. This kind of flexibility in the sequencing of activities is concerned with the concept of preferential logic, which has already been discussed in Section 4.2.5.

Generally, the experts do not use any objective method for comparing the advantages and disadvantages of each alternative sequencing of activities: this choice is usually based on their personal experience, or on the practices adopted by each contractor.

6.7.2.3 Link type

Four main types of link can be established between two activities involved in a precedence relationship in this particular model. These are:

(i) Start-start: this is the type of link most frequently used by the experts involved in the study. It assumes some overlapping between the activities;

(ii) End-start: it corresponds to the traditional head and tail type of relationship. When this kind of link is used, the expert may place a float between the end of the preceding activity and the start of the succeeding one;

(iii) End-end: such link also implies some overlapping between activities. It was mostly used for the activities that usually have their execution left for the latest possible time, so as to minimize the possibility of damages caused by the work of other trades, as described in Section 6.7.1; and

(iv) Parallel link: this link was used for expressing the relationship between pairs of activities in which a very clear interaction was assumed between the work of the gangs involved in each of them.

The circumstances in which parallel and end-end types of link occur are relatively easy to identify. On the other hand, the choice between start-start and end-start types of link depends on whether or not the activities involved in the precedence relationship are overlapped.

6.7.2.4 Floats and overlapping

Overlapping between two activities occurs when each work place is further divided into individual working areas, and the preceding and the succeeding activities can be performed simultaneously, each one of them in a distinct working area. This is the case, for instance, of the activities "plasterboard" and "skim coat": it is possible to have one gang placing plasterboards in the lower floor of the house, while there is another gang skimming the walls in the upper floor, where the activity "plasterboard" has already been concluded. Therefore, in practice, an overlapping may occur even when a mandatory type of dependency is involved.

The decision concerned with whether to overlap two activities, or to have a float between them is based on the general strategy established by the expert for delivering the houses. If the contractor wants to deliver houses very early, the activities will have to be overlapped as much as possible, and the floats reduced. This characterizes a vertical type of project. In the opposite situation, when the contractor prefers to spread the job horizontally in the

whole site, the amount of overlapping must be reduced, and the floats increased.

From the point of view of the contractor, it is advantageous in some cases to deliver individual houses as soon as possible in order to avoid problems such as vandalism, or deterioration of the work already done. Also, if the project is carried out in a speculative basis, the contractor may want to deliver houses early in order to attend the demands of a volatile market (Leopold & Bishop, 1983a). On the other hand, some contractors prefer to avoid vertical projects because they impose a high demand on site management, since different gangs are more likely to interfere with each other.

The choice between a vertical and a horizontal type of project, like many other decisions involved in construction planning, is a compromise between a number of conflicting objectives. The amount of overlapping and floats between activities adopted in this study reflects an average between the strategies followed by the experts involved in the knowledge acquisition process.

6.7.3 Definition of constraints

In traditional CPM based planning techniques, activity constraints are usually defined according to the estimated durations of the activities involved, as well as the float between the preceding and the succeeding activities, or the extent to which the succeeding activity overlaps on the preceding one.

This approach was not adopted in most precedence relationships for the following reasons: (i) it was not the approach employed by the experts in practice; (ii) such approach would demand each construction activity to be broken down further up to the level of work package, and the project duration to be further divided in periods shorter than a week; and (iii) that approach does not seem to consider the discontinuity in which each construction task is actually performed on site, which was discussed in Section 4.2.4.

Bearing in mind the conceptual model described in the previous section, a number of general principles for defining activity constraints were elicited from the experts. These are summarized below:

- (i) The kind of constraint varies according to the type of link: if

the link type is parallel, both activities should start in the same week; when the link type is end-end, the succeeding activity should finish at least one week after the end of the preceding one; and when the link type is either start-start or end-start the succeeding activity should start one week after the preceding one, in most cases;

(ii) In the case of start-start and end-start link types, the nature of the constraint is also influenced by whether it is possible to divide each work place in several working areas, and on the duration of the activities involved. The preceding and succeeding activities can start in the same week if both of them allow several working areas to be defined, and when any of them has a very short duration (typically, less than one day);

(iii) A sharp separation between the end of the preceding activity and the start of the succeeding one usually exists when the former is a project milestone. For this reason, a float is recommended for such precedence relationships. This float was established by starting the succeeding activity one week after the conclusion of the preceding one; and

(iv) When the preceding and the succeeding activities are carried out by the same gang in a continuous way, the constraint can be established by estimating the duration of each individual activity, as in traditional CPM techniques. This was the case of some activities carried out by both bricklayers and plasterers.

6.8 Assembling the plans

Once all the main parameters of the construction plan have been established, the experts can start assembling it. As mentioned in Section 6.2, the experts may find necessary to make some minor adjustments in the plan at this stage.

The first major decision made by the experts when assembling a plan is to establish the week in which the actual construction of the houses will start. If there is already a reasonable access for the first few units, the foundation stage can start as soon as the site is set up. However, if it is necessary to construct an access before starting to work on foundations, the experts have to decide whether to build temporary roads, or to postpone the beginning of the foundations until some of the permanent roads up to the base course level are

built.

If the date in which the project will start is known, it is essential to adapt the plan to the actual calendar dates. This step allows the experts to include in the plan the company collective holidays, usually two weeks at Christmas and one week at Easter, as well as to consider the possible effect of winter months in the job.

The main concern of the experts in relation to winter months is to minimize the effect of inclement weather on the activities that have to be carried out in an unprotected environment, specially those from the foundation stage. Their main strategy consists of reducing the number of houses which have their foundations carried out during the period considered to be the most critical one in terms of weather, which is between Christmas holidays and Easter holidays.

If the foundation stage is due to start a few weeks before Christmas, the experts may try to increase the number of houses that have their foundations executed before that date. This can be done by increasing the foundation rate. The main disadvantage of this measure is that it may lead to an even higher lock up of capital in the foundations. If the beginning of foundations is dependent on road access, this action could also be taken by building temporary roads, in case this decision has not been taken yet, so that the foundation stage can start earlier.

If it is not possible to carry out all foundations before winter, the experts could simply slow down the foundation stage during the winter period, so that some of the units would have their foundations built after Easter. A more radical alternative to this strategy would be to split up the foundation stage into two phases, one before Christmas and the other after Easter. The main disadvantage of this approach would be the interruption it causes in the work of the gangs involved in the foundation stage, and possible delays it may cause to the beginning of the shell/roofing stage.

If the project is due to start in the final weeks of the winter period, the expert may decide to postpone its start for the first week after Easter. This measure not only reduces the possibility of inclement weather affecting the foundation stage, but also avoids having a forced disruption in the pace of work during the first few weeks of the project. This strategy is not always feasible, since

there might exist some factors outside the planners control that force the beginning of the project to be at a certain date.

Another important decision made by the experts during the process of assembling the plan is the inclusion of buffers between stages of work. Such buffers consist of floats placed at certain points of the project in order to prevent the interference of delays caused by any unforeseen events in the work of subsequent trades. Generally, four different stage buffers are considered by the experts: (i) between site preparation and foundation stage; (ii) between foundation and shell/roofing stage; (iii) between shell/roofing and first fix/plaster stage; and (iv) between first fix/plaster and second fix/finals.

Once the first draft of the plan is produced, some of its main variables have to be checked against restrictions imposed by the client or by higher level management, such as the total duration of the project, period of time between the beginning of the job and the first handover, and the rate in which the houses will be delivered. If any of these requirements is not satisfied, some of the sub-tasks related to the plan generation will have to be performed again.

6.9 Summary and conclusions

This chapter presented a general description of the model of construction planning expertise developed in this research work.

The project representation used by the experts for generating a construction plan was relatively simple, if compared with the amount of information that is usually employed for describing a complete construction project. In this study, the decision was made to keep this representation at the same level of detail employed by the experts in order to limit the number of questions that future users would have to be asked.

A substantial amount of expertise concerned with the generation of default data was elicited from the experts, so as to make the system able to cope with missing information. The experts did not have much difficulty in providing such information, since they are usually required to do so when working in real projects.

The expertise related to the generation of plans was grouped according to five main sub-tasks: choosing the sequence of work

places, dividing the work into activities, establishing the pace of work, defining the profile of activity starts, and making minor adjustments. In practice, these sub-tasks are often performed simultaneously in an interactive way, since the knowledge involved in each of them is highly inter-related to the knowledge concerned with the others.

As discussed in Section 5.4.2, the choice of the sequence of work places was the only sub-task considered to be unsuitable to be performed by the system. For this reason, only some general guidelines for carrying out this sub-task were elicited from the experts.

The elicitation of expertise related to the division of the work into activities lead to the development of a library of activities from which the system can choose a list of activities for each particular project. This library was created according to a number of selection criteria that were elicited from the experts.

The study of the sub-task concerned with the establishment of the pace of work indicated that the experts only consider the rate of deployment of a small number of key resources. A relatively detailed model for estimating the productivity of bricklayers was developed, since this trade often imposes a limit in the pace of work for the whole project. Such model incorporates both heuristic knowledge provided by human experts, and some theoretical knowledge obtained in the literature.

An important gap in construction planning expertise was revealed during the study of this sub-task: neither the research community nor the practitioners involved in this study were able to provide any reliable "S" curve models that could be employed for establishing the building rate profiles related to the main stages of work.

A conceptual model of activity dependency was specifically developed for eliciting knowledge related to the sub-task named defining a profile of activity starts. In such model, activity precedences were described at three different levels of abstraction. This conceptual model acted as a framework for eliciting rules related to each precedence relationship, playing a key role in the establishment of a common basis about which the experts could reach an agreement.

Although the model developed is expected to provide some sound

advice to the work of construction planners, it clearly has the potential of being improved in terms of increasing the depth of the expertise it contains. This can be done either by incorporating results from research studies as they come up, or by eliciting more knowledge related to the construction process from other experts, such as site managers, estimators, etc. In this respect, the present model can act as a skeleton for organizing the expertise related to the task of planning house building projects at several levels of detail.

CHAPTER 7: DESCRIPTION OF THE APPLICATION

7.1 Introduction

The model of construction planning expertise described in the previous chapter was implemented as a computer application using Leonardo Level 3, Version 3.18. The reasons for the choice of this knowledge based system shell have already been explained in Section 5.5.4.

This chapter presents a general description of the implemented system. Section 7.2 outlines the main elements of the application, and the way in which they interact. Section 7.3 discusses the internal structure of the system, and describes some important features of Leonardo.

The major steps involved in a consultation session to the three modules of the system (Input, Build, and Context), are described in Sections 7.4, 7.5, and 7.6, respectively. An example of a typical consultation in each of the modules is presented in Appendix 4. The main lessons learnt from the implementation of the system are discussed at the end of the chapter.

Details of Leonardo are only approached in this chapter where it is necessary for illustrating some particular features of the system. A more comprehensive description of this shell can be found in its user guide (Creative Logic, 1990).

7.2 General view of the system

The main elements of the system are presented in Figure 7.1. The system was divided into three separate modules, named Input, Context, and Build. This partition was necessary in order to make the knowledge base easier to be managed, and because Leonardo had some limitations in terms of size of each module. These limitations will be discussed later in this chapter.

In the Input module, the user is able to input a description of the particular project to be planned. This module encapsulates expertise on the way in which construction planning experts generate default information when the project description available is incomplete.

Additionally, it allows the user to establish the sequence in which the houses or block of houses will be carried out. The main output of this module is a complete description of the job to be done.

In the Context module, construction planning experts are given facilities for quickly altering some of the knowledge used by the system for generating construction plans. The portion of knowledge that can be modified in this module is likely to remain constant for a number of similar projects, but may vary according to changes in the environment in which house building projects are carried out, or according to the personal preference of experts.

The Context module makes the system usable for a large number of users. As some of the rules used for generating the construction plan can actually be altered in this module, its use must be restricted to expert users who are familiarized with the knowledge encapsulated in the system.

Based on the job description created in the Input module, the user can use the Build module for producing a general plan for the construction stage in a conversational fashion: the system suggests values for all the main parameters of the plan, and the user is required to confirm or overwrite them at certain key points. Some kind of explanation can usually be obtained for the suggestions made by the system.

This mode of operation chosen for the Build module has already been discussed in the general specification of the application, in Section 5.4.2. It aims at making the system flexible in terms of coping with different levels of expertise. The less experienced planners are likely to accept the suggestions made by the system, and learn from the explanations given. On the other hand, the more experienced users are given the option of altering the system's propositions, if they find convenient, being able to evaluate the consequences of their choices in the whole plan in a relatively quick way.

The three knowledge bases are chained together, so that after running one of the modules the user is given the choice of directly starting any of the other modules, without having to leave the system. The communication of data between the three modules is automatically executed by the system, through a number of external files, most of them configured as ASCII files.

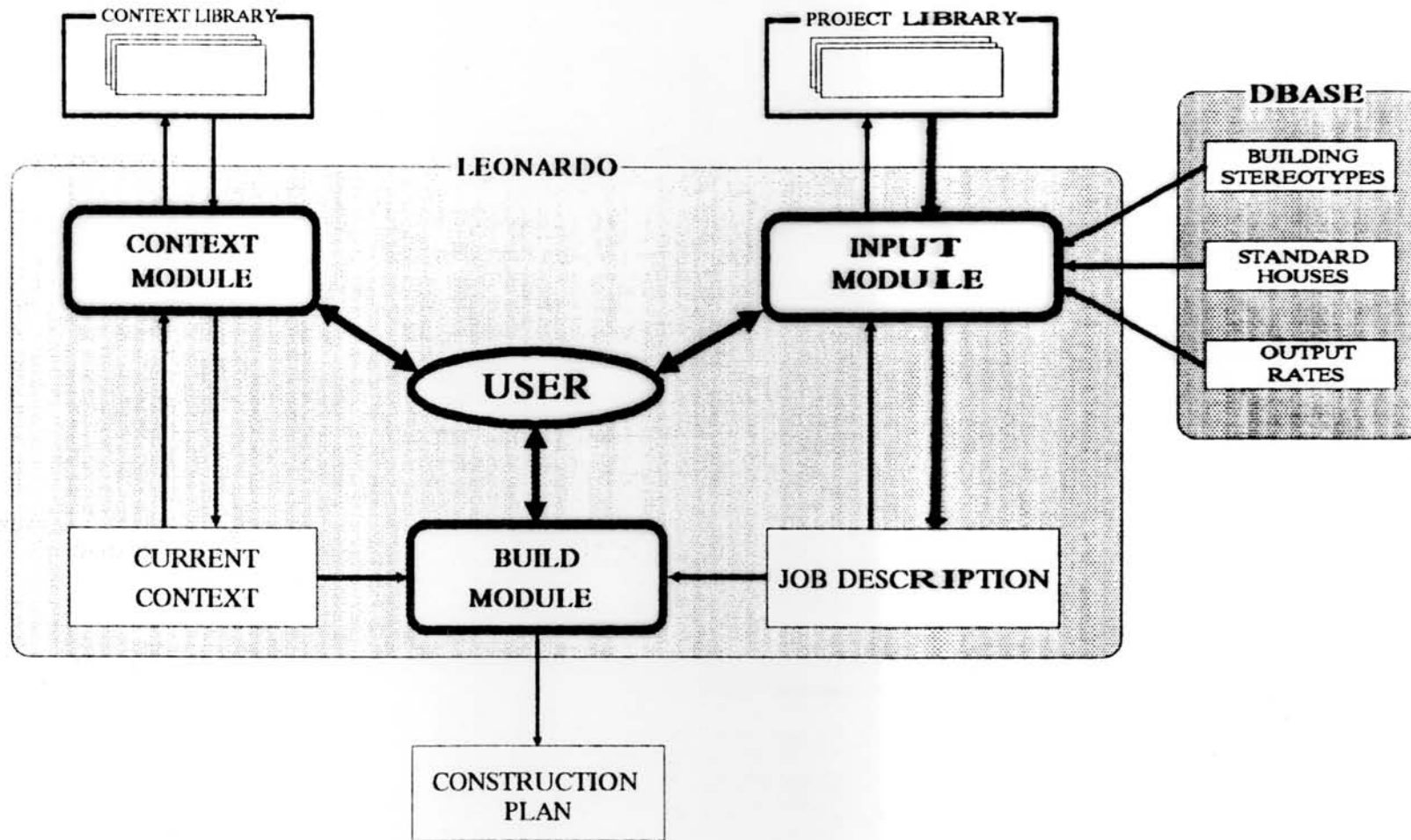


Figure 7.1: General view of the system

There are also a number of external files configured as DBASE files, which store information used by the system. It means that they can be updated by using the database management system named DBASE III Plus, or its upgrades. All the information concerned with the description of building stereotypes, the library of standard house types, and the library of output rates are stored in such files.

The main advantage of using DBASE configured external files is that the information stored in such files can be easily updated or reported through DBASE III Plus, which is one of the most widely used software packages of its kind in the UK.

7.3 Internal structure of the system

7.3.1 Rules and frames

Leonardo rule language is based on the well known condition-action format, which is demarcated by the keywords IF and THEN: conditions are formed from one or more antecedent clauses linked by AND or OR connectives, and one or more consequent clauses or actions follow the keyword THEN.

Each clause is usually formed by three elements: the first is a value carrying object, the second a predicate, and the third either another value carrying object or a value. Actions can be of several different types, such as asking a question, displaying a screen, displaying a message, or running a procedure.

Value carrying objects in Leonardo can be of three different types: (i) real objects, which can carry a numeric value; (ii) text objects, which can carry a string value; and (iii) list objects, in which a list of strings can be stored.

Figure 7.2 shows some examples of the system's rules, which were created using Leonardo's rule language. Such rules were used for expressing both inferential and task knowledge since Leonardo does not offer any specific formalism for separating them.

In Leonardo, each object is assigned a frame, such as the ones presented in the Figures 7.3(a) and 7.3(b), which are concerned with the objects named "cav_wall_inner_leaf" and "floor_ceiling_height", respectively. Some slots of the frames can only be altered by Leonardo

itself. This is the case, for instance, of the slots called "Name", "Type", "Value", "Certainty", and "DerivedFrom". All the other slots can be used by the system designer for carrying out a wide range of functions, such as displaying messages, controlling inference, running procedures, creating screens, linking the object to a class of objects, storing the value of attributes, etc.

Leonardo frames provide a facility for automatically assigning default values to objects. If a variable has a fixed default value, this can be stored in the "DefaultValue" slot of the frame. During a consultation, whenever the user informs the system that the value of an object is unknown, the value stored in that slot is automatically assigned to the object. This facility cannot be used for variables that have the default value derived from other variables. In such cases, the default value needs to be inferred by a rule, or established by a procedure.

Main ruleset

20-Jan-91 12:02

```
1 : control common
2 :
3 : seek data_input
4 :
5 : ask job
6 :
7 : if job is old
8 : and project_name is not unknown
9 : and project_database is updated
10 : and next_step is not unknown
11 : then data_input is done
12 :
13 : if job is new
14 : and project_name is not unknown
15 : and project_database is created
16 : and next_step is not unknown
17 : then data_input is done
18 :
19 : if next_step is 'run INPUT MODULE again'
20 : then cycle_mode is 'autocycle'
21 :
22 : if next_step is 'quit HOUSE PLANNER'
23 : then cycle_mode is 'stop'
24 :
25 : if next_step is 'run BUILD MODULE'
26 : then run set_chain_pointer(next_step);
27 :     cycle_mode is 'stop'
```

Figure 7.2: Main ruleset of the Input module

```

1 :      Name: cav_wall_inner_leaf
2 :      LongName:
3 :      Type: Text
4 :      Value:
5 :      Certainty:
6 :      DerivedFrom:
7 :      DefaultValue: 100mm heavy concrete block
8 :      AllowedValue: 100mm medium concrete block,
9 :                  140mm medium concrete block,215mm medium concrete block,
10 :                 100mm heavy concrete block,140mm heavy concrete block,
11 :                 215mm heavy concrete block
12 :      QueryPrompt: The specification for cavity wall inner leaf is:
13 :      QueryPreface: CAVITY WALL INNER LEAF
14 :
15 :      {if job is old then}
16 :      The previous specification of cavity wall inner leaf is
17 :      [cav_wall_inner_leaf].
18 :
19 :      IsA: cavity_wall
20 :      MemberSlots:
21 :      ground_level_area: 0
22 :      1st_floor_area: 0
23 :      2nd_floor_area: 0
24 :      3rd_floor_area: 0
25 :      gable_level_area: 0

```

(a)

```

1 :      Name: floor_ceiling_height
2 :      LongName:
3 :      Type: Real
4 :      Value:
5 :      Certainty:
6 :      DerivedFrom:
7 :      DefaultValue: 2400
8 :      AllowedValue: >= 2300.0 and <= 3200.0
9 :      QueryPrompt: Please, enter the floor-ceiling height:
10 :      QueryPreface: FLOOR TO CEILING HEIGHT
11 :
12 :      {if job is old then}
13 :      The previous value for the floor-ceiling height is
14 :      {if status: of floor_ceiling_height is not unknown_value then}
15 :      [floor_ceiling_height xxxx] mm.
16 :
17 :      {endc}
18 :      {if status: of floor_ceiling_height is unknown_value then}
19 :      unknown.
20 :
21 :      {endc}
22 :      {endc}
23 :      You may answer unknown
24 :      BoxWidth: 7
25 :
26 :      IsA: house_dimension
27 :      MemberSlots:
28 :      status:

```

(b)

Figure 7.3: Examples of object frames
 (a) "cav_wall_inner_leaf" object frame
 (b) "floor_ceiling_height" object frame

7.3.2 Class objects

Based on the hierarchical trees described in Section 6.3.1, several relationships were established between the variables of the model by using class objects. Such objects allow value carrying objects to be grouped into classes, employing a "kind of" type of relationship. The class(es) which an object belongs to is(are) indicated in the "IsA" slot of the frame.

The use of class objects in Leonardo is the basis for two important features of this shell. The first one is the property inheritance mechanism, in which the member objects of a class are able to inherit attributes from the objects that lie above them in the hierarchy. This enables descriptive information concerned with a class of objects to be shared among its members, avoiding the repetitive process of having to allocate the same properties to similar objects.

The attributes of an object can be stored into a number of special slots of the frame, named "member slots". For instance, the "cav_wall_inner_leaf" frame shown in Figure 7.3(a), which is a member of the class called "wall", contains several member slots, such as "ground_level_area", "1st_floor_area", "2nd_floor_area", "3rd_floor_area", and "gable_level_area".

Such attributes can be inherited from the frame of the class object, if they are shared by several of its members. They can also be overwritten in case a particular object has an attribute different from the other members of its class. This can be done either by storing another value in the respective member slots of the object, or by dynamically establishing such a value through a rule or procedure.

The second important feature concerned with class objects is the capability of expressing knowledge by using a special category of abstract rules named quantification rules. Such rules can be repetitively used by more than one object from the same class, which allow a considerable economy of rules to be made in the knowledge base. For instance, the quantification rule in Figure 7.4, shown below, is fired several times, once for each object included in the class "site_dimension".

```
For all site_dimension
if status: of site_dimension is default_value
then default_objects1 include name: of site_dimension
```

Figure 7.4: Example of quantification rule

Leonardo Version 3.18 allows only single level inheritance to be made, since it does not have any direct mechanisms for establishing hierarchical links between classes of objects. Consequently, the hierarchical trees formed for organizing the description of house building projects, as discussed in Section 6.3, could not be wholly represented in the knowledge base. Instead, they had to be segmented into several smaller two-level lattices of frames.

7.3.3 Procedures

Several procedures were also included in the knowledge base, using Leonardo's procedural language. They were used for carrying out some tasks which could not be executed using the rule language, such as: (i) to perform complex arithmetic computations; (ii) to read data from or to write data to external files; (iii) to use functions that are only available in the procedural language; and (iv) to manipulate screens at a level of flexibility not available in other screen generation methods.

Each procedure in Leonardo also corresponds to an object, and they are usually called directly from a rule. The ruleset from Figure 7.2, for instance contains a rule in which the procedure named "set_chain_pointer" is called. This mode of integration between rules and procedures is one of the most positive features of Leonardo knowledge representation structure, since it makes possible for the system designer to employ both kinds of representation in the same knowledge base, without sacrificing the readability of the rules.

7.3.4 Organizing knowledge in modules

Considering the three modules together, the final version of the system contains approximately 1100 rules. This number is fairly large, if compared to other knowledge based systems developed for micro-computers.

One of the main problems of building large rule based systems is that it is very difficult for the system designer to understand the

interactions among the rules, to debug them, and to control their behaviour, if they are not properly organized (Fikes & Kehler, 1985). The frame based knowledge representation scheme available in Leonardo provides a mechanism for overcoming this difficulty: the rules can be grouped into small, easily managed groups of rules, named rulesets, each one of them being placed in a particular frame. Moreover, the use of such rulesets allows the knowledge base to be organized in a modular way, by joining all the rules concerned with a particular aspect of the task in the same ruleset.

Object Number : 80 Name: road_data 20-Jan-91 11:50

```
1 :            Name: road_data
2 :            LongName:
3 :            Type: List
4 :            Value:
5 :            Certainty:
6 :            DerivedFrom:
7 :            RuleSet:
8 :
9 : if site_location is known
10 : and external_works does not overlap "roads,wearing course"
11 : then road_exc_volume = 0;
12 :        kerb_length = 0;
13 :        road_area = 0;
14 :        road_digging_depth = 0;
15 :        road_data include "volume"
16 :
17 : if site_location is known
18 : and external_works include "roads"
19 : then ask road_exc_volume;
20 :        ask kerb_length;
21 :        ask road_area;
22 :        road_data include "volume"
23 :
24 : if site_location is known
25 : and external_works does not include "roads"
26 : and external_works include "wearing course"
27 : then road_exc_volume = 0;
28 :        ask kerb_length;
29 :        ask road_area;
30 :        road_digging_depth = 0;
31 :        road_data include "volume"
32 :
33 : if site_location is known
34 : and external_works include "roads"
35 : and status: of road_exc_volume is unknown_value
36 : then ask road_digging_depth;
37 :        road_data include "digging_depth"
38 :
39 : if site_location is unknown
40 : or status: of external_works is unknown_value
41 : then road_data include "unknown"
```

Figure 7.5: Ruleset concerned with road construction

This method of organizing knowledge was adopted in all the three modules of the system. In fact, Figure 7.2 shows the main ruleset of the Input module, which contains only five rules. The remaining rules of this module are distributed into several other rulesets. The ruleset shown in Figure 7.5, for instance, contain rules that make inferences or request information about the objects used for describing road construction.

Perhaps the best example of modular organization of knowledge in the system is the way in which the library of activities was structured in the Build module.

Each activity from the library of activities was regarded as an object in the Build module. The frames associated to the activities were grouped into six different classes, each one of them corresponding to a stage of work. Figure 7.6 shows the frame created for the activity called "roof carcass".

A number of attributes related to construction activities are represented by member slots in the frame. These attributes describe several features of each activity, such as type of activity, main trade involved, stage of work, duration, man-hour content, etc.

If an attribute has a fixed value, it can be stored in the respective member slot of the frame. This is the case, for instance, of the "activtype", "trade", "stage", and "posslinks" slots of the frame "roof carcass", shown in Figure 7.6. When the value of an attribute is variable, it can be dynamically established in Leonardo by a rule or procedure.

All the rules and procedures used for establishing the value of activity attributes are gathered in the ruleset of the frame of each activity. This means that all the knowledge concerned with the attributes of a particular activity is represented in its frame, either in its member slots or in the ruleset.

This way of organizing the knowledge related to each activity turned out to be very convenient in this study, in terms of checking the validity of the knowledge, updating it, or expanding the knowledge base in a modular way.

```

1 :      Name: roof carcass
2 :      LongName:
3 :      Type: Text
4 :      Value:
5 :      Certainty:
6 :      DerivedFrom:
7 :      ISA: activity3
8 :      MemberSlots:
9 :      activtype: continuous
10 :      trade: joiner
11 :      stage: shell/roofing
12 :      num:
13 :      dependency:
14 :      linktype:
15 :      manhours:
16 :      duration:
17 :      firstweek:
18 :      posslinks: brickwork to peaks,scaffold 2nd stage,scaffold 4th stage,
19 :                  scaffold 6th stage
20 :      factor:
21 :
22 :      RuleSet:
23 :
24 :      Control noforward
25 :
26 :      For some activity3
27 :      if name: of activity3 is "roof carcass"
28 :      and precedence is not unknown
29 :      and overlapping is done
30 :      then number = number + 1;
31 :          num: of activity3 = number;
32 :          dependency: of activity3 is precedence;
33 :          preced_num = num: of &precedence;
34 :          run build_schedule(num: of activity3,duration: of activity3,
35 :                          firstweek: of activity3,preced_num,
36 :                          activtype: of activity3,stage: of activity3,
37 :                          dependency: of activity3,trade: of activity3,
38 :                          name: of activity3,holi_weeks);
39 :          'roof carcass' is done
40 :
41 :      if roof_type is gable
42 :      then precedence is "brickwork to peaks"
43 :
44 :      if roof_type is hipped
45 :      and num_bungalows = n_house
46 :      then precedence is "scaffold 2nd stage"
47 :
48 :      if roof_type is hipped
49 :      and num_2_floor_houses > 0
50 :      and num_3_floor_houses = 0
51 :      then precedence is "scaffold 4th stage"
52 :
53 :      if roof_type is hipped
54 :      and num_2_floor_houses = 0
55 :      and num_3_floor_houses > 0
56 :      then precedence is "scaffold 6th stage";
57 :
58 :      if precedence is "brickwork to peaks"
59 :      then firstweek: of 'roof carcass' = firstweek: of &precedence;
60 :          linktype: of 'roof carcass' is "parallel";
61 :          factor: of 'roof carcass' is "multi-layer";
62 :          overlapping is done
63 :
64 :      if precedence is not "brickwork to peaks"
65 :      then firstweek: of 'roof carcass' = firstweek: of &precedence + 1;
66 :          linktype: of 'roof carcass' is "end-start";
67 :          factor: of 'roof carcass' is "provide service";
68 :          overlapping is done

```

Figure 7.6: Frame for the activity "roof carcass"

7.3.5 Inference control mechanism

The standard method of inferencing in Leonardo can be described as a depth-first backward chaining with opportunistic forward chaining. It means that the system looks for rules with the goal object as their final conclusion and attempts to satisfy them in a depth-first manner, but it also propagates the immediate results of obtaining a value for any object.

Leonardo provides some limited facilities for changing the default method of inferencing. There are some control directives which can simply turn off and on either the backward chaining or the forward chaining inference mechanism.

However, Leonardo does not have any sophisticated mechanism for establishing an explicit strategy of firing rules. The sequence in which rules are used is determined by their position in the ruleset. As meta-rules have to be represented in the same way as any ordinary rules, they have very limited control over the way in which the inference mechanism works. It is not possible, for instance to set rules to 'unfired', or to re-run a portion of the knowledge base.

7.3.6 Man-machine interface facilities

7.3.6.1 Default screens

The man-machine interface in Leonardo can be developed using three different methods: employing Leonardo default screens, using the Screen Design utility, or executing a procedure.

Figures 7.7(a) and 7.7(b), for instance, present the default screens produced by Leonardo in the Input module for querying the value of the objects named "cav_wall_inner_leaf", and "floor_ceiling_height", respectively. All the messages displayed in such screens were determined by the contents of the slots "QueryPrompt" and "QueryPreface", which are shown in Figure 7.4.

CAVITY WALL INNER LEAF

The previous specification of cavity wall inner leaf is
140mm heavy concrete block.

The specification for cavity wall inner leaf is:

100mm medium concrete block
140mm medium concrete block
100mm heavy concrete block
140mm heavy concrete block
timber frame panels
unknown

FKeys: 1 Help 2 Quit 3 Why? 7 Expand 8 Review

(a)

FLOOR TO CEILING HEIGHT

The previous value for the floor-ceiling height is
2350 mm.

You may answer unknown

Please, enter the floor-ceiling height:

2350

FKeys: 1 Help 2 Quit 3 Why? 7 Expand 8 Review

(b)

Figure 7.7: Example of input screens
(a) "cav_wall_inner_leaf" input screen
(b) "floor_ceiling_height" input screen

The control over the values entered in a default screen can be done through the content of the "AllowedValue" frame slot. In the case of a real object, such as "floor_ceiling_height", this slot allows a range of acceptable values to be declared, as shown in Figure 7.4(b). If the user inputs a value outside the specified range, the system displays the error message contained in the "OnError" slot, or Leonardo's default error message if this slot is empty or inexistent.

In the case of text or list objects, a number of alternative values for the object can be stored in the "AllowedValue" slot. During runtime sessions, the system displays a menu from which the user can choose one of the options, when the object is a text object, or multiple options, if it is a list object. The screen reproduced in Figure 7.4(a) is an example of such menu type of screen.

Leonardo's default screen has the capability of displaying any additional explanatory text at the request of the user. This can be done by storing a piece of text in the "Expansion" slot of the frame. During a consultation, whenever the user presses the "F7" key, the system displays the information contained in that slot.

The default screen also provides two facilities which are intended to give the user some control over the consultation: one allows the user to volunteer the value of any object, and the other gives the user the option of moving back to the previous screen. However, the user is not encouraged to use any of them in the current application, because they sometimes result in a confusing sequence of queries and actions.

Standard screens were intensively used in the Input module, for querying the values of most variables involved in the job description. The main advantage of the interface facilities offered by such screens is that they allow a great amount of text to be displayed to the user, without any coding other than the text itself.

7.3.6.2 Screen Design utility

The Screen Design utility was used whenever it was necessary to have a higher level of control over the interface than Leonardo default screens could provide. In the Input and Context modules, this facility was mainly used for producing an interaction mode in which

the user was required to input the values of more than one object in the same screen, and when it was necessary to display information in a very basic graphic fashion.

Some of the facilities available for the default screen can also be used by the screens generated through the Screen Design utility. This is the case, for instance, of the input control set by the "AllowedValue" slot, and the capability of displaying additional text stored in the "Expansion" slot.

Another important feature of the Screen Design utility is the capability of linking a number of screens into a chain: the user can be allowed to page forward and back among the screens from the chain, until all the data displayed or input in the entire screen set is considered to be adequate. Such capability gives the user a higher level of control over the consultation than it is provided in default screens. The main disadvantage of using chained screens is that the knowledge concerned with the sequencing of screens is not expressed anywhere as rules, but it is implicit in the internal code of the screens.

7.3.6.3 Screens generated by procedures

The need for using procedures for generating screens occurs when it is necessary to impose a more complex control over the user input than it is enabled by the "AllowedValue" slot.

In the present application, for instance, there are situations in which groups of variables need to have their input checked in combination: if there is any inconsistency between them, the system must be able to start the querying process again, as many times as necessary, until the user inputs consistent data. As Leonardo rules cannot be set to "unfired", there is no effective way of performing such loops using the rule language. Consequently, the screens used for querying the user in such cases had to be executed by procedures.

7.4 Input module

7.4.1 Main consultation steps

The main steps involved in a consultation session to the Input module are presented in Figure 7.8. Through this module, the user can either create a description of a new job, or update a project description which has been previously input.

The variables used for describing house building projects in this study were grouped under the five main headings: general information, design parameters, site conditions, specification of components, and sequence of construction. Section 7.4.2 describe the content of each of these groups in general terms.

This classification was created in order to organize the sequence in which the questions are asked to the user, as well as to take into account some relationships that exist between variables from the same group. For instance, when the user informs that the type of foundation needed is strip, the system will immediately ask the dimensions of the strip foundations, and infer that all the dimensions related to the other types of foundations are equal to zero. From the point of view of the user, it makes much more sense if all the questions related to a particular aspect of the job are asked jointly, rather than spread over the consultation session.

When the project is new, the user obviously has to go through questions related to all the five groups of variables. However, if the user needs to update a job description, he/she can choose which particular groups of variables to go through. This avoids the user to be locked into a lengthy consultation in case only a few items need to be changed.

The number of entries that the user has to make for a new job varies according to the complexity of the project, and the amount of information available about the job. It usually ranges from 20 to 200 items.

As mentioned in Section 7.3.6.1, most screens used in the application for querying the user are default screens generated by Leonardo. In general, the data initially displayed to the user in such screens is limited to some essential information for guiding the user

through the consultation, so as to avoid an overload of information to experienced users. For those variables that might not have a clear meaning among less experienced users, the system is also able to provide some additional explanation at the user's request.

At the end of the consultation the system performs some calculations in order to put some of the data into a suitable format for the Build module. After that, the complete description of the job is saved in a number of external files. The data concerned with the description of house types and block types are stored into DBASE files, and all the remaining variables are stored into ASCII files.

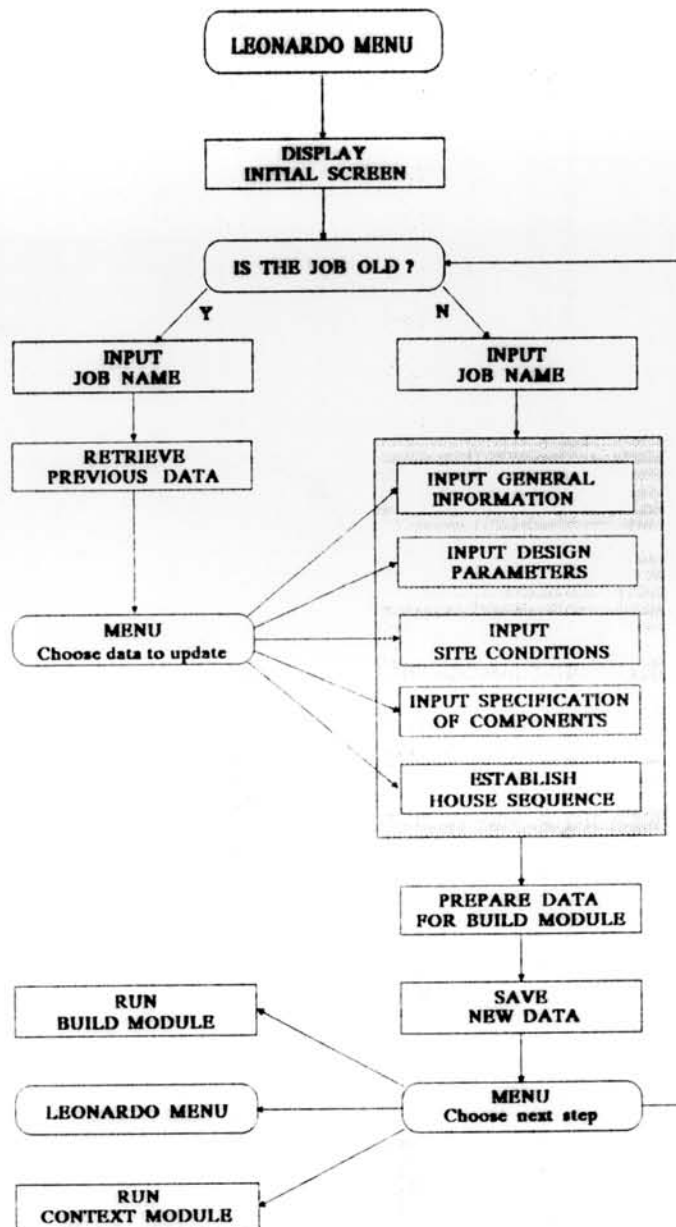


Figure 7.8: Main consultation steps in the Input module

7.4.2 Content of each group of variables

7.4.2.1 General information

General information includes a miscellaneous of variables related to several different aspects of the project: (i) the date in which the project is due to start; (ii) some restrictions that might have been imposed by the client or higher level management; and (iii) the availability of the two most potentially critical resources - bricklayers and management, both expressed in qualitative terms.

If the user is able to inform the starting date, the system automatically generates a calendar for the project. Otherwise, the construction plan will have to be expressed in terms of week numbers, rather than real dates.

7.4.2.2 Design parameters

Design parameters comprise all the variables which describe the buildings in geometric terms. It is usually the group that involves the largest number of items: the user has to input a geometric description for each house type and terraced block type, as well as the main dimensions of external walls (i.e. walls not incorporated into the main body of the houses).

If a complete set of architectural plans is available, the user is asked to input the main dimensions of each house type, and to describe the way in which the terraced houses are grouped into blocks. This is quite a lengthy process, since several items have to be entered for each house or block type.

The system is able to use descriptions of standard house types that have been previously stored in a DBASE file. This facility is useful for construction planners who are involved in planning several projects for clients whose house building projects involve only a limited number of house types. In such cases, the user only needs to enter the number of units for each design type, and the system obtains its description from the respective DBASE file.

The system can also cope with the situation in which a complete set of architectural plans is not available. In such case, the user is required to define each house type by some of its of general features, such as the number of floors, number of bedrooms, number of people,

frontage type (narrow, medium, wide), and shape (rectangular, or "L" shaped). The system consults the database of building stereotypes, stored in a DBASE file, and adopts the dimensions of the particular stereotype that matches the general description of the house type.

7.4.2.3 Site conditions

Site conditions include all variables related to the current state of the site chosen for the project. Some of these variables are simply used for describing the general conditions of the site, such as the type of urban area in which the project is located, and the average slope. Other variables define more specifically the external works that need to be executed, such as roads, drainage, services, landscaping, etc., and the kind of infra-structure required for the buildings.

The system is able to cope with the situation in which the site has not been chosen yet. In this case, the system asks only a few general questions about the site, and assigns default values for all the remaining variables.

7.4.2.4 Specification of components

Specification of components groups all the variables used for describing the specification of a number of building components that are considered to be of key importance for the construction plan.

The system can also handle the situation in which a design specification is not available. In such case, the user is simply required to inform the level of complexity of the finishings and services, expressed in qualitative terms, and the system establishes default values for the remaining variables from this group.

7.4.2.5 Sequence of construction

The group named sequence of construction contains a number of variables used for describing the sequence in which the houses or block of houses will be built. The user is required to input the sequence in which the units will be carried out, one by one, by defining the type of block (detached, semi-detached, or terraced), the design type number, and the pool of work in which it is located.

Before these variables are entered, the system is able to provide some general advice, at the user's request, on how to divide the site into pools of work, and which factors to consider when choosing the sequence of construction.

If the user is unable to establish a sequence of construction, the construction plan generated in the input module will have to be expressed in terms of generic houses.

7.5 Context module

Through this module, the user can either create a description of a new context, or update a set of context parameters that have been previously input.

The user is initially required to identify the context being described in terms of location, period, and the range of project size which the set of parameters will be valid for. After that, the system asks the user to input or confirm the value of each of the parameters. At the end of the consultation, the complete set of parameters is saved into an ASCII file.

The way in which the user and the system interact in the Context module is fairly similar to what happens in the Input module. The entries which the user is required to make are organized in groups containing related parameters. The screens displayed to the user contains only a limited amount of information about the particular parameter(s) being asked, but the system usually provides some additional explanations at the user's request.

The context parameters were organized in seven main groups. These are:

(i) Range of bricklayers' availability: this range expresses numerically the amount of bricklayers that can be hired in extreme situations in terms of availability;

(ii) "S" curve parameters: contains the parameters from three different "S" curves, one for each main stage of work (i.e. foundations, shell/roofing, and finishings);

(iii) Range of excavation rate: it expresses, in global terms, a range of usual paces of work for reduced level excavation;

(iv) Usual allocation of some resources in the foundation stage: this includes the usual size of formwork joiner gangs and the average volume of concrete poured each week;

(v) Maximum number of plasterers;

(vi) Bricklayers' productivity data: this includes usual range of output targets, usual range of repetition effect, weights of productivity factors, design simplicity indices for individual house types; and

(vii) Range of building rates for the finishing stages.

Several different context files can be created for each user of the system, although only one of them is assumed by the Build module to be the current one. The possibility of having a number of different sets of context parameters can be useful for contractors that have to carry out house building projects in different environments.

A default context file was established in the system using parameters elicited from the experts involved in this study. This file can be employed by users who are not able to set their own context parameters.

7.6 Build module

7.6.1 Main consultation steps

Figure 7.9 diagrammatically represents the main steps followed in a consultation to the Build module. The process of generating a construction plan in this module was divided in three phases: establishing the pace of work, selecting activities and defining the profile of activity starts, and final steps.

The first phase consists of establishing the profile of building rates for each of the stages of work related to the construction of the houses. In the second one, the system performs simultaneously two of the planning sub-tasks described in Section 6.4: breaking down the job into construction activities, and defining a profile of activity starts. The final phase includes generating schedules for a number of key resources, printing or displaying the construction programme in a number of different formats, and choosing the next task to be performed in the system.

7.6.2 Establishing the pace of work

In this phase, the system initially proposes a value for each of the main building rates, i.e. shell rate, finishing rate, and foundation rate. The user can either confirm or overwrite them, and the system offers an explanation about the way such rates have been inferred, as indicated in Figure 7.9.

After the user has confirmed or overwritten the value of each building rate, the system calculates the corresponding values of a number of parameters which depend on such rate, and displays them. The total duration of the activities from the stage(s) of work concerned, the rate of deployment of the resources that are potentially critical, and the name of the resource that is more likely to be the critical one are among such parameters. In the particular case of the shell rate, the system also displays the expected productivity of bricklayers, which is usually the critical resource for the shell/roofing stage. Such sequence of screens allow the user to visualize immediately the main consequences of his/her choice of building rates.

All the screens used for inputting the building rates are inserted in a set of chained screens, which was designed by using the Screen Design utility. The user has an absolute control over the interaction with the system in this phase: it is possible to move forward and back in the chain, as shown in Figure 7.9, until a suitable combination of building rates for the job being analysed is established.

Whenever the user changes the value of a building rate, the system recalculates the value of all related parameters, and display them to the user. This mechanism allows the user to try several different values for each rate, in a 'what if' fashion, until a convenient level of resource deployment is set.

Once the building rates have been chosen, the system draws a rate profile for each of the corresponding stages of work, based on the "S" curve parameters set in the Context module.

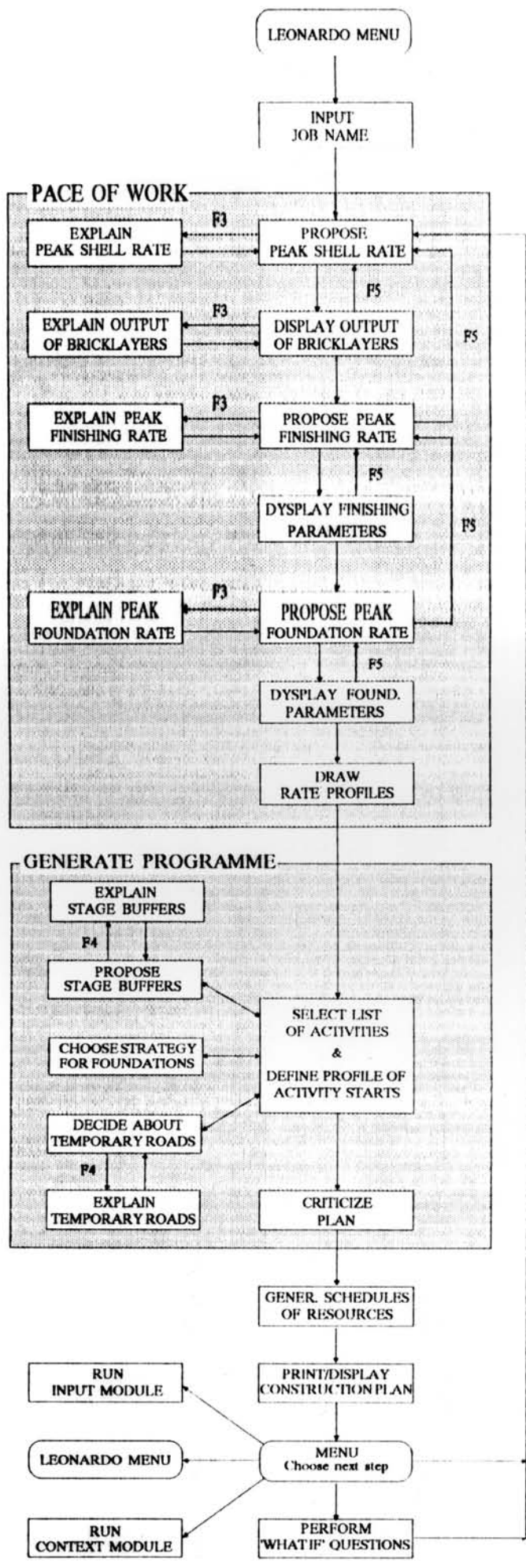


Figure 7.9: Main consultation steps in the Build module

7.6.2 Selecting activities and defining profile of activity starts

As this phase involves a relatively large number of minor decisions, the user is not given the option of overwriting all suggestions made by the system, in order to avoid the consultation to be excessively lengthy.

The breakdown of the job into activities is established by selecting a number of construction activities for each stage of work from the library of activities available in the Build module. The system uses a number of relatively straight forward rules for making these decisions, such as the ones presented in Figure 7.10, which are concerned with the choice of ground floor activities.

As discussed in Section 6.7, the sub-task of defining a profile of activity starts involves assigning precedence relationships between activities, and between activities and site events. Each precedence relationship is defined in the system by a number of attributes of the succeeding activity. Such attributes can be either stored in the frame of the activity, or dynamically established by a rule or procedure. The way in which the knowledge concerned with activity attributes is organized in the system has already been explained in Section 7.3.4.

Object Number : 201 Name: ground_floor_list 20-Jan-91 17:42

```
1 :            Name: ground_floor_list
2 :            LongName:
3 :            Type: List
4 :            Value:
5 :            Certainty:
6 :            DerivedFrom:
7 :            RuleSet:
8 :
9 : if foundation_type is raft
10 : then ground_floor_list equiv nothing
11 :
12 : if ground_floor is not 'timber floor'
13 : and ground_floor is not 'suspended concrete slab'
14 : and foundation_type is not raft
15 : and hardcore is done
16 : and 'concrete slab' is done
17 : then ground_floor_list includes "hardcore,concrete slab"
18 :
19 : if ground_floor is 'suspended concrete slab'
20 : and susp_concrete_slab is 'precasted hollow beams'
21 : and 'hollow beams(gr.)' is done
22 : then ground_floor_list includes "hollow beams(gr.)"
23 :
24 : if ground_floor is 'suspended concrete slab'
25 : and susp_concrete_slab is 'precasted beams & blocks'
26 : and 'beams/blocks(gr.)' is done
27 : then ground_floor_list includes "beams/blocks(gr.)"
28 :
29 : if ground_floor is 'timber floor'
30 : and 'gr.floor joists' is done
31 : then ground_floor_list includes "gr.floor joists"
```

Figure 7.10: Ruleset used for choosing ground floor activities

While the general programme for the construction stage is assembled, it is displayed to the user activity by activity in a bar chart form. This programme is similar to the one reproduced in Figure 5.3, which was generated by one of the experts involved in the knowledge acquisition process.

Each type of activity is represented by a different convention: bar chart activities are expressed by a bar; repetitive continuous activities are expressed by the number of houses finished each week; and stretched activities are indicated by a double line.

The process of assembling the programme is interrupted at certain points, when the system requires the user to confirm or overwrite some decisions concerned with the inclusion of stage buffers, whether temporary roads are to be built, or rescheduling the foundation stage in case it has been programmed to be carried out during winter months. Such decisions give the user some control over the profile of activity starts.

After the construction plan has been generated, some of its main variables are checked against any restrictions that might have been imposed by the client or higher level management. These can include a maximum duration for the project, a maximum period of time between the beginning of the job and the first handover, or a minimum rate in which the houses are delivered to the client or users. In case any of them is not satisfied, the system proposes some possible changes in some parameters of plan, which, if implemented, can make the plan acceptable.

7.6.3 Final steps

The current version of the system is able to produce automatically the schedules of only a few resources. These are formwork joiners, bricklayers, and plasterers. The system does not generate schedules for all trades involved in house building projects, because that would demand the user to input much more data than it is currently needed. Moreover, most of the experts involved in the knowledge acquisition process find unnecessary to obtain the schedule of all trades involved, since many of them are usually sub-contracted. Figure 7.11 shows the schedule of bricklayers produced for a particular project.

SCHEDULE OF BRICKLAYERS

PROJECT NAME: epsom DATE: 26-Jan-91 14:30

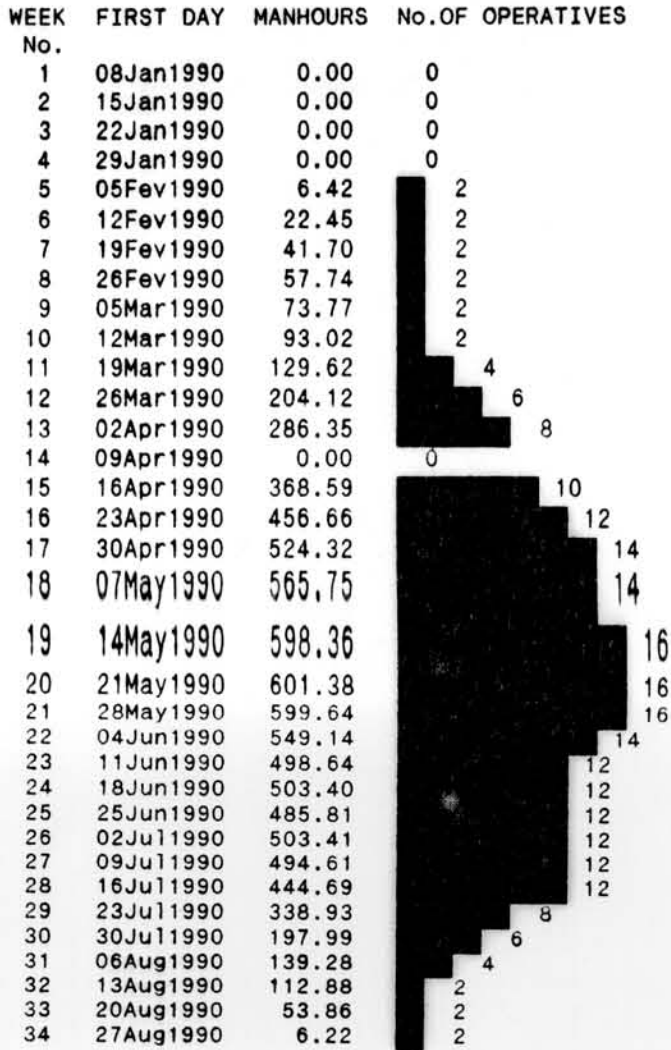


Figure 7.11: An example of resource schedule

A hard copy of the general construction programme can be obtained in three different formats. Besides the bar chart format, described above, the system is also able to print the programme as a schedule of milestones, and as a list of activities with all their attributes.

Figure 7.12 presents an example of construction programme in a bar chart form. The dependency of each activity is indicated in this programme by the preceding activity number (column 3).

Figure 7.13 shows an example of a schedule of milestones. This schedule indicates the target dates for the main project milestones, for each individual work place. If the sequence of work has not been defined yet, the schedule of milestones is related to generic houses, otherwise it is defined in relation to each individual block of houses, or pool of work.

CONSTRUCTION PROGRAMME

PROJECT NAME: epsom

CONTEXT NAME: default

RUN No.1



Figure 7.12: A construction programme in the bar chart form

SCHEDULE OF MILESTONES

PROJECT NAME:seaf02 CONTEXT NAME:default DATE:26-Jan-91 18:33 RUN No.

YEAR: 85 86
 MONTH: JJJJJJAAAASSSSOOOONNNDDDDJJJJFFFFMMMMMAAAAMMMMJ
 WEEK STARTING ON: 20012201120012301220112001230122011201123012201120
 41852952962963074184185296306307307430741741852962
 WEEK No.: 11111111112222222222333333333344444444445
 12345678901234567890123456789012345678901234567890

UNIT No.	UNIT TYPE	SIZE	DES No.	1	2	3	4
1	semi-detached	2	6	1	2	3	4
2	terraced	2	1	1	2	3	4
3	terraced	2	2	1	2	3	4
4	terraced	2	2	1	2	3	4
5	terraced	2	3	1	2	3	4
6	detached	1	9	1	2	3	4
7	semi-detached	2	7	1	2	3	4
8	semi-detached	2	7	1	2	3	4
9	semi-detached	2	8	1	2	3	4
10	detached	1	10	1	2	3	4
11	detached	1	9	1	2	3	4
12	semi-detached	2	8	1	2	3	4
13	terraced	2	4	1	2	3	4
14	terraced	2	4	1	2	3	4

- 1 - End of substructure
- 2 - Shell water tight
- 3 - Wet trades completion
- 4 - Unit handover

Figure 7.13: A schedule of milestones

The main project milestones corresponds to the conclusion of the four stages of work related to the construction of houses: conclusion of the infra-structure, completion of the water tight shell, completion of the work of all wet trades, and unit handover.

Appendix 5 presents an example of construction programme expressed as a list of activities and their attributes.

At the end of each cycle in the Build module, the user can perform some "what if" type of questions: a limited number of variables from the job description can be provisionally altered, and the whole cycle repeated. This facility enables the user to generate a variety of construction plans for a range of slightly different scenarios.

The construction plan that is generated using the suggestions made by the system can be regarded as representing the natural pace of work proposed by the system. Different "what if" scenarios could be created, for instance, for assessing the effect that changes in the job description are likely to have in such natural pace of work.

7.7 Lessons learnt from the implementation of the system

A number of lessons were learnt from the implementation of the system. Some of them are specifically related to the features of the shell used, while others involve broader issues. They were grouped in nine main headings, as follows:

(i) Usage of memory: as Leonardo does not need to load the whole knowledge base into the memory of the machine, the size of each module is not limited by the remaining amount of RAM available, as it is the case of CRYSTAL.

In practice, however, the size of a knowledge base in Leonardo is limited by the total amount of text that it contains, because of the way the usage of memory is managed in Leonardo. It means that, when developing large knowledge bases, the system designer has to bear in mind the necessity of minimizing the amount of text used in screens, rulesets, and procedures.

This limitation turned out to be even more severe in Leonardo Versions 3.20 and 3.22. Unfortunately, none of them so far has been able to cope with the size and complexity of the current system, despite of the great effort carried out by the author for optimizing its usage of memory. Consequently, it has not been possible yet to use of any of the new features of Leonardo provided by these new versions in the development of the current application.

Unless Leonardo is not improved in this particular aspect, it will not be possible to extend the application much further without having to split both the Input and Build modules into a number of smaller modules.

(ii) Number of objects: another limit to the size of a knowledge base in Leonardo, when running in a PC, is the number of permanent objects in each knowledge base - one thousand objects is the maximum amount.

Such limitation was partially overcome in the application by defining the variables used exclusively in procedures as local variables - these do not count as permanent objects. This restriction could be virtually eliminated in Leonardo if it was also possible to declare objects that are used exclusively in a particular ruleset as

local.

(iii) Speed of the system: the duration of each consultation depends on the complexity and size of the job, and obviously on the hardware used. Using a 80386 microprocessor based micro-computer, each cycle in the Build module usually takes between 15 and 25 minutes, and the time needed for collecting and entering the complete description of a job in the Input module normally ranges from 15 minutes to 2 hours. This indicates that the system performs quite well in terms of time savings, since the experts typically take between 1 and 5 working days to perform this task manually.

The system can also run in slower machines, such as 8088 or 80286 microprocessor based PC's. However, some of these machines can make the consultation boring, because of the relatively long waiting times that the user is submitted to, specially when the hard disk has a long access time.

From the point of view of the system designer, 80386 based machines are also highly recommended for developing applications as complex as the present one. A high productivity in the implementation stage is very difficult to be achieved in slow machines: each knowledge base needs to be compiled frequently and the compilation time for large knowledge bases can be quite long in some 8088 or 80286 based micro-computers. For instance, the compilation of the Build module in such machines usually takes 40 to 50 minutes

(iv) Knowledge representation: both frames and rules in Leonardo can be designed in a fairly readable way, especially when expressing pure domain knowledge. Moreover, the way in which rules and procedures are integrated allow some conventional procedural routines to be run from the knowledge base without affecting the clarity of the rule language.

As Leonardo contains no specific formalism for representing task knowledge, several meta-rules had to be represented in the same way as rules related to domain knowledge. To some extent, this resulted in a reduction of clarity in the knowledge base.

One of the main drawbacks of the frame based formalism in Leonardo Version 3.18 is the lack of multi-level inheritance. For that reason, the hierarchical trees formed for organizing the project description

could not be totally represented in the knowledge base. This limitation has already been eliminated in the Versions 3.20 and 3.22 of this shell.

Another limitation related to class objects in Leonardo is the fact that only "IsA" links are allowed in a lattice of frames. As a result, sometimes the class objects created have to be artificially adapted to this particular type of link, whenever other kinds of hierarchical relationship are required. For instance, the object "foundation" in the current application had to be expressed as an "IsA" member of the class called "building_component", instead of being simply expressed as, for instance, an "a part of" member of a class named building.

(v) Control over the consultation: the runtime facilities available in Leonardo's default screen for transferring the user some control over the consultation turned out to be largely ineffective in this particular application.

Whenever it was necessary to give more control over the consultation to the user, special purpose facilities had to be designed in the system, by using either sets of chained screens or procedures. Such facilities could not be effectively developed through Leonardo's rule language, because of the limited flexibility of its inference control mechanism.

The use of sets of chained screens and procedures usually implies a reduction in the explicitness of the knowledge base, which is one of the main advantages of knowledge based systems over conventional computer systems. In this situation, the system designer must always balance the benefits of transferring the control over the consultation to the user against a loss in the explicitness of the knowledge base.

(vi) Explanation facilities: when the default screen is used, Leonardo can trace the rules used by the system, as a form of explaining why a question is being asked, or how a certain conclusion has been reached. Although this facility was very useful during the development stage as a tool for debugging rules, it very rarely provides an acceptable explanation to the user.

The same problem has already been identified in several other knowledge based system shells (Kidd & Cooper, 1985; Berry & Broadbent, 1987; Brandon, 1990). The limitation of such explanation facilities is caused by the fact that much of the knowledge vital to providing a

good explanation is not completely expressed by the rules, but it is partly implicit in the way groups of rules are structured. For this reason, most explanations provided by the system during a consultation consist of canned texts, generally developed through the Screen Design utility.

(vii) Updating and expanding the knowledge base: the way in which the domain knowledge was organized in the system allows to some extent each knowledge base to be modified or expanded without having to radically change its structure, or without having to spend much time in checking the modified system. This is possible because of the clarity of Leonardo's rules and frames, and the fact that its rules can be grouped into small, self-contained rulesets. Obviously, modifications at this level must not be carried out by an ordinary user, but by people that have some knowledge about Leonardo and the structure of the system.

(viii) Effort spent in the development of the interface: the development of the application has confirmed the importance of the cost of devising the man-machine interface in relation to the total cost of implementing the system. Although the aim of this study was to develop the application up to the stage of a working system, rather than to a commercial stage, approximately 60% of the time needed for implementing the system was actually spent in the development of the man-machine interface, and only 40% spent in the reasoning part of the system. Similar percentages have also been found in the development of several other knowledge based system (Berry & Broadbent, 1987; Brandon et al., 1988).

(xix) Pitfalls of the early prototyping approach: some of the main advantages and disadvantages of developing a prototype of the system early in the development process have already been discussed in Chapter 5. The development of the current application has also pointed out some pitfalls which this approach has specifically in relation to the implementation process.

The first main pitfall was concerned with the fact that early versions of the system were constantly used in the knowledge acquisition process, as an expedite mean of checking the validity of the knowledge being modelled. This practice required the man-machine interface to be kept relatively attractive to the experts, and the

system reasonably debugged. Both these procedures demanded a considerable amount of effort, in relation to the total time spent in the implementation of the system.

The second main difficulty was related to the way in which the structure of the knowledge base evolved. The initial versions of the system were based on a very simplified model of the task to be performed, because only a small amount of knowledge had been elicited from the experts by then. Several upgrades had to be performed in the system up to its final version, as more complex aspects of the task were modelled and new situations were considered. Several of the early upgrades required very time consuming restructuring of the knowledge base, because the interim versions of the system did not provide the necessary structural hooks, and processing mechanisms that could cope with the new demands. This problem would probably much less severe if the implementation of the system had started later in the development process.

7.8 Summary and conclusions

This chapter presented a general overview of the knowledge engineering application developed in this study.

The implementation of the system in Leonardo Level 3 can be considered as reasonably successful. The main advantages of using this shell were: fairly good speed, availability of a wide range of facilities for developing the man-machine interface, clarity of the knowledge base, and availability of formalisms for organizing the knowledge base in a modular way. Its main shortcomings in this particular study were: limitations in the amount of text contained in each knowledge base, lack of a specific formalism for representing task knowledge, and lack of more effective runtime facilities for transferring the control over the consultation to the user.

The final version of the system is a fairly large application in terms of number of rules, if compared to other knowledge based systems developed for standard micro-computers. The performance of the system in terms of time savings is quite good: the user usually takes between 35 minutes and 2.5 hours to perform a task that can take from 1 to 5 working days, when executed manually.

In the next chapter, the process of validating the system will be

described. Although such process focused on testing the validity of the model of expertise, rather than on the overall performance of the system, some of conclusions attained are actually related to the way in which the system was implemented.

CHAPTER 8 - VALIDATION OF THE SYSTEM

8.1 Introduction

The third and final stage of development of the application consisted of the validation of the implemented system. The approach to validation adopted in this study is similar to the one used in the field of operational research, which is concerned with testing the agreement between the behaviour of the model and the real world system being modelled (Finlay & Wilson, 1987). In the particular case of knowledge based systems, validity can be defined as the degree at which the outcomes of the resulting system resembles the outcomes of the human expertise modelled in the knowledge base (Preece, 1989).

In more specific terms, the aims of the validation stage were: to check whether the system has reached a reasonable level of quality at the end of its development; to identify any necessary improvements in the system; and to make explicit gaps in the knowledge base, which could guide future knowledge acquisition exercises or research in the field of construction planning.

The importance of formally validating knowledge based systems is concerned with the scientific respectability of artificial intelligence. Many fields will not accept technological innovation without rigorous demonstration of the breadth and depth of the new products capabilities (Buchanan & Shortliffe, 1984; Green & Keyes, 1987).

Although much of effort has been devoted to the tasks of designing and constructing knowledge based systems, very little has been reported on the measurement of their performance (Ludvigsen et al., 1988). The techniques that have been used for validating knowledge based systems are usually "ad hoc", informal and of dubious value (O'Keefe et al., 1987).

Validation is frequently confused with verification. While validation is related to model correctness, software verification is a more specific concept, concerned with testing that a computer code fully and exclusively implements the requirements of a superior specification (Ortolano et al., 1990; Ludvigsen et al., 1988; Finlay et al., 1988; O'Keefe et al., 1987). Particularly in connection to

knowledge based systems, verification is also applied to testing that the knowledge base is logically sound and complete (Suwa et al., 1982; Preece, 1989).

Validation is one dimension of a much broader area named software evaluation, which is concerned with the process of assessing the overall quality of software products (O'Keefe et al., 1987; Ortolano et al., 1990). This research has focused on the validity of the model of expertise developed, rather on the evaluation of the global quality of the implemented system, because the primary objective of the study was not to develop a high performance commercial package. Another reason for emphasizing the issue of testing the validity of the system is the fact that validation is the corner-stone of the evaluation of computer systems: highly efficient implementations of invalid systems are useless (O'Keefe et al., 1987).

On the other hand, there have been indications that it is difficult to separate completely performance validation from the measurement of other quality characteristics (O'Keefe et al., 1987). For instance, testing the validity of a knowledge base is impossible if the system is unreliable, or if it does not have an adequate man-machine interface. For this reason, a preliminary investigation was made on the applicability of software quality models to the evaluation of the system, which is presented in Section 8.2.

In Section 8.3, the major problems found in the validation of knowledge based systems are discussed, and some of the techniques available are examined. Section 8.4 is devoted to reporting the validation procedures prescribed for this research and the results achieved.

8.2 Software quality models

Software quality is defined by Watts (1987) as the degree of compliance (or non-compliance) of a product with specified requirements. A number of quality models have been proposed, in which the global concept of quality is broken down into a variety of attributes or characteristics, such as: usability, security (or integrity), efficiency, correctness, reliability, maintainability, testability, flexibility, re-usability, portability, and interoperability (Watts, 1987).

A number of techniques have been proposed for measuring each of the quality characteristics mentioned above. These techniques are based either on subjective rating methods performed by experts, or on formulae which consider aspects of computer programmes that are possible to quantify, such as the number of lines of code, the average length of sentences and words displayed to the user, etc. The main limitation of such techniques is that most of their outcomes have not been actually proved to be correlated to the characteristics they are supposed to measure (Watts, 1987).

The measurement of the overall quality can be obtained by a weighted summation of the measures of individual attributes. Watts (1987) introduces six methods that can be used for getting such a global measure, in which the relative significance of each characteristic is subjectively established. The relative importance of each attribute varies according to the type of software. For example, usability is one of the characteristics that is likely to be highly rated for decision support systems.

Gillies (1990) pointed out some major shortcomings of current software quality measures, as follows: (i) there are several measures associated with maintainability and reliability, but other characteristics are not conveniently measured by any existing measures; (ii) the single 'figure of merit' used for measuring the overall quality is of limited practical value; and (iii) the range of characteristics is usually oriented towards system developers, rather than users.

Considering the relative character of the measurement involved in software quality models, it seems that their usefulness is restricted to comparing the performance of a number of alternative systems or comparing the performance of a single system to an acknowledged gold standard. Such procedures can only be effective if incorporated into a long term software quality control programme, usually carried out by organizations that systematically develop or use a wide range of software products.

In the particular case of knowledge based systems, there are a number of additional difficulties concerned with the measurement of software quality. Firstly, knowledge bases are usually built on the top of another software, a shell or a knowledge engineering

environment. Any attempt at measuring the quality of a knowledge based system would have to consider the combination of the knowledge base with the programming tool. Secondly, the approach of rapid prototyping, widely used for developing knowledge based systems, generally leads to a lack of precise specification which the system's performance can be compared to (Taylor, 1989). Finally, knowledge engineering is an emerging technology, which is under a very rapid pace of development. Most systems developed so far have not reached a stage of commercial tools, in which they would be able to contribute to a database of quality measurements.

For the reasons presented above, the application of the software quality models currently available was not considered feasible for this research project.

8.3 Difficulties in validating knowledge based systems

8.3.1 The nature of models of expertise

"The paradox of applying knowledge based systems is that we want them to do perfectly things that we don't really understand" (Hollnagel, 1989).

This quotation illustrates one of the major difficulties in the process of validating knowledge based systems: knowledge based systems may occasionally make mistakes (McDermot, 1981). While conventional programs are designed to produce a supposedly correct answer every time, knowledge based systems are designed to a certain extent to behave like human experts, usually producing correct answers, but sometimes producing incorrect ones (Waterman, 1986).

Besides that, there are a number of important practical issues involved in devising the validation process. They are summarized in the following sections.

8.3.2 Validation criteria

Validation may involve several different criteria, such as the correctness and accuracy of the final results, the correctness of the internal reasoning, model sensitivity, model robustness, time savings, cost effectiveness (Hollnagel, 1989). Each one of the different parties involved in the development of a knowledge based system (i.e.

client, developer, expert, and users) probably disagree about the relative significance of the various criteria (Gaschnig et al., 1983).

Gaschnig et al. (1983) stated that the larger the number of distinct criteria included in the validation process, the more information would be available on which to base an overall validation. O'Keefe et al. (1987) highlighted the importance of validating the internal reasoning of knowledge based systems, even when a knowledge based system is apparently giving accurate results. They stated that neglecting the validation of the internal reasoning may lead to a lack of robustness, specially when the knowledge base has to be frequently updated or expanded.

8.3.1.3 Gold standard

Validation requires an objective standard of excellence, i.e. a generally accepted correct answer to which the system's conclusions can be compared (Buchanan & Shortliffe, 1984). This "gold standard" can be human expert performance or data from the real world. In some fields, the only gold standard available is the human expert performance, because the cost of obtaining data from the real world is very high (Weiss & Kulikowski, 1984). In such cases it may be difficult to know how the system performs in relation to the real world, since there might not be an adequate measure of the quality of human expertise (Berry & Broadbent, 1987).

The standards of performance should be defined realistically (Gaschnig et al., 1983). It is not fair to expect a knowledge based system to have a very high performance if it encapsulates the knowledge of human experts who are imperfect in their understanding.

8.3.4 Test cases

Since it is very unlikely that a set of test cases available can cover all possible combinations of inputs in most real complex problems, it is necessary to ensure that the test cases used are representative of the situations that may possibly occur (Hollnagel, 1989). The main issue is not the number of test cases, but their coverage, i.e. how well they reflect the input domain (O'Keefe et al., 1987). Ortolano et al. (1990) suggested to use both routine and difficult cases: the latter serve to 'push' the knowledge based system

in order to learn its limitations.

If not enough historic cases are available for the validation, it may be possible to use a number of hypothetical test cases created by experts. The main limitation of using hypothetical cases is that they might not represent a well-stratified sample of possible cases, and the experts are unlikely to spend as much time and effort on them as on real problems (O'Keefe et al., 1987).

8.3.5 When to validate

Validation is an intrinsic part of the process of developing a knowledge based system (Buchanan & Shortliffe, 1984). The validation process should be continuous, beginning with system design, extending in an informal way through the early stages of development, and becoming increasingly formal as the system begins to achieve a real-world implementation (Gaschnig et al., 1983).

Most knowledge based systems never reach a state of static completion, since human expertise generally grows and changes continuously (Welbank, 1983). For this reason, such systems should also have their validity periodically tested while they are being used in the field.

Some validation criteria are more appropriate than others at a particular stage of the validation process (Buchanan & Shortliffe, 1984). Validating the internal reasoning should start early in the development process, while validation of the final advice is more adequate to later stages of development (O'Keefe et al., 1987).

8.3.6 Cost of validation

Developing a system is a process of negotiation and compromise, in which the final product is one that is feasible, given a number of practical constraints, rather than an ideal one (Hart, 1990). Validation may be time consuming and expensive. For instance, the validation process involved in the development of the knowledge based systems MYCIN and R1 required over a year (Gaschnig et al., 1983), and approximately thirty per cent of the total effort needed for developing the knowledge based system DEMOTOX was devoted to formal evaluation (Ludvigsen et al., 1988).

It is difficult to establish exactly when to stop validating a

system. The value of validation depends on the value of the system to its users and on the risk involved in using a poor validated system (O'Keefe et al., 1987).

8.3.7 Control of bias

There are two main types of bias. The first one relates to the experts involved in validation who might have bias against (or for) results produced by computer programmes. Such bias can be controlled by using blinded validation, in which the experts are not able to distinguish which results were produced by the computer and which ones were produced by human experts.

The other kind of bias relates to the difficulties that the development team (developers and experts) might have in validating their own system, once they are very much involved in the project. This problem can be minimized by having an independent team for the validation stage.

8.3.8 Complex results

Even when an adequate gold standard is available, validating a knowledge based system might not be easy if its results cannot be easily classified as absolutely correct or absolutely incorrect.

If a system produces a piece of text from the concatenation of several statements as a conclusion, it may be difficult to break that text in a number of firm endpoints that can be compared to a gold standard (Weiss & Kulikowski, 1984). In such cases, it may be necessary to use a range of acceptance measures (e.g. ideal, highly acceptable, acceptable, unacceptable, etc.), rather than simply reducing the analysis to a binary decision (e.g. correct, or incorrect). Weiss & Kulikowski (1984) stressed that validating complex results usually demands some kind of subjective validation, such as showing external experts the system's results and asking whether they agree with the conclusions.

8.3.9 Disagreement between experts

The difficulties of coping with disagreements between experts in the knowledge acquisition process have already been discussed in Chapter 5. This problem obviously also affects the validation process,

since different experts may disagree about the validity of a particular piece of knowledge encapsulated in the system.

8.4 Techniques currently used

Validation can range from formal to informal. Informal validation is a long-term feedback process which cycles between knowledge engineers, domain experts, and users, beginning at project initiation and extending throughout software development (Ludvigsen et al., 1988). Formal evaluation, on the other hand, usually begins once a prototype has been developed, focusing on testing design objectives and identifying system improvements via a structured approach (Ludvigsen et al., 1988).

Validation methods can be either qualitative or quantitative. Qualitative validation employs subjective comparisons of performance, while quantitative validation employs statistical techniques to compare knowledge based system performance to a gold standard (O'Keefe et al., 1987).

Qualitative validation does not mean informal validation. It is possible to develop a highly formal qualitative validation. O'Keefe et al. (1987) and Hollnagel (1989) described some commonly used qualitative validation techniques:

(i) Face validation: the system performance is subjectively compared to the human experts' by the developers, users, or people knowledgeable about the application domain. The results obtained from a knowledge based system are compared to a prescribed acceptable performance range, for a given set of test cases. Its main disadvantage is that it requires availability of time from human experts.

(ii) Predictive validation: the system is used in some historical cases and its results are compared to corresponding results - either known results or those obtained from human experts. It needs a number of representative historical cases.

(iii) Field tests: a prototypical knowledge based system is placed in the field and performance errors are corrected as they occur. This technique cannot be used in critical applications, where the cost of imperfect answers is very high, or where lives are at risk (O'Keefe et

al., 1987). It is recommended for the later stages of validation, when the system has already reached a reasonable standard of performance (Buchanan & Shortliffe, 1984). One of the main advantage of field tests is that they place the burden of testing upon users (O'Keefe et al., 1987).

(iv) Sensitivity analysis: the knowledge based system's inputs are changed over some range of interest and the effect upon system performance is observed. It is especially useful when few or no test cases are available. Also, it is highly appropriate for systems that use uncertainty measures, since these can be altered and the effect on intermediate or final results can be examined. This approach was adopted for validating the knowledge based system for the selection of contract strategy of construction projects developed by Sodipo (1987).

(v) Visual interaction: a visual animation of the knowledge based system task which allows human experts to interact, altering parameters as desired, is provided. In essence, it is simply an environment for other validation methods.

(vi) Sub-system validation: the system is decomposed into sub-systems, which are individually validated using some of the methods above. This technique usually makes validation easier, since sub-systems are less complex and more manageable than the whole system, making error detection less time-consuming. Also, sub-system validation can be carried out along the several stages of development, before the whole system is completed. Its main limitation is that a successful validation of sub-systems does not necessarily imply that the whole system is validated.

(vii) Static validation: the set of rules that make up the knowledge base are simply checked by experts. The main limitation of this approach is that it assumes the rules are stable, and that the inference engine works correctly. It is feasible for only relatively small rulesets, since the number of alternative paths grows exponentially with the number of rules (Hollnagel, 1989).

(viii) Robustness tests: the robustness of the knowledge base can be tested by using a number of hypothetical test cases that reflect extreme conditions which the system may be submitted to.

Very few systems have been submitted to a complete formal

validation so far (O'Keefe et al., 1987). The most common approach has been to show a system to experts and to ask them if they agree with the conclusions for a number of test cases (Gaschnig et al., 1983). Very little has been reported on the validation of knowledge based systems in the construction field, probably because only few of them have reached an operational stage. From the knowledge based systems for construction planning described in the Section 2.3, only Elsie, CONSAS and Mason have had their validation process reported.

8.5 Validation of the implemented system

8.5.1 Practical constraints

Considering that there is still no widely accepted, reliable methods for conducting validation studies (O'Keefe et al., 1987; Green & Keyes, 1987; Ortolano et al., 1990), a prescriptive method was devised for validating the present system. The proposed method involved some degree of pragmatism, since there were practical constraints concerned with the objectives and limitations of this particular research project, as well as with the nature of the construction planning process.

One of the main constraints related to the construction planning process was the difficulty of obtaining a single gold standard which could be compared to the advice given by the system. Due to the complexity and the uncertainty involved in the construction process, it is very difficult, or even impossible to find a unique best solution for the planning problem. The optimisation approach, used in other engineering fields, is largely ineffective in the construction practice (Levitt, 1986). Generally, construction planners search for a feasible arrangement of actions for the production stage of a project, rather than an optimum one (Laufer & Tucker, 1987).

Considering that there is an infinite number of feasible arrangement of actions for any real construction project, it is very unlikely that the construction plans generated by different human experts for the same project can be identical. For the same reason, it is not fair to expect that a plan generated by a knowledge based system that encapsulates the expertise from a number of practitioners should be identical to any chosen gold standard.

Another important difficulty related to the planning task is the

fact that construction planning is a multi-response problem (O'Keefe et al., 1987). There are a large number of variables that make up a construction plan, such as activity durations, activity precedences, stage buffers, building rates, milestones, gang sizes, etc. The process of validating knowledge based systems for construction planning must consider not only the validity of each individual variable, but also the validity of the resulting plans as a whole.

The main constraints related to this particular research are summarized as follows:

(i) The author had a limited amount of time for carrying out the validation process;

(ii) The experts in construction planning could devote only a limited amount of time to the research, due to the normal pressures of a commercial environment. They did not have time, for instance, to create and analyse a large set of hypothetical test cases;

(iii) The number of real projects which could be used as test cases was not very large, undermining the possibility of using quantitative techniques;

(iv) The information available about each historical case did not include data about the way in which the construction process really happened on site. Thus, it was not feasible to validate the system's performance against data from the real world;

(v) None of the historical cases available had been planned by more than one of the experts involved in the study. Consequently, no evidence could be provided about how different are the strategies followed by different experts when planning the same project; and

(vi) None of the experts contacted was considered to have a significant higher level of expertise than the others. For that reason, it was not possible to build a panel of third-party expert evaluators able to judge the performance of the other experts and the system's.

8.5.2 General view of the validation process

The approach adopted in this research aimed at performing validation as formal, as unbiased, and as exhaustive as possible. For

that reason, the validation process consisted of a combination of as many techniques as possible, involving not only experts that had provided the expertise for the system, but also some external experts.

The role of the experts in the validation process was restricted to analysing the main aspects of the system. Most of the detailed work was carried out by the author, in order to make an efficient use of the experts' time.

From the eight validation techniques described in Section 8.4, only visual interaction could not be used in this research, because the man-machine interface facilities available in Leonardo are limited in this respect. The more formal techniques focused on those aspects of construction plans that are possible to quantify, while the less formal ones concentrated on more subjective matters.

The techniques of sub-system validation and static validation have already been mentioned in Chapter 5. They were carried out during the second stage of the system's development, and their role consisted of providing a short term feedback to the knowledge acquisition process.

The remaining techniques were applied during the validation stage itself, i.e. as soon as the first full version of the system was finished. A detailed description of each technique and the main results accomplished will be presented in Section 8.5.3.

The presence of several rules-of-thumb in the knowledge base, and the fact that some disagreement was found among experts indicate that a fine-tuning of the system will be periodically needed during its working life, especially before it is used in a new context. However, the development of a formal method for validating the system while it is being used in the field is outside the scope of the research, because of the limited time available for this research.

There is no evidence that the method of validation devised for this particular application can be applied in the development of other systems. However, it can be expected that some of the lessons learnt in the validation of the system will contribute towards the development of more general methods for validating knowledge based systems in the field of construction planning, since several of the difficulties faced along this study are likely to be found in other similar studies. O'Keefe et al. (1987) and Green & Keyes (1987) pointed out that widely accepted methods for validating knowledge

based systems will evolve only in the light of future collective experience, and critical appraisal of that experience.

8.5.3 Predictive validation

8.5.3.1 General description

This technique consisted of comparing, in a very detailed way, construction plans generated by the experts who provided the expertise to the system to the ones suggested by the system for the same projects. This analysis was mostly carried out by the author. Only major inconsistencies were taken to further discussion with the panel of experts.

Fifteen historical cases were employed, all of them selected amongst the twenty three projects that were available during the knowledge acquisition process. These fifteen projects were chosen because the information available about their design and site conditions was enough for carrying out a meaningful analysis, and also because they corresponded to a fair variety of project types. Their descriptions are summarized in Table 8.1.

FIRM	PROJ. No.	TOTAL HOUSES	DET. HOUSES			S.DET.HOUS.			TER. HOUSES			FLATS	TOTAL BLOCKS
			1f1	2f1	3f1	1f1	2f1	3f1	1f1	2f1	3f1		
A	1	51	1			2			1	48			10
A	2	55							6	48			15
A	3	76				20	56						38
A	4	134				12	122						67
A	5	48				24	24						24
B	6	48				10	38						24
B	7	39					2		9	28			9
B	8	44		3			10		4	27			22
B	9	25		3			10		2	10			13
C	10	50					50						25
C	11	145				2	14		39	90			48
C	12	101					18			65	18		28
D	13	65								19		46	9
D	14	49								49			7
E	15	75					2			43		30	13

Table 8.1: Summarized description of test cases

Appendix 6 lists the variables from the construction plans, which were selected for performing predictive validation. It was necessary to consider approximately seventy variables, so that the reasons behind any discrepancies between the system's and the experts' plans could be traced down. Not all variables could be considered in every historical case, because some of the plans available were not very detailed: the less detailed was the construction plan generated by the experts, the smaller was the set of variables considered.

Considering that there is an infinite number of feasible alternative plans for each construction project, predictive validation did not concentrate in the accuracy of the system's plans in relation to the experts'. Instead, it focused on checking whether the approach followed by the system was acceptable from the point of view of the experts, and whether the system provided the necessary facilities to work as a decision support system, during the planning task.

As shown in Appendix 6, the variables were grouped into six main headings, according to the aspect of the plan that they were mostly related to. These are: (i) total project duration; (ii) activity content; (iii) house completion time; (iv) pace of work; (v) activity dependencies; and (vi) durations of bar chart activities. The main conclusions extracted from each item will be presented in the following sections of this chapter.

The data available about each project during the validation process did not necessarily corresponded to the job description employed by the experts when the planning task was actually carried out: unfortunately, some of this information was not kept in the records of the company. Consequently, the default data encapsulated in the system had also to be employed for replenishing any information concerned with the project description that had been lost.

8.5.3.2 Total project duration

The total duration established in the experts' plans for each project was initially compared to the duration that resulted from the pace of work proposed by the system. As discussed in Section 7.6.3, such pace of work can be regarded as the natural rhythm that the system suggests for each particular project.

A comparison between the duration chosen by the experts and the natural duration proposed by the system is presented in Table 8.2. The system's durations were on average 14.90% longer than the experts'. However, this comparison has a fairly limited significance, since, as previously discussed in Section 4.5.2, the total duration chosen for a project is usually established at a more strategic level of decision. In other words, the resulting total duration of a project may not correspond to what construction planners consider to be the natural pace of work, but instead, the experts may have to adjust their plans to a pre-established duration.

For that reason, the validation of the model in this particular respect focused on examining whether the system provides suitable facilities for quickly adapting a plan to required duration. Such investigation was performed by attempting to adjust each of the plans suggested by the system to the duration established in the corresponding expert's plan.

The adjusted plans were generated by cycling through the Build module a few times. Table 8.2 also presents the project duration established in the adjusted plans (column 5), and the changes that had to be made in order to achieve such duration (column 6). All the comparisons performed in predictive validation were based on these adjusted plans.

In four cases, the plan was adapted to the required duration by simply changing one of the building rates proposed by the system. When that was not possible, the required duration had to be achieved by changing the value of some variables from the job description, such as the availability of management, and the availability of bricklayers. Both variables can have their values altered through a "what if" type of question. Only the project No. 10 could not have its duration reduced through the Build module, because the leading resource was the plastering trade, and the number of plasterers was already at its maximum level. Such limit can only be altered through the Context module.

Further discussions with the experts indicated that they find necessary the system to have facilities for quickly adapting a construction plan to a wider range of durations, even if it demands to temporarily change some of the assumptions which the plan generation was based on.

PROJ. No. (1)	EXPERT'S DURATION (2)	SYSTEM'S DURATION (3)	DIF. % (4)	SYSTEM'S ADJUSTED DUR. (5)	CHANGES MADE IN THE PLAN FOR ADJUSTING IT TO THE EXPERTS' DURATION (6)
1	78	78	0.00		
2	55	76	38.18	56	availab. of bricklayers & management increased to very high
3	57	77	35.09	59	availab. of bricklayers & management increased to very high
4	74	99	33.78	81	availab. of bricklayers & management increased to very high
5	40	60	50.00	47	availab. of bricklayers & management increased to very high
6	50	55	10.00	53	availab. of bricklayers & management increased to high
7	52	60	15.38	51	availab. of bricklayers increased to high
8	52	58	11.54	51	availab. of bricklayers & management increased to high
9	52	50	-3.85		
10	50	56	12.00		
11	113	123	8.85	108	finishing rate increased
12	111	102	-8.11	107	shell stage slowed down
13	58	55	-5.17	59	shell stage slowed down
14	50	65	30.00	55	availab. of bricklayers & management increased to very high
15	72	69	-4.17	73	shell stage slowed down

AVERAGE= 14.90
CV = 1.12

NOTE: all durations are expressed in number of weeks.

Table 8.2: Comparison of total durations

It seems that the most effective way to improve the flexibility of the system in this particular respect is to increase the number of items that can be altered through "what if" questions. The main advantages of using such facilities are: they can be quickly accessed by the experts at the end of each cycle in the Build module; and the value of each item is only altered in a temporary basis. In future upgrades of the system, all variables and parameters used by the system which have a significant influence in the total duration should be adjustable by "what if" questions, including those that currently can only be updated through the Context module.

8.5.3.3 Activity content

Table 8.3 compares the number of construction activities from the plans generated through the system, with the number of items from the plans manually produced by the experts. It can be observed that the work breakdown of the system's plans tends to be more detailed than the experts'.

In five historical cases (Nos. 5, 10, 11, 12, and 15), the plans produced by the experts were segmented into a small number of major stages of work, much more aggregated than the construction activities used in the system's plans. For this reason, such cases were not used in the comparison of activity content.

PROJ. No. (1)	No. OF ACTIVITIES	
	EXPERTS' (2)	SYSTEM'S (3)
1	69	80
2	69	75
3	65	77
4	70	77
5	11	78
6	63	77
7	61	80
8	49	77
9	48	67
10	19	74
11	11	74
12	10	70
13	44	73
14	44	73
15	8	75
MIN	8	67
MAX	70	80
AVER.	42.73	75.13
CV	55.01	4.53

Table 8.4: Comparison of No. of activities

Tables 8.4 and 8.5, respectively, list the names of the activities that were included in the system's plans but not in the experts', and of the activities that were found in the experts' plans but not in the system's. The main reasons behind such differences are summarized below.

Most differences in activity content were concerned with level of detail of the plans. Often, the same construction tasks that were represented in the system's plans by a group of activities, were expressed in the experts' plans by a single item. The inverse situation also was found, although more rarely.

As the activities employed in the system's plans were selected from a library of activities, such plans generally had a more consistent activity content than the plans produced by the experts. For instance, the experts admitted that their plans had a number of unintended omissions, such as the absence of the activities ducts/gullies, service entries, gas meter, electric meter (see Table 8.4). Moreover, some of the experts used distinct criteria for breaking down virtually the same job in different projects. The expert from Company A, for example, segmented the construction of walls into five phases in two plans, but into only two phases in the other two cases, although no radical difference existed in the design of the walls, or in the way in which such work was going to be executed.

Differences in the activity content were also caused by distinct forms of dividing the work between trades. For instance, some experts employed a particular activity, named "builders' work" for representing the preparatory work necessary before starting the hydraulic and electrical installations, because they assumed that such work was to be executed separately by a gang of specialist subcontractors. On the other hand, the system assumed that such work was performed by the plumbing and electricity trades. Similar circumstances justify the inclusion of a number of other activities in the experts' plans, such as paramount partitions, and kitchen units.

PROJ. No.	ACTIVITY NAME
1	- Brickwork 2nd lift, brickwork 4th lift, brickwork to peaks, floor screed, permanent kerbs.
2	- Brickwork 2nd lift, brickwork 4th lift, brickwork to peaks, floor screed, permanent kerbs.
3	- External openings, heating 1st & 2nd fix, floor screed, permanent kerbs.
4	- Ducts/gullies, service entries, external openings, floor screed, permanent kerbs.
6	- Ducts/gullies, service entries, electric meter, gas meter.
7	- Service entries, porch joinery, porch roof tiling.
8	- External openings, glazing, porch joinery, porch roof tiling, gas meter, electric meter, plumbing testing, joinery final fix, loft insulation.
9	- External openings, porch wall, porch joinery, porch roof tiling, gas meter, electric meter, plumbing testing, joinery final fix, loft insulation.
13	- Brickwork 2nd lift, brickwork 4th lift, external openings, floor screed, gas meter, electric meter, permanent kerbs
14	- Brickwork 2nd lift, brickwork 4th lift, external openings, floor screed, gas meter, electric meter, permanent kerbs

Table 8.4: Activities included in the system's plans but not in the experts'

PROJ. No.	ACTIVITY NAME
1	- Paramount partitions, electric & gas cupboard, permanent external doors, kitchen units.
2	- Prep. for vibro-compaction, paramount partitions, electric & gas cupboard, permanent external doors, kitchen units.
3	- Paramount partitions, kitchen units.
4	- Paramount partitions, prepare for electr./gas meters, permanent external doors, kitchen units.
6	- Joiner bay windows, Joiner skirts & archs., vehicular drives.
7	- Joiner skirts & archs., kitchen units, pre-paint snags
8	- Builders' work.
9	- Builders' work.
13	- Builders' work, floor boards & ceiling noggins, ceiling plasterboard, pergolas trellis & seats
14	- Remove existing kerbs, builders' work, floor boards & ceiling noggins, ceiling plasterboard, pergolas trellis & seats.

Table 8.5: Activities included in the experts' plans but not in the system's

A few omissions were also found in the plans generated through the system, usually involving activities from the site preparation and landscape stages (e.g. "pergolas trellis & seats", "vehicular drives"). The main difficulty related to these two stages of work is that their activities tend to be much less recurrent than the ones directly related to the construction of houses. It is very difficult to establish a priori all possible alternative activities, since the construction work involved has a very close relationship with the uniqueness of the site conditions. This problem could be circumvented by providing the system with a facility for incorporating any activity defined by the user in the schedule of activities from those two stages of work.

8.5.3.4 House completion time

Table 8.6 shows the house completion time, and the lead-lag times between the project milestones from both the system's and the experts' plans, for each of the historical cases. It can be observed that the house completion times proposed by the system are generally shorter than the ones established by the experts.

An investigation was made on the lead-lag times between activities, in order to check whether there was any remarkable inconsistency between the approach adopted by the experts and the system's. Table 8.7 lists the activity lead-lag times which had distinct values in the experts' and in the system's plans. This table shows that, although there were many dissimilarities, none of them appeared in the majority of projects.

The experts explained such discrepancies by the fact that the nature of the construction process allows overlapping extents and floats between activities to vary a lot, even in similar projects carried out by the same company. In their opinion, the system lacks flexibility in terms of coping with different degrees of overlapping between activities.

PROJ. No. (1)	FOUND. STAGE			SHELL STAGE			1ST FIX STAGE			2ND FIX STAGE			HOUSE COMP. TIME		
	EXP. (2)	SYS. (3)	DIF.% (4)	EXP. (5)	SYS. (6)	DIF.% (7)	EXP. (8)	SYS. (9)	DIF.% (10)	EXP. (11)	SYS. (12)	DIF.% (13)	EXP. (14)	SYS. (15)	DIF.% (16)
1	5	6	20	7	11	57	4	9	125	12	14	17	28	40	30
2	8	5	-38	6	10	67	4	7	75	8	13	63	26	35	26
3	5	6	20	8	10	25	6	7	17	14	11	-21	33	34	3
4	3	6	100	8	10	25	5	8	60	14	12	-14	30	36	17
5	3	5	67	9	10	11	5	6	20	10	11	10	27	32	16
6	4	5	25	12	10	-17	8	6	-25	11	11	0	35	32	-9
7	3	5	67	8	10	25	3	6	100	10	11	10	24	32	25
8	5	5	0	5	10	100	6	6	0	12	11	-8	28	32	13
9	4	4	0	6	10	67	9	6	-33	13	12	-8	32	32	0
10	5	5	0	6	9	50	4	7	75	6	10	67	21	31	32
11	7	7	0	13	11	-15	4	7	75	5	11	120	29	36	19
12	5	7	40	6	15	150	5	7	40	8	11	38	24	40	40
13	3	5	67	11	10	-9	6	7	17	11	12	9	31	34	9
14	3	5	67	11	10	-9	7	6	-14	9	11	22	30	32	6
15	4	6	50	6	11	83	4	7	75	7	12	71	21	36	42
MIN	3	4	-38	5	9	-17	3	6	-33	5	10	-21	21	31	-9
MAX	8	7	100	13	15	150	9	9	125	14	14	120	35	40	42
AVER.	4.5	5.5	32.3	8.1	10	40.6	5.3	6.8	40.4	10	12	25.0	28	34	17.8
CV	33	15		30	13		30	12		27	8		14	8	

NOTE: all durations are expressed in terms of number of weeks.

Table 8.6: Comparison of house completion times

PROJ. No.	PRECEDING ACTIVITY	SUCCEEDING ACTIVITY	SYSTEM'S L.L.TIME	EXPERTS' L.L.TIME
1	Service entries	House drainage	1	2
	SVP gutters & RWP	Roof tiling	0	1
	Strip scaffold	External openings	1	0
	External openings	Glazing	1	0
	Joinery 2nd fix	Plumbing 2nd fix	0	1
	Plumbing 2nd fix	Electric. 2nd fix	1	0
	2	Concrete footings	Brickwork to DPC	1
Service entries		House drainage	1	2
Roof carcass		SVP gutters & RWP	1	0
SVP gutters & RWP		Roof tiling	0	1
Strip scaffold		External openings	1	0
External openings		Glazing	1	0
Plumbing 2nd fix		Electric. 2nd fix	1	0
Floor tiling		Ironmongery	1	0
Artex on ceilings		Joinery final fix	1	0
Artex on ceilings		Wall tiling	1	0
3	Service entries	Concrete slab	1	0
	Brickwork to peaks	Roof carcass	0	1
	SVP gutters & RWP	Tile roof	0	1
	Joinery 2nd fix	Plumbing 2nd fix	0	1
	Loft insulation	Artex on ceilings	1	2
	Floor tiling	Ironmongery	1	0
	4	Brickwork to peaks	Roof carcass	0
Tile roof		Strip scaffold	0	1
Plumbing 1st fix		Electric. 1st fix	1	2
Joinery 2nd fix		Plumbing 2nd fix	0	2
6		Concrete footings	Brickwork to DPC	1
	Joinery 2nd fix	Plumbing 2nd fix	0	1
	7	Set up site	Site shaping	0
Joinery 2nd fix		Plumbing 2nd fix	0	2
Internal painting		External painting	1	2
8	Plumbing 2nd fix	Heating 2nd fix	0	2
	House footpath	Fencing	0	1
9	Plumbing 2nd fix	Heating 2nd fix	0	2
	House footpath	Fencing	0	1
10	Roof carcass	SVP gutters & RWP	1	2
13	SVP gutters & RWP	Roof tiling	0	1
	Joinery 2nd fix	Plumbing 2nd fix	0	1
14	SVP gutters & RWP	Roof tiling	0	1
	Joinery 2nd fix	Plumbing 2nd fix	0	1

Table 8.7: Comparison of activity lead-lag times

Two main suggestions for improving the system resulted from further discussions with the experts. Firstly, the system should have a facility which allows the user to decide whether the site management will give priority to the quick conclusion of the first house, or to keep a high rate of progress for all activities. In the first case, the system would increase the extent to which some activities are overlapped, and, at the same time, slow down the pace of work.

The second suggestion is concerned with the confirm/overwrite points which exist while the system is generating the plan. In the experts' opinion, the user should be allowed not only to introduce buffers between stages of work in such points, but also to overlap them, in case he/she finds necessary.

8.4.3.5 Pace of work

In Table 8.8, a comparison is made between the average building rates employed by planners and the ones suggested by the system for the foundation, shell/roofing, and finishing stages. The rates used by the system had to be higher than the experts' in most cases because of the longer house completion times adopted by the system.

In the plans generated by the system, the average foundation rate is consistently higher than the average shell rate, and the average shell rate is higher than the average finishing rate in most cases. This approach was recommended by the experts in the knowledge acquisition process, as reported in Chapter 6.

On the other hand, only six of the plans produced by the experts have an average foundation rate higher than the average shell rate, and nine of them have a finishing rate lower than the average shell rate.

PROJ. No. (1)	FOUNDATION RATE		SHELL RATE		FINISHING RATE		FOUND/SHELL RATIO		SHELL/FIN. RATIO	
	EXPERT'S (2)	SYSTEM'S (3)	EXPERT'S (4)	SYSTEM'S (5)	EXPERT'S (6)	SYSTEM'S (7)	EXPERT'S (8)	SYSTEM'S (9)	EXPERT'S (10)	SYSTEM'S (11)
1	1.21	1.88	1.21	1.82	1.21	1.46	1.00	1.03	1.00	1.25
2	2.39	3.23	2.39	3.06	2.39	3.06	1.00	1.06	1.00	1.00
3	5.06	4.22	5.06	4.22	5.06	3.61	1.00	1.00	1.00	1.17
4	3.94	4.19	3.72	4.06	3.35	3.35	1.06	1.03	1.11	1.21
5	4.00	4.36	4.00	4.00	4.00	3.69	1.00	1.09	1.00	1.08
6	3.69	4.00	3.20	3.42	3.20	2.82	1.15	1.17	1.00	1.21
7	3.90	3.25	2.05	3.00	2.05	2.60	1.90	1.08	1.00	1.15
8	4.40	3.67	2.93	3.14	2.44	2.93	1.50	1.17	1.20	1.07
9	4.17	3.57	1.78	1.92	1.56	1.78	2.34	1.86	1.14	1.08
10	2.00	2.94	2.00	2.78	2.00	2.38	1.00	1.06	1.00	1.17
11	2.50	2.84	1.88	2.16	1.88	2.16	1.33	1.31	1.00	1.00
12	1.60	2.06	1.46	1.98	1.32	1.68	1.10	1.04	1.11	1.18
13	5.25	3.82	3.00	2.62	1.82	1.91	1.75	1.46	1.65	1.37
14	5.44	3.50	3.06	2.88	2.88	2.58	1.78	1.22	1.06	1.12
15	1.57	2.40	1.57	2.31	1.57	1.94	1.00	1.04	1.00	1.19
MIN	1.21	1.88	1.21	1.82	1.21	1.46	1.00	1.00	1.00	1.00
MAX	5.44	4.36	5.06	4.22	5.06	3.69	2.34	1.86	1.65	1.37
AVER.	3.41	3.33	2.62	2.89	2.45	2.53	1.33	1.17	1.08	1.15
CV	40.16	22.58	39.77	26.22	42.49	27.08	31.20	18.67	15.07	8.13

NOTE: all rates are expressed in terms of number of houses per week.

Table 8.8: Comparison of average building rates

Further discussions with the experts revealed that the main reason for this inconsistency is the fact that the experts often have to generate very simplified plans, because of the limited time available for performing the planning task. They admit that sometimes a single pace of work is established for the whole project, based only on the lowest building rate - usually the finishing rate. In such cases, the other stages of work are represented as if they followed the same pace. In this respect, the system introduces an improvement in the planning process, since it enables planners to generate construction plans which are more consistent with the strategies that they assume to be correct, in a much shorter time.

Another important aspect related to the pace of work that can be observed in Table 8.8 is the wide range of ratios between the foundation activity duration (i.e. total duration of foundation activities) and shell activity duration, and between shell activity duration and finishing activity duration. These large variations contrast with the fixed relationships between peak rates recommended by the experts during the knowledge acquisition process. Such discrepancy can be explained by the fact that the knowledge used by the experts for establishing ratios between building rates was not investigated to a very deep level, for the reasons explained in Section 6.6.6.

PROJ. No. (1)	EXPERT'S PEAK RATE			PEAK RATIO			ACC/DEC.PERIOD RATIO		
	FOUND. (2)	SHELL (3)	FINIS. (4)	FOUND. (5)	SHELL (6)	FINIS. (7)	FOUND. (8)	SHELL (9)	FINIS. (10)
1	2	2	2	1.64	1.64	1.64	0.94	0.94	0.94
2	6	6	6	1.18	1.18	1.18	*	*	*
3	3	3	3	1.25	1.25	1.25	1.00	1.80	3.60
4	5	4	4	1.26	1.47	1.19	1.00	1.00	0.78
5	4	4	4	1.00	1.00	1.00	*	1.00	1.00
6	4	3	3	1.08	0.94	0.94	*	*	*
10	2	2	2	1.00	1.00	1.00	*	*	*

NOTES: Only seven of the experts' plans indicated the building rates. In projects Nos.2 and 10 the building rates were constant. (*) indicates that there is no acceleration or/and deceleration period. All rates are expressed in number of houses per week.

Table 8.9: Rate profiles adopted by the experts

Table 8.9 presents some information about the building rate profiles adopted by the experts in the test cases. It can be observed that eight of the plans produced by the experts do not make explicit the way in which each stage of work would accelerate and decelerate. Moreover, from the plans that make explicit the rate profile, two have all the peak ratios equal to one, which can be taken as a simplification. In this particular respect, the plans generated through the system generally offer more information than the ones produced by the experts.

8.5.3.6 Activity dependencies

A comparison was made between the activity dependencies established by the system and the ones employed by the experts. This comparison made explicit a number of alternative sequences of work for certain groups of construction tasks. The reasons behind such variations have already been discussed in Section 6.7.

Table 8.10 presents the variations in the activity dependencies that were most frequently found in the historical cases. Such conflicts were further discussed with the experts, leading to a thorough review of the rules from the knowledge base concerned with activity dependencies.

8.5.3.7 Durations of bar chart activities

Table 8.11 compares the durations of bar chart activities established by the system to the ones estimated by the experts. It can be observed that they diverge a lot: the average difference between such durations, expressed as a percentage of the experts' duration, ranged from -117% to 174%.

In some cases, the disparity between the estimated durations can be explained by the fact that a different classification of activity types was adopted by the system and by the experts. For instance, some of the bar chart activities were defined as continuous in the system, but as stretched by some of the experts (e.g. permanent kerbs); while others were assumed to be stretched activities in the system, but as continuous in a number of experts' plans (e.g. public footpath, service mains, base course, wearing course).

ACTIVITY NAME	ALTERNATIVE ACTIVITY DEPENDENCIES	LINK TYPE
House drainage	Service entries Floor screed	start-start start-start
SVP gutters & RWP	Roof carcass Tile roof	start-start parallel
Tile roof	SVP gutters & RWP Roof carcass	parallel start-start
Glazing	External openings Electric. 1st fix Skim coat Floor screed Joinery 2nd fix	start-start start-start start-start start-start start-start
Joinery 1st fix	Glazing Plumbing 2nd fix	end-start start-start
Plumbing 1st fix	Joinery 1st fix Glazing Electric. 1st fix	start-start end-start start-start
Electric. 1st fix	Plumbing 1st fix Joinery 1st fix Glazing	start-start start-start start-start
Floor screed	Skim coat Joinery 2nd fix Tile roof	end-start end-start end-start
Joinery 2nd fix	Floor screed Plumbing 2nd fix Electric. 2nd fix	end-start start-start start-start
Plumbing 2nd fix	Joinery 2nd fix Floor screed	start-start
Electric. 2nd fix	Plumbing 2nd fix Joinery 2nd fix	start-start start-start
Porch roof *	Floor screed Loft insulation Roof carcass External rendering	end-start start-start parallel end-end
Permanent kerbs	Wearing course Kerb race	end-end start-start
External painting	Internal painting Internal painting Strip scaffold	start-start end-end end-end

NOTE: "porch roof" represents the first activity related to the construction of the porch, e.g. porch brickwork, porch joinery.

Table 8.10: Main conflicts in the activity dependencies

Another factor that may have contributed to the dispersion between the experts' and the system's durations is the fact that the method of estimating durations adopted by the system is relatively simplified, for the reasons explained in Section 6.6.8. Additionally, the quantities of work related to several bar-chart activities were unavailable when the plans were generated through the system. Such quantities had to be roughly estimated by using the system's default data, which might have contributed to lower the system's accuracy.

The low accuracy of bar chart activity durations does not greatly affect the quality of the plan, because they have very little influence in the main variables of the construction plan, such as total duration of the project, the house completion time, or the pace of work. However, the improvement of the system in this particular respect is advisable for its future upgrades, especially if there is intention of increasing the level of detail of the plans produced.

8.5.4 Robustness tests

Performing robustness tests consisted of using the system for generating plans for a number of unusual job descriptions. The aim was to check whether the system was able give a meaningful response or degrade gracefully, in case the job to be carried out had some extreme conditions. Such tests were performed by the author.

A battery of test cases was created, each one focusing on testing a particular aspect of the system. The extreme conditions considered included: (i) very simple and very complex design; (ii) very small and very large project size; (iii) very little information available; (iv) very large amount of site preparation required; and (v) very fast pace of work.

In practice, the role of robustness tests was more concerned with verifying the correctness of the knowledge base, rather than checking its validity. They were also employed for re-testing the system whenever significant modifications were made in the knowledge base, in order to check whether its consistency has been maintained.

PROJ. No. (1)	SET UP SITE			CLEAR SITE			SITE SHAPING			VIBROCOMPACTING			ROADS (TOTAL)			MAIN DRAINAGE		
	EXP. (2)	SYS. (3)	DIF.% (4)	EXP. (5)	SYS. (6)	DIF.% (7)	EXP. (8)	SYS. (9)	DIF.% (10)	EXP. (11)	SYS. (12)	DIF.% (13)	EXP. (14)	SYS. (15)	DIF.% (16)	EXP. (17)	SYS. (18)	DIF.% (19)
1	6	2	-67		2		7	3	-57	7	2	-250	13	5	-62	7	2	-71
2	2	2	0				2	4	100	1	1	0	10	7	-30	4	5	25
3	2	2	0	5	2	-60	5	4	-20	5	2	-150	10	13	30	6	10	67
4	1	2	100				2	5	150				17	9	-47	13	7	-46
5	1	2	100		2		2	3	50	2	2	0	9	13	44	4	11	175
6	3	2	-33	3	2	-33	5	5	0	2	1	-100	6	7	17	4	4	0
7	2	2	0				5	3	-40	3	1	-200	5	7	40		4	
8	3	2	-33				2	4	100				6	9	50	2	6	200
9	3	2	-33				3	2	-33									
10	3	2	-33				10	4	-60				14	7	-50		5	
11		2						1						23			20	
12		2			2		14	4	-71									
13	2	2	0		2		5	2	-60				7	9	29	5	6	20
14	2	2	0		2		5	2	-60					5			3	
15	3	2	-33		2		4	4	0				10	9	-10	4	7	75
MIN	1	2	-67	3	2	-60	2	1	-71	1	1	-250	5	5	-62	2	2	-71
MAX	6	2	100	5	2	-33	14	5	150	7	2	0	17	23	50	13	20	200
AVER.	2.5	2.0	-2.6	4.0	2.0	-47	5.1	3.3	-0.1	3.3	2	-117	9.7	9.5	1.0	5	7	49.3
CV	48	0		25	0		65	34		62	33		37	48		55	65	

NOTE: all durations are expressed in terms of number of weeks.

Table 8.11(a): Comparison of bar-chart activity durations

PROJ. No. (1)	BASE COURSE			PERMANENT KERBS			WEARING COURSE			LANDSCAPING			PUBLIC FOOTPATH			SERVICE MAINS		
	EXP. (2)	SYS. (3)	DIF.% (4)	EXP. (5)	SYS. (6)	DIF.% (7)	EXP. (8)	SYS. (9)	DIF.% (10)	EXP. (11)	SYS. (12)	DIF.% (13)	EXP. (14)	SYS. (15)	DIF.% (16)	EXP. (17)	SYS. (18)	DIF.% (19)
1	4	2	-50	3	1	-67	2	1	-50	42	35	-17	42	35	-17	10	24	140
2	3	3	0	24	2	-92	3	1	-67	24	18	-25	22	18	-18	3	21	600
3	5	6	20	34	5	-85	4	2	-50	19	21	11	31	20	-35	6	20	233
4	8	4	-50	5	3	-40	5	1	-80	40	40	0	40	40	0	40	21	-48
5		6			1			1		20	13	-35	20	13	-35		18	
6	3	3	0	4	1	-75	3	1	-67	13	17	31	14	17	21	15	18	20
7		3			2			1		14	15	7	14	15	7	14	18	29
8	1	1	0	2	3	50	2	2	0	20	15	-25	19	14	-26	14	18	29
9										16	14	-13	14	14	0			
10		3			2		2	1	-50	25	21	-16		20			18	
11		11			10			2			64			63			24	
12											60			60				
13		4		4	2	-50	8	1	-88	7	22	214	7	22	214	6	20	233
14		2		2	2	0	3	1	-67	8	19	138	15	19	27	15	19	27
15	4	1	-75	2	2	0	2	1	-50		31			31		4	23	475
MIN	1	1	-75	2	1	-92	2	1	-88	7	13	-35	7	13	-35	3	18	-48
MAX	8	11	20	34	10	50	8	2	0	42	64	214	42	63	214	40	24	600
AVER.	4.0	3.8	-22	8.9	2.8	-40	3.4	1.2	-57	21	27	22.5	22	27	12.5	13	20	174
CV	50	68		124	84		53	34		51	58		50	59		80	11	

NOTE: all durations are expressed in terms of number of weeks.

Table 8.11(b): Comparison of bar-chart activity durations (cont.)

Although performing these robustness tests has turned the system less prone to errors, it is worth noting that large and complex computer programs, such as this, are never proven to be correct (Hollnagel, 1989).

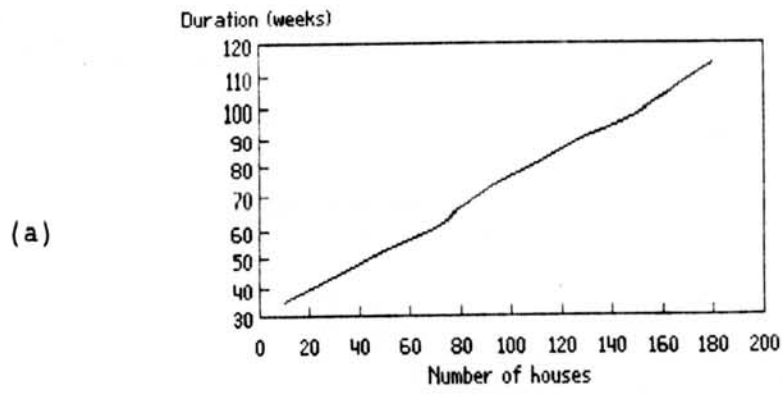
8.5.5 Sensitivity analysis

A number of sensitivity tests were carried out by the author, in order to test how the system's reasoning reacted to subtle changes in the value of some variables from the job description. Such tests allowed some inconsistencies to be detected in the system. As in the application of robustness tests, this technique also acted as an effective tool for debugging the knowledge base.

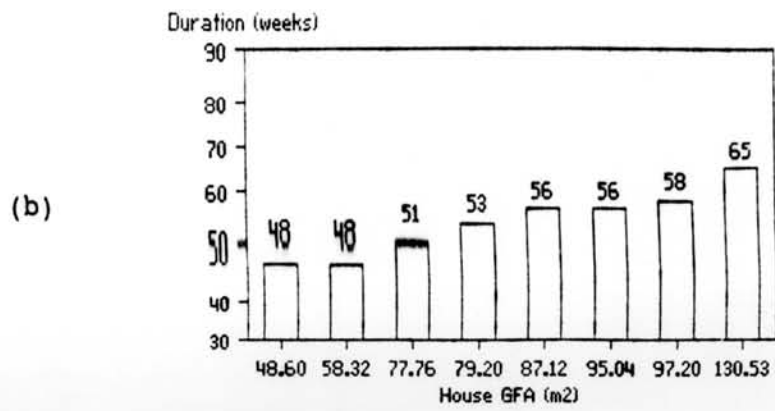
The main project variables considered in such tests were: job size, geographical continuity, design dimensions, work concentration, design repetitiveness, design complexity, availability of management, and availability of bricklayers. Figure 8.1, for instance, presents a number of graphs which resulted from some of the sensitivity tests. They express the effect of several project variables in the total duration of the construction stage.

One of the main inconsistencies in the model made explicit through sensitivity tests was the effect of the job size on the house completion time. The system was used for generating the plans of nine different hypothetical projects, each of them containing a different number of semi-detached houses with identical design. All the other conditions were kept unchanged.

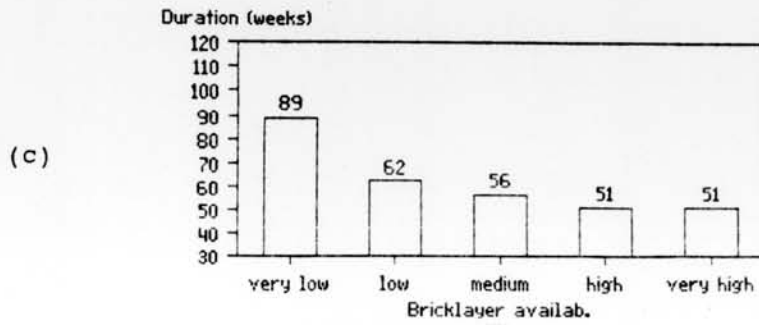
Table 8.12 shows the value of some variables from the resulting plans. It can be observed that there is a wide variation in the house completion time from the smallest to the largest project. Such variation is a consequence of the combined effect of the chosen "S" curve model, and the method adopted for establishing floats between stages of work. Neither the experts nor the literature provided any evidence that the house completion time should increase as the number of houses grows. This indicates that it is advisable to revise the way in which the house completion time is established, in future versions of the system.



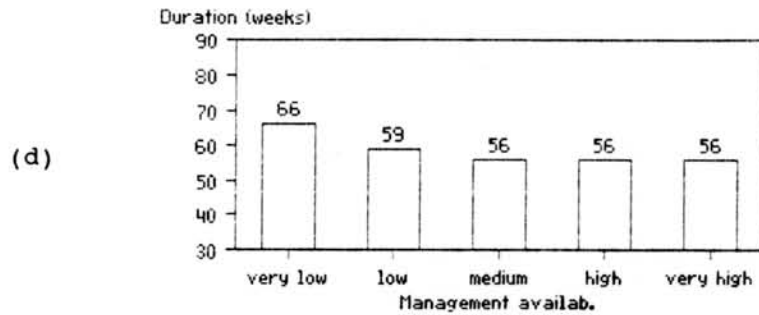
NOTE: all houses are 2 floor, 3 bedroom, 5 people, semi-detached houses.



NOTE: Each project has 50 identical semi-detached houses.



NOTE: All projects have 50 two floor, three bedroom, five people, semi-detached houses.



NOTE: All projects have 50 two floor, three bedroom, five people, semi-detached houses.

Figure 8.1: Some examples of sensitivity tests
 (a) Total duration vs. No. of houses
 (b) Total duration vs. house gross floor area
 (c) Total duration vs. bricklayers availability
 (d) Total duration vs. management availability

Besides its relevance as a validation technique, sensitivity analysis can also be used as a management tool. For instance, several families of curves, such as the ones from Figure 8.1, could be used by managers for estimating the total duration of the construction stage, when making strategic decisions at the early stages of the project.

No. OF UNITS (1)	BRICK-WORK CONTENT (2)	TOTAL PROJECT DURATION (3)	HOUSE COMPLET. TIME (4)	FINISH. ACTIV. DURATION (5)
10	1720	35.00	28.00	5.00
30	5160	44.00	31.00	12.00
50	8600	53.00	31.00	21.00
70	12040	61.00	32.00	28.00
90	15480	72.00	35.00	37.00
110	18920	81.00	36.00	45.00
130	22360	91.00	38.00	54.00
150	25800	98.00	37.00	62.00
180	30960	114.00	38.00	78.00

NOTES: The brickwork content is expressed in terms of the equivalent amount of half brick wall, m². All periods of time are expressed in weeks.

Table 8.12: Analysis of the effect of project size

8.5.6 Field tests

This system seems to be suitable for field validation because it can be used experimentally in real situations, without causing any serious trouble to the users. As it has been designed for supporting experts during the planning task, rather than replacing them, the user has an overall control over the final form of the plans.

A run-time version of the system was installed in the offices of two construction companies for several months, with the objective of giving to some of the experts the chance of using the system without the author's help.

The outcome of such tests was relatively limited for two main reasons. Firstly, the experts unfortunately did not have much chance to use the system in real projects, because those two companies were not intensively involved in house building during that particular period.

The second difficulty was concerned with the stage of development of the system: although it has reached the stage of a working system, there is still a lack of man-machine interface facilities and documentation, which does not allow non-familiarized users to use it confidently. Consequently, the feedback obtained from this validation technique was mostly related to the quality of the man-machine interface, rather than to the model validity.

Their main critiques to the man-machine interface were: (i) they find rather tedious to input the word "unknown", whenever the value of a real object is not available; (ii) they pointed out that making small changes in an existing job description in the INPUT module is time consuming, since the number of items in each group of variables is fairly large; and (iii) they perceived the format of the print-outs as somewhat crude, and suggested some improvements. The first problem is a drawback of Leonardo's default screen, while the other two can be overcome by enhancing the knowledge base in the next upgrades of the system.

8.5.7 Face validation

This validation technique involved experts that had not participated in the knowledge acquisition process. Two experts participated of this panel, one from Company B, and the other from a major national contractor, specialized in house building, named Company F in this research.

Face validation was carried out in two phases. The first phase involved making a very detailed demonstration of the system to experts. The second one consisted of using the system for generating the construction plans of a number of past projects, provided by the two external experts, and comparing the outcome of the system to the plans manually generated by them.

Four historical cases were used in this second phase, three from Contractor B, and one from Contractor F. The knowledge base had to be extended in order to cope with the historical case provided by Contractor F, because the houses from that project were timber framed, rather than traditional.

The aim was to use these four projects for performing the same kind of analysis and discussion which was carried out during predictive

validation. However, the external experts were unable to comment on the knowledge base content, except in general terms, due to the limited amount of time that they could devote to this research. Their criticism was relatively informal, and focused only on general aspects of the system.

In broad terms, both the external experts agreed with the general planning strategy adopted in the system. As in field tests, they also provided several comments about the system's man-machine interface.

Perhaps their most valuable contribution from the external experts was a list of likely project conditions which the system is presently unable to handle, which should be considered in its future upgrades. Most drawbacks of the system in this respect related to the fact that some of the variables from the job description are assumed to be the same for all houses. For instance, the system cannot cope with a mix of traditional and timber framed houses, different types of foundations in the same site, a variety of external cladding, etc.

8.6 Summary and conclusions

This chapter presented a review of some fundamental concepts related to the validation of knowledge based systems, and examined the validation exercise carried out at the end of the system's development.

The validation method prescribed involved some degree of pragmatism, due to existing practical constraints. These were mostly concerned with the limited resources available for this study, and to the complex nature of the planning process.

Five different techniques were employed during the validation stage. One of these techniques involved two experts who had not been involved in the knowledge acquisition process, in order to introduce a more independent view on the validity of the model.

The main conclusions that resulted from the application of validation techniques are summarized as follows:

(i) One major advantage of using several different techniques was that to some extent they complemented each other. They should not be thought as being mutually exclusive, since each of them tends to focus

on a different aspect of the system's validity;

(ii) Predictive validation provided the most detailed analysis among the techniques. Its role can be regarded as a structured extension of the knowledge acquisition process, compensating to some extent the fact that knowledge elicitation was relatively informal. The application of this technique provided some indications that the plans generated through the system had some improvements in terms of consistency and completeness in relation to the plans manually produced by experts;

(iii) Robustness tests were more effective as a debugging procedure than as a validation technique. They played an important role in keeping the consistency of the knowledge base, when the system had to be updated or expanded;

(iv) Sensitivity analysis was an useful technique for detecting inconsistencies in the knowledge base, which cannot be easily detected by simply running the system through individual cases. With reference to this particular application, this technique also seems to have a good potential as a management tool;

(v) Field validation was not very successful because the man-machine interface was not completely developed, and the system was not thoroughly documented. This technique seems to be more suitable for more advanced stages of validation;

(vi) Face validation involved the participation of external experts not familiarized with the knowledge base. Their contribution tended to be restricted to general aspects of the system, such as the man-machine interface, or the range of situations which the system can handle. Getting them to examine some more detailed features of the system would demand much more time than they were able to devote to this research;

(vii) A number of improvements in the system were suggested by both internal and external experts, as a result of the application of validation techniques. These suggestions will be considered in future upgrades of the system; and

(viii) A number of gaps in the knowledge encapsulated in the system were made explicit or highlighted during the validation process. These include: lack of an adequate "S" curve model for the building rates,

need for investigating deeper knowledge concerned with the ratio between building rates, inadequate method for establishing the house completion time, and lack of more sophisticated methods for estimating the duration of bar-chart activities.

It seems that the main outcome of the validation stage was that it led to a more systematic appreciation of the structure and limits of the expertise modelled by the system. Whether the system has reached an acceptable level of performance in global terms is a subjective matter. However, the results produced by the validation process, and the interest demonstrated by construction planning experts offered indications that it is worthwhile to continue investing in its development.

CHAPTER 9: CONCLUSIONS

9.1 Summary of conclusions

The general objective of the research project described in this thesis was to investigate the feasibility of using knowledge engineering for modelling construction planning expertise, through the development of a practical application. The resulting application can be described as a knowledge based framework which is able to support the work of construction planners, during the process of planning the production stage of house building projects at a tactical level.

This application was developed in close co-operation with people from the industry, and had a number of practical limitations in terms of time and resources available. This seems to be both a strength and a weakness of this study. On one hand, the research involved modelling expertise that is actually used in real projects, covers a range of situations that are typical of construction companies, and considered the practical needs of the industry in terms of planning tools.

On the other hand, the research had some constraints resulting from the pressures of work that exist in a commercial environment: the time that the experts were able to devote to knowledge elicitation and model validation was very limited. For this reason, several decisions made during the study involved some degree of pragmatism.

The application was developed up to the stage of a working system. Its present version is a fairly large application in terms of number of rules (approximately 1100), if compared to other knowledge based systems developed for standard micro-computers. As far as the literature in the field of construction planning is concerned, this is the first application of this kind, designed specifically for low rise, repetitive building projects.

The system seems to perform very well in terms of time savings: a user familiarized with the system is expected to take between 35 minutes and 2.5 hours to carry out a task that can take between one and five working days, when executed manually. Also, a comparison between the outcomes of the system and the plans manually produced by experts, for a number of historical cases, indicated that the system

tends to improve the performance of the experts in terms the completeness and the consistency of the plans produced.

Besides these advantages, the system also offers a number of facilities that enable planners to extend their role in the planning task. For instance, they can quickly generate alternative plans, or to perform sensitivity analysis by asking "what if" questions to the system.

The general response given by the experts involved in both knowledge elicitation and model validation to the development of the application was fairly good. All of them agreed that such kind of tool would be very useful for supporting their work in the task of planning the construction stage of house building projects.

The hypothesis which guided this research stated that knowledge engineering can provide tools for improving the construction planning experts' capability of manipulating qualitative and experiential information, removing some of the painstaking work from their hands, and allowing them to analyse a large number of construction alternatives in a short time. The conclusions presented above indicate that this hypothesis was successfully proved: knowledge based systems seems to be able to improve substantially the performance of construction planning experts, even if implemented in standard micro-computers.

The main lessons learnt from the development of the application are summarized in Section 9.2. They can be grouped under four main headings, which correspond to the four specific research objectives established in Section 1.4: knowledge acquisition, model of expertise, implementation of the system, and model validation.

9.2 Lessons for the future

9.2.1 Knowledge acquisition

The main conclusions related to knowledge acquisition are summarized below:

(i) The development of an early prototype played a key role in forming a panel of multiple experts, and in keeping them motivated;

(ii) Working through the several historical cases available was a very useful strategy for using efficiently the limited time available

from the experts;

(iii) The use of a paper model was useful for performing checks in the knowledge elicited from experts before it was implemented, especially during the early stages of knowledge acquisition. Such documentation was also useful when the application had to be transferred from one shell, where the prototype had been implemented, to the environment where the full working system was developed. Its role was gradually reduced as more detailed knowledge were elicited, due to the excessive manual work required;

(iv) The knowledge elicitation techniques of step listing and introspection were relatively successful in this study, because they were very natural to the experts; and

(v) Eliciting knowledge from multiple experts was confirmed to be an interesting approach for three main reasons. Firstly, the elicitation sessions in which two experts were simultaneously involved tended to be more productive in relation to the ones that had the participation of only one expert. Secondly, each expert was able to focus his contribution in those particular aspects that he was more specialized in. Finally, the most experienced planners were able to find solutions for the most difficult situations, while the less experienced ones were, in general, able to explain causal relationships in a more orderly way.

9.2.2 Model of expertise

Relative to the model of expertise, it is worth mentioning the following remarks:

(i) The project representation used by the experts for generating a construction plan was relatively simple, if compared with the amount of information that is usually employed for describing a complete construction project;

(ii) The experts have not had much difficulty in providing default data for variables from the site description, since they are usually required to do so when working in real projects;

(iii) The expertise related to the generation of plans was grouped according to five main sub-tasks. One of them, named choosing the sequence of work places, was considered to be unsuitable to be

performed by the system, because of the limitations of this research project in terms of time and resources. For this reason, only some general guidelines for carrying out this sub-task were elicited from the experts;

(iv) The study of the sub-task concerned with the establishment of the pace of work indicated that the experts only consider the rate of deployment of a small number of leading resources. Most activities follow the same pace of work established by such resources;

(v) Investigating the deeper knowledge behind shallow rules-of-thumb was an effective approach for getting an agreement among the experts. Furthermore, this approach made possible to incorporate in the model some results from past research studies; and

(vi) The knowledge acquisition process revealed some gaps in the domain knowledge. The most important one was the lack of a reliable "S" curve model for drawing the profiles of building rates.

9.2.3 Implementation of the system

The main lessons learnt from the implementation of the system are outlined below:

(i) The implementation of the system in Leonardo Level 3 was reasonably successful. The main advantages of using this knowledge based system shell include: fairly good speed, if running on 80386 microprocessor based microcomputers; availability of a wide range of facilities for developing the man-machine interface; clarity of the knowledge base; and availability of formalisms for organizing the knowledge base in a modular way;

(ii) The main shortcomings of Leonardo in this particular study were: limitations in the amount of text contained in each knowledge base, lack of a specific formalism for representing meta-rules, and lack of more effective runtime facilities for transferring the control over the consultation to the user;

(iii) As in most other shells, the default explanation facilities provided in Leonardo are based on tracing the rules used by the system. Although this facility was very useful during the development stage as a tool for debugging rules, it very rarely provided an acceptable explanation to the user;

(iv) The development of the application has confirmed the importance of the cost of devising the man-machine interface in relation to the total cost of implementing the system: approximately 60% of the time needed for implementing the system was actually spent in the development of the man-machine interface; and

(v) Two important pitfalls related to the early prototyping approach were identified in this particular study. Firstly, as the early versions of the system were intensively used during knowledge elicitation, a considerable amount of effort had to be spent in keeping the the man-machine interface attractive to the experts and the system reasonably debugged. Secondly, several of the early upgrades of the system required radical alterations in the structure of the knowledge base, which were considerably time consuming.

9.2.4 Model validation

The main conclusions concerned with the process of model validation were:

(i) Using several different validation techniques was an useful approach because they complemented each other to some extent. Each technique tends to focus on a different aspect of the system's validity;

(ii) Predictive validation was regarded as a structured extension of the knowledge acquisition process, compensating to some extent the fact that knowledge elicitation was relatively informal;

(iii) Robustness tests played an important role in keeping the consistency of the knowledge base, whenever the system had to be updated or expanded;

(iv) Performing sensitivity analysis helped noticing some inconsistencies in the knowledge base, which could not be easily detected by simply running the system through individual cases;

(v) Field validation was not very successful at the current stage of development of the system. This technique seems to require a more developed man-machine interface as well as a more supportive documentation of the system;

(vi) Involving external experts through the technique of face

validation introduced a fresh perspective in the validation process. However, due to the limited time available, their criticism tended to be restricted to general aspects of the system, such as the man-machine interface, or the limited range of situations which the system is capable of handling; and

(vii) Formally validating the model at the end of its development provided a more systematic appreciation of the structure and limits of the expertise that it encapsulates. It emphasized some positive features of the system, identified a number of necessary improvements for future upgrades, and highlighted the main gaps in the domain knowledge.

9.3 Suggestions for future work

Several suggestions for future research work came out from this study. They are summarized below:

(i) The results achieved in this study and the relatively good response given by people from the industry indicate that the system has a good potential of being further developed, up to the stage of a commercial package. In order to make such upgrading, it would be necessary to enhance the man-machine interface; to improve the system's documentation; and to implement a number of minor changes in the knowledge base, some of which have been suggested by the experts during the model validation stage;

(ii) If the system is developed as a commercial package, this could take two different forms: as a decision support system for experts in construction planners which work for construction companies, or as a consultancy type of system for other construction professionals. In the first case, the system would contain facilities similar to the ones available in its present version. The second one would correspond to a compact version of the system, which would simply have the capability of estimating some variables related to the duration of the construction stage, similarly in some respects to the Time module of Elsie. This compact alternative has the potential of improving the integration of the construction industry, by making available to the design team some expertise from construction planning specialists;

(iii) The presence of several rules-of-thumb in the knowledge base, and the fact that some disagreement was found among experts indicate

that a fine tuning of the system will be periodically needed during its working life, especially before it is employed in a different context. This indicates the necessity of developing a formal method for continuously validating the system, in case it is actually used in the field;

(iv) The choice of the sequence of work is the only planning sub-task that the system is currently unable to perform. One possible upgrading for future versions of the system is to make it also capable of performing this particular planning sub-task. This would require the development of an interface to a CAD system, and, obviously, the elicitation of knowledge related to the choice of the sequence of work places, at a deeper level;

(v) Developing an interface to a CAD package can also enable the system to obtain automatically the geometric description of buildings. This would substantially reduce the number of items that the user needs to input for describing a job;

(vi) Another way of extending the system's capability would be to interface it to other similar knowledge based tools. In this particular respect, the most common suggestion made by the experts involved in this study was the need for developing similar tools for cost estimating and for project control. One of the main advantages of such integration would be the possibility of using information produced by the other tools in the construction planning task, and vice-versa. For instance, cost estimates obtained from a knowledge based cost estimating tool could be used by the current system for choosing the ratio between building rates;

(vii) In the long term, the application has the potential of being used as a skeleton for organizing expertise concerned with the task of planning house building. This could be done by either increasing the depth of the expertise that is encapsulated in the system, or by increasing the number of alternative designs, site conditions, and construction technologies that it is able to handle. The depth of knowledge can be increased by considering other sources of expertise, such as results from research studies as they come up, or eliciting knowledge from other specialists involved in the construction process, e.g. site managers, estimators, etc.;

(viii) The development of the system revealed a number of gaps in

the domain knowledge which could be fulfilled by developing research in the construction planning field. The following studies, for instance, are likely to produce some results that could be used for making improvements in the system: to develop mathematical "S" curve models for predicting the pattern of building rates for each main stage of work; to study the relationship between peak rates and the factors that affect their choice; to develop more sophisticated models for estimating the productivity of key trades;

(xix) The knowledge acquisition process was carried out in a relatively informal way in this research project, due to limitations of time and resources. It would be worthwhile, in the future, to develop some controlled experiments for studying some cognitive aspects of the construction planning task. These could be used, for instance, for investigating the applicability of the techniques of step listing and introspection in this particular field;

(xx) The role of the paper model in the final stages of knowledge acquisition was considerably reduced, because of the excessive manual work that was required to keep it updated up to a fine degree of detail. This indicates the need for developing automated tools for knowledge analysis, which could reduce the time necessary for building and updating paper models in complex domains;

(xx) Several suggestions for improving the knowledge based shell Leonardo came out from this research. These include: need for a more efficient way of managing the usage of memory; ability to declare objects that are exclusively used in a particular ruleset as local objects; development of specific formalisms for representing task knowledge; introduction of other types of parent-child relationship in the lattice of frames (only "IsA" links are currently allowed); and improvement in the runtime facilities available in the default screen, in order to give more control over the consultation to the user; and

(xxii) Leonardo is a diagnosis oriented knowledge based system shell, as are most shells currently available in the UK market. In the near future, it is likely that some planning oriented shells will also be available at an affordable price. It would be interesting to consider developing construction planning applications, such as the present one, in such tools, since they have formalisms specifically designed to tackle planning problems.

GLOSSARY

approximate reasoning: any reasoning technique designed to describe uncertain or incomplete information in knowledge based systems. They usually attempt to emulate the manner in which humans approach and think about uncertain situations or relationships.

ASCII: American National Standard Code for Information Exchange.

backward chaining: a control procedure that attempts to achieve goals recursively, first by enumerating antecedents that would be sufficient for goal attainment, and second by attempting to achieve or establish the antecedents themselves as goals (Hayes-Roth et al., 1983).

Bayesian logic: representation of uncertainty based on Bayes theorem. It considers a measure of the degree of belief (or disbelief) in a hypothesis when a piece of evidence is true and also a degree of disbelief (or belief) when the evidence is false (Allwood et al., 1985).

Boolean logic: logic system which allows a proposition to have only two possible logic values: true or false (Allwood et al., 1985).

certainty factor: numerical measure of uncertainty (in some ways analogous to a probability), which expresses a degree of certainty in the statement or rule. Some knowledge based system shells have a way of combining these factors in order to make inferences (Hart, 1986).

CAD: Computer Aided Design.

class: abstract description of one or more similar objects (Stefik & Bobrow, 1986).

depth-first search: a search technique that evaluates only one item at a given level of the search space before proceeding to the next level (Allwood et al., 1985).

forward chaining: a control procedure that produces new decisions recursively, by affirming the consequent propositions associated within an inferential rule with antecedent conditions that are currently believed. As new affirmed propositions change the current

set of beliefs, additional rules are applied recursively (Hayes-Roth et al., 1983).

frame: a knowledge representation scheme that associates one or more features with an object in terms of various slots and particular slot values (Hayes-Roth et al., 1983).

fuzzy logic: a method of approximate reasoning which uses relative values or indicators, such as "true", "not very true", "many", and "few" (Brandon et al., 1988)

hybrid knowledge representation: knowledge based representation structures which integrate more than one kind of formalisms, such as production rules and frames (Fikes & Kehler, 1985).

inference control mechanism: the part of a knowledge based system that takes the given facts and rules and works out the conclusions that follow from them (Brandon et al., 1988).

knowledge base: the repository of knowledge in a computer system (Hayes-Roth et al., 1983).

lattice: it is similar to a tree, but each member admits more than one parent (Stefik & Bobrow, 1986).

message passing: an operation to be performed on an object. It is similar to a procedure call, except that the operation is named indirectly through a selector whose interpretation is determined by the class of the object, rather than a procedure name with a single interpretation (Stefik & Bobrow, 1986).

meta-rules: rules that prescribe the manner in which ordinary rules should be employed (Hayes-Roth et al., 1983).

objects: entities that combine the attributes of procedures and data. They store data in variables, and respond to messages by carrying out procedures (Stefik & Bobrow, 1986).

object-oriented programming: very wide range of programming techniques which have objects as primitive elements. All actions in object-oriented programming come from sending messages between objects.

predicate logic: a logic system that deals with the validity of declarative sentences made up of predicates and connectives. Predicates break up the sentences used in propositional logic, so

that each sentence can be examined and considered in more detail (Allwood et al., 1985).

production rule: an item of knowledge which takes the form "IF this condition is true, THEN this action is appropriate" (Slatter, 1987).

property inheritance: the ability of an object from the knowledge base to assume the characteristics of a parent object, higher up in the structure or hierarchy.

propositional logic: a logic system that reaches a conclusions from a series of statements controlled by a set of rules. It only deals with the syntax of the relationships (e.g. and, or, not, implies, etc.). Unlike predicate logic, it does not reason about the semantics of propositions (Allwood et al., 1985).

slot: a feature or component description of an object in a frame. Slots may correspond to intrinsic features such as name, definition, or creator; or may represent derived attributes such as value, significance, or analogous objects (Hayes-Roth et al., 1983).

APPENDIX 1: DATABASE OF BUILDING STEREOTYPES

TYPE No.	No. OF FLOORS	No. OF BEDROOMS	No. OF PEOPLE	TYPE OF FRONTAGE	SHAPE	WIDTH (mm)	DEPTH (mm)	WING WIDTH (mm)	WING DEPTH (mm)	HEAVY PARTIT. AREA(m2)	LIGHT PARTIT. AREA(m2)	PARTIT. FOUND. LGTH(mm)	GROSS FLOOR AREA(m2)
1	2	3	4	narrow	rect.	4800	8100	0	0	24.50	63.25	9800	77.76
2	2	3	5	narrow	rect.	4800	9000	0	0	26.00	69.50	10400	86.40
3	2	3	6	narrow	rect.	4800	9900	0	0	28.25	73.63	11300	95.04
4	2	4	6	narrow	rect.	4800	9900	0	0	28.25	78.62	11300	95.04
5	2	3	4	medium	rect.	6600	6000	0	0	30.00	72.87	12000	79.20
6	2	3	5	medium	rect.	6600	6600	0	0	33.00	70.63	13200	87.12
7	2	3	6	medium	rect.	6600	7200	0	0	37.50	78.37	15000	95.04
8	2	3	4	wide	rect.	7200	5400	0	0	45.12	41.76	18050	77.76
9	2	3	5	wide	rect.	8100	5400	0	0	50.50	39.50	20200	87.48
10	2	4	6	wide	rect.	9000	5400	0	0	57.55	54.75	23100	97.20
11	1	1	2	wide	rect.	7200	6600	0	0	20.00	27.88	8000	47.52
12	1	2	3	wide	rect.	7200	8100	0	0	21.00	46.38	8400	58.32
13	1	1	2	wide	L-shap.	7500	4000	3600	5300	9.75	39.25	3900	49.08
14	1	2	3	wide	L-shap.	10200	4000	3600	5300	9.75	49.50	3900	59.88
15	1	2	4	wide	L-shap.	12000	4200	3900	5100	10.50	73.25	4200	70.29
16	1	1	2	medium	rect.	6000	8100	0	0	20.25	35.50	8100	48.60

APPENDIX 2: LIST OF CONSTRUCTION ACTIVITIES

SITE PREPARATION	FOUNDATIONS	SHELL/ROOFING	FIRST FIX/PLASTER	SECOND FIX/FINALS	LANDSCAPE
set up site demolishing clear site remove top soil exc./fill cellars vibrocompacting site shaping piling main drainage roads to subbase kerb race ducts/gullies base course	excavate footings str. reinforcement concrete footings excavate for raft edge beam formwork raft reinforcement raft formwork concrete edge beam concrete raft excavate for caps caps formwork caps reinforcement concrete caps excavate for caps pad/pier formwork pad/pier reinforc. concrete pad/pier gr.beam formwork gr.beam reinforc. concrete gr.beams place/joint beams service entries house drainage hardcore concrete slab gr.floor joists hollow beams(gr.) beams/blocks(gr.)	sole plates gas ducts electric ducts floor screed * erect scaffold panel erection external brickwork brickwork 1st lift scaffold 1st stage brickwork 2nd lift scaffold 2nd stage loadb.studs (1st) 1st floor joists hollow beams(1st) beams/blocks(1st) brickwork 3rd lift scaffold 3rd stage brickwork 4th lift scaffold 4th stage loadb.studs (2nd) 2nd floor joists hollow beams(2nd) beams/blocks(2nd) brickwork 5th lift scaffold 5th stage brickwork 6th lift scaffold 6th stage brickwork to peaks roof carcass SVP gutters & RWP tile roof timber cladding external painting * strip scaffold * external openings glazing porch wall * porch joinery * porch roof tiling *	external rendering strip scaffold * joinery 1st fix plumbing 1st fix heating 1st fix electric. 1st fix internal rendering plasterboard gypsum plaster skim coat plate ceiling floor screed * insulation * artex on ceilings *	joinery 2nd fix plumbing 2nd fix heating 2nd fix electric. 2nd fix porch wall * porch joinery * porch roof tiling * gas meter electric meter plumbing testing joinery final fix wall tiling insulation * artex on ceiling * internal painting floor tiling external painting * ironmongery handover	white lining wearing course permanent kerbs landscaping house footpath fencing * place top soil public footpath street lighting communal TV aerial ext. foundations external walls garage joinery garage roof tiling garage finishings water connection gas connection elect.connection BT connection water mains gas mains electric mains BT mains clear away

NOTE: (*) means that the activity may be placed in different stages.

APPENDIX 3: PRODUCTIVITY INDICES

A3.1 Design simplicity

The design simplicity index related to the whole project is the average of the design simplicity indices of the individual houses. In relation to design simplicity, fourteen different categories of house types were identified. These are:

- (i) Rectangular detached house;
- (ii) "L" shaped detached house;
- (iii) Irregular (i.e. any other shape) detached house;
- (iv) Rectangular semi-detached house;
- (v) "L" shaped semi-detached house;
- (vi) Irregular semi-detached house;
- (vii) Rectangular terraced house in a block with neither steps nor staggers;
- (viii) Non rectangular terraced house in a block with neither steps nor staggers;
- (ix) Rectangular terraced house in a block with steps but no staggers;
- (x) Non rectangular terraced house in a block with steps but no staggers;
- (xi) Rectangular terraced house in a block with staggers but no steps;
- (xii) Non rectangular terraced house in a block with staggers but no steps;
- (xiii) Rectangular terraced house in a block with both staggers and steps;
- (xiv) Non rectangular terraced house in a block with both staggers and steps;

The experts were asked to provide an index for each category of house. When planning a job, the system uses the description of the

houses to choose an index for each of them, and then calculate the average index for the whole project.

A3.2 Work concentration

This index is based on the work content of two arbitrarily chosen blocks of houses, which try to reflect extreme conditions in relation to the concentration of the work of bricklayers.

The lower extreme consists of a small detached bungalow (5400 mm x 5400 mm), while the upper extreme is a block of 10 large two floor terraced houses (8400 mm x 6800 mm). The work content of each block was calculated in terms of the equivalent amount of half brick wall.

The work concentration index related to the whole project is established by comparing the average work content per block of houses to those two extreme situations. Three different situations may occur:

(i) If the average work content of the blocks is less or equal to the work content of the small detached bungalow, then the work concentration index is 0;

(ii) If the average work content of the blocks is greater or equal to the work content of the large terraced house block, then the work concentration index is 1;

(iii) If the average work content of the blocks is between those two extremes, then the work concentration index is interpolated between 0 and 1;

A3.3 Geographical continuity

The geographical continuity index (GC_index) is calculated as follows:

$$GC_index = (num_units - num_plots) / (num_units - 1) \quad (A3.1)$$

In the above formula, "num_units" is the total number of separate blocks in the project, either detached, semi-detached, or terraced; and "num_plots" is the number of separate plots in which the site is divided.

The geographical concentration index is equal to 0 when the number of blocks is equal to the number of plots, and equal to one when all

blocks are located in the same plot.

A3.4 Design repetitiveness

The design repetitiveness index (DR_index) is established as follows:

$$\text{DR_index} = (\text{num_houses} - \text{num_des_types}) / (\text{num_houses} - 1) \quad (\text{A3.2})$$

In the above formula, num_houses is the total number of houses in the project, and num_des_types is the number of different house design types.

When all houses have the same design, the number of design types is 1 and the design repetitiveness index is equal to 0. If there are as many design types as houses, then the design repetitiveness index is equal to 0.

APPENDIX 4: A TYPICAL CONSULTATION SESSION TO THE SYSTEM

A4.1 Input Module

UNIVERSITY OF SALFORD
DEPARTMENT OF QUANTITY AND BUILDING SURVEYING
HOUSE PLANNER - V. 2.20
INPUT MODULE

Hit any key to continue

Screen I1

OLD OR NEW JOB

Please, inform whether this job is old or new:

old
new

FKeys: 1 Help 2 Quit 3 Why? 5 Volunteer 6 Backup 7 Expand 8 Review

NOTE: option "old" chosen

Screen I2

NAME OF THE PROJECT

Could you type the name of the project (max 6 characters):

Epsom

FKeys: 2 Quit

Screen I3

INFORMATION TO UPDATE

Use the <Ins> and keys to select.

Which kind of information would you like to confirm ?

general questions
design parameters
site conditions
component specification
house sequence

FKeys: 1 Help 2 Quit 3 Why? 5 Vol 6 Back 7 Exp 8 Rev <Ins> Add Remove

NOTE: all five alternatives selected

Screen I4

YEAR

The previous value for the starting year is 1990.

Please, enter the year in which the job will start:

1985
1986
1987
1988
1989
1990
unknown

FKeys: 1 Help 2 Quit 3 Why?

7 Expand 8 Review

Screen I5

BEGINNING MONTH

The previous value for the beginning month is Jan.

Please, enter the month in which the job will start:

Jan
Fev
Mar
Apr
May
Jun
Jul
Aug
Sep
Oct
Nov
Dec
unknown

FKeys: 1 Help 2 Quit 3 Why?

7 Expand 8 Review

Screen I6

STARTING DAY

The previous value for the starting day is 8.

You may type unknown.

Please, enter the day in which the job will start:

8

FKeys: 1 Help 2 Quit 3 Why?

7 Expand 8 Review

Screen I7

PROJECT DURATION LIMIT

Could you inform whether a limit in the duration of the project is required or not.

The previous value for the project duration limit is required.

Please, choose the correct answer:

not required
required

FKeys: 1 Help 2 Quit 3 Why?

7 Expand 8 Review

NOTE: option "required" chosen

Screen I8

MAXIMUM DURATION OF THE JOB

The previous maximum duration of the job is 65 weeks.

Please, enter the maximum duration of the job, in weeks:

65

FKeys: 1 Help 2 Quit 3 Why?

7 Expand 8 Review

Screen I9

TYPE OF ORGANIZATION

Could you inform the type of organization that is used in the current project.

The previous value for type of organization is conventional.

Please, choose the correct answer:

conventional
design-build
speculative

FKeys: 1 Help 2 Quit 3 Why?

7 Expand 8 Review

Screen I10

HANDOVER STRATEGY

The previous value for the handover strategy is
houses delivered gradually in groups.

Please, enter the handover strategy required:

houses delivered gradually one by one
houses delivered gradually in groups
all houses delivered at the end

FKeys: 1 Help 2 Quit 3 Why?

7 Expand 8 Review

Screen I11

AVAILABILITY OF MANAGEMENT

Could you inform what is the situation within the company in terms of
availability of management for the current job.

The previous value for the availability of management is
medium.

Please, type the correct answer:

very high
high
medium
low
very low
unknown

FKeys: 1 Help 2 Quit 3 Why?

7 Expand 8 Review

Screen I12

AVAILABILITY OF BRICKLAYERS

Could you inform how intense is the availability of bricklayers in the market at the moment.

The previous value for the availability of bricklayers is medium.

Please, type the correct answer:

very high
high
medium
low
very low
unknown

FKeys: 1 Help 2 Quit 3 Why?

7 Expand 8 Review

Screen I13

HOUSE PLANS

The previous value for house plans is available.

Please, inform whether house plans are available:

available
not available

FKeys: 1 Help 2 Quit 3 Why?

7 Expand 8 Review

NOTE: option "available" selected

Screen I14

NUMBER OF HOUSES

In the current context, the project size can range from 10 to 180 houses.

Please, enter the total number of houses:

48

FKeys: 1 Help 2 Quit

4 FldHelp

Screen I15

NUMBER OF HOUSE TYPES

Please, type the number of units for each house type:

Number of detached houses.....:	0
Number of semi-detached houses:	48
Number of terraced houses.....:	0

FKeys: 2 Quit

Screen I16

ROOF TYPE

The previous value for the roof type is gable.

The specification for roof type is:

gable
hipped
unknown

FKeys: 1 Help 2 Quit 3 Why?

7 Expand 8 Review

Screen I17

ROOF ANGLE

The previous value for the roof angle is 23.

You may answer unknown.

The angle specified for the roof, in degrees is:

23

FKeys: 1 Help 2 Quit 3 Why?

7 Expand 8 Review

Screen I18

FLOOR TO CEILING HEIGHT

The previous value for the floor-ceiling height is
2350 mm.

You may answer unknown

Please, enter the floor-ceiling height:

FKeys: 1 Help 2 Quit 3 Why?

7 Expand 8 Review

Screen I19

FLOOR THICKNESS

The previous value for the floor thickness is 200 mm.

You may answer unknown

Please, enter the floor thickness:

FKeys: 1 Help 2 Quit 3 Why?

7 Expand 8 Review

Screen I20

EXTERNAL WALL LENGTH (IN THE WHOLE SITE)

The previous value for the external wall length is
996 m.

You may answer unknown.

Please, enter the length of external walls, in m:

FKeys: 1 Help 2 Quit 3 Why?

7 Expand 8 Review

Screen I21

EXTERNAL WALL AREA (IN THE WHOLE SITE)

The previous value for the external wall area is
1658 m².

You may answer unknown.

Please, enter the area of external walls, in m²:

FKeys: 1 Help 2 Quit 3 Why?

7 Expand 8 Review

Screen I22

PORCH ROOF

The previous value for the porch roof is existent.

Please, inform whether any houses have porch:

existent
non existent
unknown

FKeys: 1 Help 2 Quit 3 Why?

7 Expand 8 Review

Screen I23

PORCH WALL AREA

The previous value for the porch wall area is 0 m2

You may answer unknown.

Please, enter the total area of porch wall, in m2:

0

FKeys: 1 Help 2 Quit 3 Why?

7 Expand 8 Review

Screen I24

EXTERNAL GARAGES

The previous value for external garages is non existent.

Please, inform whether there are external garages:

existent
non existent

FKeys: 1 Help 2 Quit 3 Why?

7 Expand 8 Review

Screen I25

STANDARD DESIGN DATABASE

The previous value for standard design database is not available.

Is there a database of standard designs available?

not available
available

FKeys: 1 Help 2 Quit 3 Why?

7 Expand 8 Review

NOTE: option "not available" selected

Screen I26

NUMBER OF SEMI-DETACHED HOUSE DESIGN TYPES

The maximum number of semi-detached house design types is 24.

Please, enter the number of semi-detached house design types:

3

FKeys: 1 Help 2 Quit

4 F1dHelp

Screen I27

DESIGN TYPE No. 1

Please, type F3 to confirm or F4 to retype parameters:

Number of houses...: 24 Type....:semi-detached
Number of floors.....:1 Shape...:rectangular
House width.: 6445 mm
House depth.: 9115 mm
Gross floor area.....: 58.75 m2
Part. area: Heavy: 0.00 m2 Light: 65.01 m2
Partitions foundations length.....: 0 mm

FKeys: 2 Quit 3 Confirm 4 Retype

NOTE: option "confirm" selected"

Screen I28

DESIGN TYPE No. 2

Please, type F3 to confirm or F4 to retype parameters:

```
Number of houses...: 20 Type....:semi-detached
Number of floors.....:2 Shape...:rectangular
House width.: 4522 mm
House depth.: 7745 mm
Gross floor area.....: 70.05 m2

Part. area: Heavy: 23.27 m2 Light: 31.35 m2
Partitions foundations length.....: 9902 mm
```

FKeys: 2 Quit 3 Confirm 4 Retype

NOTE: option "confirm" chosen

Screen I29

DESIGN TYPE No. 3

Please, type F3 to confirm or F4 to retype parameters:

```
Number of houses...: 4 Type....:semi-detached
Number of floors.....:2 Shape...:rectangular
House width.: 5196 mm
House depth.: 7745 mm
Gross floor area.....: 80.49 m2

Part. area: Heavy: 24.85 m2 Light: 43.64 m2
Partitions foundations length.....: 10576 mm
```

FKeys: 2 Quit 3 Confirm 4 Retype

NOTE: option "retype" selected

Screen I30

NUMBER OF UNITS FOR EACH DESIGN TYPE

DATA PREVIOUSLY ENTERED	DETACHED	SEMI-DET	TERRACED	TOTAL
Total number of design types.....:	0	3	0	3
Number of design types already entered:	0	2	0	2
Total number of houses.....:	0	48	0	48
Number of houses already entered.....:	0	44	0	44

Please, enter the parameters concerning the design type No. 3:

Number of houses...: 4 Type....:semi-detached
Number of floors.....:2 Shape...:rectangular

Gross floor area.....: 80.49 m2

FKeys: 2 Quit

Screen I31

TYPE OF DESIGN

Please type either detached, semi-detached or terraced

Please, enter the parameters concerning the design type No. 3:

Number of houses...: 4 Type....:semi-detached
Number of floors.....:2 Shape...:rectangular

Gross floor area.....: 80.49 m2

FKeys: 2 Quit

Screen I32

NUMBER OF FLOORS

The options available are: 1, 2 and 3

Please, enter the parameters concerning the design type No. 3:

Number of houses...: 4 Type...:semi-detached
Number of floors.....:2 Shape...:rectangular

Gross floor area.....: 80.49 m2

FKeys: 2 Quit

Screen I33

SHAPE OF THE HOUSE

The options available are rectangular, L-shaped and irregular (any other shape).

Please, enter the parameters concerning the design type No. 3:

Number of houses...: 4 Type...:semi-detached
Number of floors.....:2 Shape...:rectangular

Gross floor area.....: 80.49 m2

FKeys: 2 Quit

Screen I34

DESIGN MAIN DIMENSIONS

Please, enter the parameters concerning the design type No. 3:

Number of houses...: 4 Type....:semi-detached
Number of floors.....:2 Shape...:rectangular
House width.: 5196 mm
House depth.; 7745 mm
Gross floor area.....: 80.49 m2
Part. area: Heavy: 24.85 m2 Light: 43.64 m2
Partitions foundations length.....: 10576 mm

FKeys: 2 Quit

Screen I35

NUMBER OF PLOTS

The previous value for the number of plots is 1.

You may type unknown.

How many plots is the site divided in?

1

FKeys: 1 Help 2 Quit 3 Why? 5 Volunteer 6 Backup 7 Expand 8 Review

Screen I36

SITE LOCATION

The previous value for the site location is known.

Please, inform whether the site location is known:

known
unknown

FKeys: 1 Help 2 Quit 3 Why?

7 Expand 8 Review

NOTE: option "known" selected

Screen I37

SITE ZONE

The previous value for site zone is near city centre.

Please, enter the type of zone where the site is located:

rural area
outskirts of a town
near city centre
inner city

FKeys: 1 Help 2 Quit 3 Why?

7 Expand 8 Review

Screen I38

SITE ZONE

- (i) Rural area: Very few developments in the area. Site is a green field. Roads, drainage, service mains, and other infra-structure works are probably needed.
- (ii) Outskirts of a town: Very few developments in the area. Site is likely to be a green site. Some infra-structure works are likely to be needed.
- (iii) Near city centre: The site may have been previously developed. There may be restrictions to working hours and access. Only a few infra-structure works are needed.
- (iv) Inner city: The site has been previously developed. Demolitions and rubbish removal are likely to be needed. Services and drainage need to be checked and/or repaired.

Hit any key to continue

NOTE: this screen displays an explanation required from Screen I38

Screen I39

EXTERNAL WORKS

Use <Ins> and keys to select the options.

Please, enter the external works needed:

excavate and fill cellars
main drainage
roads
wearing course
service mains
service branches
public footpath
street lighting
communal TV aerial
house footpath
fencing
landscaping
none
unknown

FKeys: 1 Help 2 Quit 3 Why?

7 Exp 8 Rev <Ins> Add Remove

Screen I40

PRESENT CONDITIONS OF THE SITE

The previous value for present conditions of the site is
demolition rubbish.

You may answer unknown.

Please, choose the correct answer:

buildings to be demolished
demolition rubbish
vegetation
top soil
reduced level
unknown

FKeys: 1 Help 2 Quit 3 Why?

7 Expand 8 Review

Screen I41

SITE SLOPE

The previous value for the site slope is medium.

Please, enter the existing site slope:

flat
approximately flat
medium
steep
very steep
unknown

FKeys: 1 Help 2 Quit 3 Why?

7 Expand 8 Review

Screen I42

SITE SLOPE

Each category of site slope is concerned with a certain number of characteristics, as follows:

- (i) Flat: The site is virtually flat. No cutting and filling is needed.
- (ii) Approximately flat: The site is approximately flat. Very little cutting and filling is needed.
- (iii) Medium: The site has a medium slope. Some cutting and filling is needed.
- (iv) Steep: The site has a steep slope. A moderate amount of cutting and filling is needed. Some blocks may have to be built in steps.
- (v) Very steep: The site has a very steep slope. A lot of cutting and filling is needed. Most blocks are likely to be built in steps.

Hit any key to continue

NOTE: this screen displays an explanation required from Screen I42
Screen I43

VOLUME OF EXCAVATION FOR REDUCE LEVELS

The previous value for the reduce level excavation volume is 2428.00 m3.

You may type unknown.

Please, type the volume of excavation, in m3:

2428

FKeys: 1 Help 2 Quit 3 Why?

7 Expand 8 Review

Screen I44

VOLUME OF EARTHMOVING FOR GROUND FILLING AND COMPACTION

The previous value for the volume of ground filling is
0 m3.

You may type unknown.

Please, type the volume of ground filling, in m3:

FKeys: 1 Help 2 Quit 3 Why?

7 Expand 8 Review

Screen I45

VOLUME OF EXCAVATION FOR ROADS

The previous value for the road excavation volume is
442.00 m3.

You may type unknown.

Please, type the volume of excavation, in m3:

FKeys: 1 Help 2 Quit 3 Why?

7 Expand 8 Review

Screen I46

ROAD AREA

The previous value for the area of roads is 1475 m2.

You may type unknown.

Please, enter the area of roads in m2:

FKeys: 1 Help 2 Quit 3 Why?

7 Expand 8 Review

Screen I47

KERB LENGTH

The previous value for the length of kerbs is 295 m.

You may type unknown.

Please, enter the total length of kerbs in m:

FKeys: 1 Help 2 Quit 3 Why?

7 Expand 8 Review

Screen I48

PRIMARY DRAINAGE LENGTH

The previous value for the primary drainage length is
557 m.

You may answer unknown.

Please, enter the length of primary drainage, in m:

FKeys: 1 Help 2 Quit 3 Why?

7 Expand 8 Review

Screen I49

SECONDARY DRAINAGE LENGTH

The previous value for the secondary drainage length is
996 m.

You may answer unknown.

Please, enter the length of secondary drainage, in m:

FKeys: 1 Help 2 Quit 3 Why?

7 Expand 8 Review

Screen I50

FOUNDATION TYPE

The previous value for foundation type is strip.

Please, input the foundation type required:

strip
pad
pile
raft
unknown

FKeys: 1 Help 2 Quit 3 Why?

7 Expand 8 Review

NOTE: option "strip" selected

Screen I51

TYPE OF STRIP FOUNDATION

The previous value for the type of strip foundation is trench fill.

Please, enter the type of strip foundation required:

wide strip
trench fill
unknown

FKeys: 1 Help 2 Quit 3 Why?

7 Expand 8 Review

Screen I52

DPC LEVEL

Could you enter the average distance between the ground and the DPC level.

The previous value for the distance to the DPC level is 300 mm.

You may answer unknown.

Please, enter the DPC level, in mm:

300

FKeys: 1 Help 2 Quit 3 Why?

7 Expand 8 Review

Screen I53

STRIP DEPTH

Press F7 to explain.

The previous value for strip depth is 600 mm.

You may answer unknown.

Please, enter the average strip depth, in mm:

600

FKeys: 1 Help 2 Quit 3 Why?

7 Expand 8 Review

Screen I54

VOLUME OF CONCRETE FOR FOUNDATIONS

The previous value for the foundations concrete volume is
534.00 m2.

You may type unknown.

Please, type the volume of concrete, in m2:

534

FKeys: 1 Help 2 Quit 3 Why?

7 Expand 8 Review

Screen I55

VOLUME OF EXCAVATION FOR FOUNDATIONS

The previous value for the foundations excavation volume is
458.00 m2.

You may type unknown.

Please, type the volume of excavation, in m2:

458

FKeys: 1 Help 2 Quit 3 Why?

7 Expand 8 Review

Screen I56

VIBRO-COMPACTION

Could you inform whether the soil under the foundations or the floor slab needs to be vibro-compacted.

The previous value for vibro-compaction is needed.

Please, type the correct answer.

needed
not needed
unknown

FKeys: 1 Help 2 Quit 3 Why?

7 Expand 8 Review

NOTE: option "needed" selected

Screen I57

VIBROCOMPACTION DEPTH

The previous value for the average vibrocompaction depth is 2850 mm.

You may answer unknown.

Please, enter the average vibrocompaction depth, in mm:

2850

FKeys: 1 Help 2 Quit 3 Why?

7 Expand 8 Review

Screen I58

SPECIFICATION OF COMPONENTS

The previous value for the specification of components is available.

Please, inform whether the specification of components is

available
not available

FKeys: 1 Help 2 Quit 3 Why?

7 Expand 8 Review

Screen I59

NUMBER OF VIBROCOMPACTION POINTS

The previous value for number of vibrocompaction points is 432.

You may type unknown.

Please, enter the number of vibrocompaction points:

432

FKeys: 1 Help 2 Quit 3 Why?

7 Expand 8 Review

NOTE: option "available" selected

Screen I60

COMPLEXITY OF FINISHINGS AND SERVICES

Press F7 to explain.

The previous value for the complexity of finishings and services is simple.

Please, choose the correct option:

very simple
simple
medium
complex
very complex
unknown

FKeys: 1 Help 2 Quit 3 Why?

7 Expand 8 Review

Screen I61

COMPLEXITY OF FINISHINGS AND SERVICES

(i) Very simple: wall lining is likely to be dry lining; ceiling decoration is artex, or similar material; floor tiling is likely to 4mm carpet, and thermoplastic in the wet areas; minimum number of electric sockets; very simple hydraulic installations; fairly simple heating system.

(ii) Simple: intermediary between very simple and medium.

(iii) Medium: wall lining is either dry lining or plasterboard & plaster; some amount of wall tiling is required; heating system is likely to include hot water radiators; standard electrical and hydraulic installations.

(iv) Complex: intermediary between medium and very complex.

(v) Very complex: high quality wood in doors and windows; walls are likely to be all rendered; a large amount of wall tiling is required; floor tiling is likely to include ceramic tiles; heating system is fairly complex; several electric sockets per room.

Hit any key to continue

NOTE: this screen displays an explanation required from Screen I61

Screen I62

EXTERNAL FINISHINGS

The previous value for the external finishings is facing bricks.

The specification for external finishings is:

facing bricks
18mm two coat rendering
unknown

FKeys: 1 Help 2 Quit 3 Why?

7 Expand 8 Review

Screen I63

CAVITY WALL INNER LEAF

The previous specification of cavity wall inner leaf is 140mm heavy concrete block.

The specification for cavity wall inner leaf is:

100mm medium concrete block
140mm medium concrete block
100mm heavy concrete block
140mm heavy concrete block
timber frame panels
unknown

FKeys: 1 Help 2 Quit 3 Why?

7 Expand 8 Review

Screen I64

CAVITY WALL OUTER LEAF

The previous specification of cavity wall outer leaf is pointed half facing brick.

The specification for cavity wall outer leaf is:

pointed half facing brick
rough half common brick
facing brick and timber cladding
unknown

FKeys: 1 Help 2 Quit 3 Why?

7 Expand 8 Review

Screen I65

HEAVY PARTITIONS

The previous specification for heavy partitions is 100mm medium concrete block.

The specification for heavy partitions is:

100mm medium concrete block
140mm medium concrete block
100mm heavy concrete block
140mm heavy concrete block
none
unknown

FKeys: 1 Help 2 Quit 3 Why?

7 Expand 8 Review

Screen I66

WALL UP TO DPC

The previous specification for the foundation wall is same as cavity wall.

The specification for walls up to DPC is:

same as cavity wall
pointed 1 1/2 common bricks
pointed two common bricks
unknown

FKeys: 1 Help 2 Quit 3 Why?

7 Expand 8 Review

Screen I67

PARTY WALL

The previous specification for party wall is 140mm heavy concrete block.

The specification for party wall is:

double 100mm medium concrete block
140mm medium concrete block
double 100mm heavy concrete block
140mm heavy concrete block
double rough half common brick
rough one common brick
rough 1 1/2 common bricks
unknown

FKeys: 1 Help 2 Quit 3 Why?

7 Expand 8 Review

Screen I68

LIGHT PARTITIONS

The previous specification for light partitions is paramount partitions.

The specification for light partitions is:

stud partitions
paramount partitions
100mm light concrete block
140mm light concrete block
215mm light concrete block
none
unknown

FKeys: 1 Help 2 Quit 3 Why?

7 Expand 8 Review

Screen I69

EXTERNAL WALL

The previous specification for external wall is pointed half facing brick.

The specification for the external wall is:

pointed half facing brick
pointed half common brick
rough half common brick
unknown

FKeys: 1 Help 2 Quit 3 Why?

7 Expand 8 Review

Screen I70

WALL FINISHINGS

The previous specification for wall finishings is 18mm cement rendering.

The specification for wall finishings is:

18mm cement rendering
12mm cement rendering
13mm gypsum plaster
13mm plasterboard & 10mm gypsum plaster
15mm gypsum plasterboard
unknown

FKeys: 1 Help 2 Quit 3 Why?

7 Expand 8 Review

Screen I71

CEILING LINING

The previous specification for the ceiling lining is 13mm plasterboard & 10mm gypsum plaster.

The specification for ceiling lining is:

13mm plasterboard & 10mm gypsum plaster
15mm gypsum plasterboard
plate ceiling
unknown

FKeys: 1 Help 2 Quit 3 Why?

7 Expand 8 Review

Screen I72

FLOOR SLAB

The previous specification of floor slab is reinforced concrete slab.

The specification for the floor slab is:

unreinforced concrete slab
timber floor
reinforced concrete slab
suspended concrete slab
unknown

FKeys: 1 Help 2 Quit 3 Why?

7 Expand 8 Review

Screen I73

VOLUME OF CONCRETE FOR GROUND FLOOR

Please, enter the total volume of concrete for floor slab and cavity wall filling.

The previous value for the ground floor concrete volume is unknown.

You may type unknown.

Please, type the volume of concrete, in m2:

unknown

FKeys: 1 Help 2 Quit 3 Why?

7 Expand 8 Review

Screen I74

GROUND FLOOR SLAB THICKNESS

The previous value for the slab thickness is unknown.

You may answer unknown

Please, enter the ground floor thickness, in mm:

unknown

FKeys: 1 Help 2 Quit 3 Why?

7 Expand 8 Review

Screen I75

SUSPENDED FLOOR

The previous specification for the suspended floor is timber floor.

The specification for the suspended floor is:

timber floor
suspended concrete slab
unknown

FKeys: 1 Help 2 Quit 3 Why?

7 Expand 8 Review

Screen I76

TYPE OF HEATING

The previous specification for type of heating is gas.

The specification for type of heating system is:

gas
electric
gas and electric
unknown

FKeys: 1 Help 2 Quit 3 Why?

5 Volunteer 6 Backup 7 Expand 8 Review

Screen I77

SEQUENCE OF CONSTRUCTION

The previous value for the sequence of construction is unknown.

Type F7 to get some guidelines for establishing the sequence of construction.

Please, inform whether the construction sequence is known:

known
unknown

FKeys: 1 Help 2 Quit 3 Why?

7 Expand 8 Review

NOTE: option "unknown" selected

Screen I78

SEQUENCE OF WORK PLACES

If the sequence in which the houses will be delivered has not been previously established by the client, I suggest the following guidelines for establishing the sequence of construction:

- (i) The job should start by houses that have already road access, or by the ones for which the necessary access can be quickly constructed;
- (ii) Sequential work places should be located as near as possible from each other, in order to avoid an excessive movement of gangs and equipment around the site;
- (iii) The section of the site where the compound is located should preferably be one of the last ones to be concluded, so that the traffic concerned with the work on site does not have to cross sections where the houses have already been concluded; and
- (iv) If vandalism in the area is likely, the newly completed houses can be used, after being delivered, as a barrier between the site and other housing states in the neighbourhood.

Hit any key to continue

NOTE: this screen displays an explanation required from Screen 78

Screen I79

ROAD ACCESS TO ALL HOUSES

The sequence of houses in this project is unknown. However, you might know whether there is road access for all houses.

The previous value for access to all houses is unknown.

Please, inform whether road access to all houses exist:

existent
non existent
unknown

FKeys: 1 Help 2 Quit 3 Why?

7 Expand 8 Review

Screen I80

NEXT STEP

Please, choose the next step:

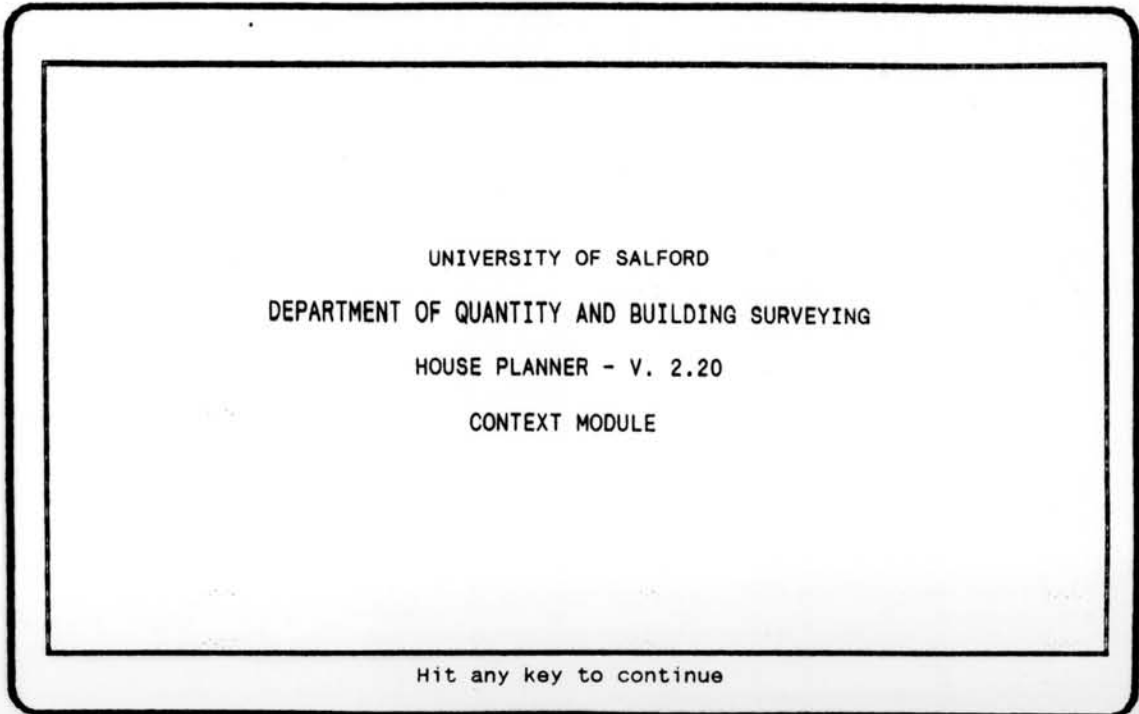
quit HOUSE PLANNER
run INPUT MODULE again
run BUILD MODULE

FKeys: 1 Help 2 Quit 3 Why?

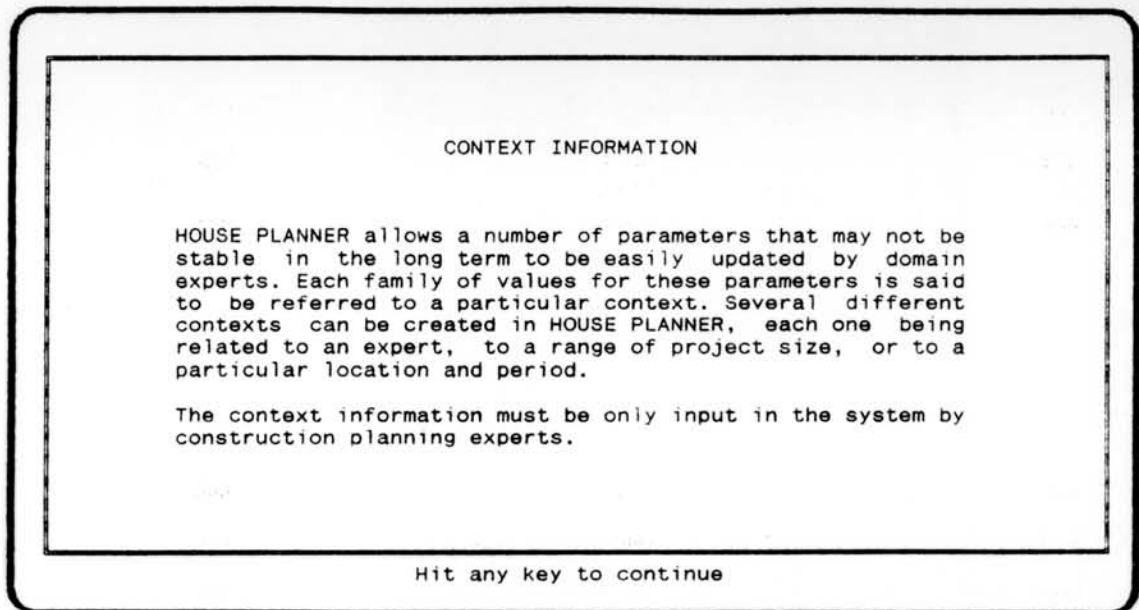
7 Expand 8 Review

Screen I81

A4.2 Context Module



Screen C1



Screen C2

OLD OR NEW CONTEXT

Could you inform whether the context you want to use is old or new.

Please, choose the correct answer:

old
new

FKeys: 1 Help 2 Quit 3 Why? 5 Volunteer 6 Backup 7 Expand 8 Review

NOTE: option "old" selected

Screen C3

NAME OF THE CONTEXT

Could you type the name of the context (max 8 characters):

default

FKeys: 2 Quit

Screen C4

CONTEXT LOCATION

In this form you can identify the context in terms of location.

The previous location for this context is North West.

Please, type the context location (max 15 characters):

North West

FKeys: 1 Help 2 Quit 3 Why?

5 Volunteer 6 Backup 7 Expand 8 Review

Screen C5

MINIMUM NUMBER OF HOUSES

Could you enter the minimum size of project, expressed in terms of the number of houses, that can be considered in the current context. You may type unknown.

The previous value for the minimum number of houses is 10.

Please, type the minimum number of houses:

10

FKeys: 1 Help 2 Quit 3 Why?

5 Volunteer 6 Backup 7 Expand 8 Review

Screen C6

MAXIMUM NUMBER OF HOUSES

Could you enter the maximum size of project, expressed in terms of the number of houses, that can be considered in the current context.
You may type unknown

The previous value for the maximum number of houses is
180.

Please, type the maximum number of houses:

FKeys: 1 Help 2 Quit 3 Why? 5 Volunteer 6 Backup 7 Expand 8 Review

Screen C7

MINIMUM AVAILABILITY OF BRICKLAYERS

Could you enter the maximum number of bricklayers that might be expected to be hired for a single project in a situation of shortage of labour in the market, in the current context.
You may type unknown.

The previous value for minimum availability of bricklayers is
8.

Please, type the number of bricklayers available:

FKeys: 1 Help 2 Quit 3 Why? 5 Volunteer 6 Backup 7 Expand 8 Review

Screen C8

MAXIMUM AVAILABILITY OF BRICKLAYERS

Could you enter the maximum number of bricklayers that might be expected to be hired for a single project in a situation of high availability of labour in the market, in the current context. You may type unknown.

The previous value for maximum availability of bricklayers is 30.

Please, type the number of bricklayers available:

FKeys: 1 Help 2 Quit 3 Why?

5 Volunteer 6 Backup 7 Expand 8 Review

Screen C9

RATIO BETWEEN PEAK AND AVERAGE FOUNDATION SPEED

Could you enter the number of times the peak rate should be greater than the average rate in the foundation stage.

You may type unknown.

The previous value for the ratio between peak and average foundation speed is 1.40.

Please, enter a number, or type F7 for explain:

FKeys: 1 Help 2 Quit 3 Why?

5 Volunteer 6 Backup 7 Expand 8 Review

Screen C10

RATIO BETWEEN PEAK AND AVERAGE SHELL SPEED

Could you enter the number of times the peak rate should be greater than the average rate in the shell/roofing stage.

You may type unknown.

The previous value for the ratio between peak and average shell speed is 1.20.

Please, enter a number, or type F7 for explain:

FKeys: 1 Help 2 Quit 3 Why?

5 Volunteer 6 Backup 7 Expand 8 Review

Screen C11

RATIO BETWEEN PEAK AND AVERAGE FINISHING SPEED

Could you enter the number of times the peak rate should be greater than the average rate in the finishing stages.

You may type unknown.

The previous value for the ratio between peak and average finishing speed is 1.20.

Please, enter a number, or type F7 for explain:

FKeys: 1 Help 2 Quit 3 Why?

5 Volunteer 6 Backup 7 Expand 8 Review

Screen C12

RATIO BETWEEN ACCELERATION AND DECELERATION PERIOD

Could you enter the ratio between the length of the acceleration period and the length of the deceleration period.

You may type unknown.

The previous value for the ratio between the acceleration and the deceleration period is 2.00.

Please, type a number:

2

FKeys: 1 Help 2 Quit 3 Why? 5 Volunteer 6 Backup 7 Expand 8 Review

Screen C13

MINIMUM EXCAVATING RATE

In this form you can enter the minimum amount of reduced level excavation, expressed in terms of m3/week, that can be considered as reasonable for house building projects.

You may type unknown.

The previous value for the minimum excavating rate is 500 m3/week.

Please, enter the economic minimum excavating rate:

500

FKeys: 1 Help 2 Quit 3 Why? 5 Volunteer 6 Backup 7 Expand 8 Review

Screen C14

MAXIMUM EXCAVATING RATE

In this form you can enter the maximum amount of reduced level excavation, expressed in terms of m³/week, that can be considered as reasonable for house building projects.

You may type unknown.

The previous value for the maximum excavating rate is 5000 m³/week.

Please, enter the economic maximum excavating rate:

5000

FKeys: 1 Help 2 Quit 3 Why? 5 Volunteer 6 Backup 7 Expand 8 Review

Screen C15

MAXIMUM CONCRETING RATE

In this form you can enter the maximum amount of concrete that is considered as reasonable to be casted per week in a house building site.

You may type unknown.

The previous value for the maximum concreting rate is 160 m³.

Please, enter the maximum weekly concreting rate in m³:

160

FKeys: 1 Help 2 Quit 3 Why? 5 Volunteer 6 Backup 7 Expand 8 Review

Screen C16

MAXIMUM FORMWORK GANG SIZE

You may type unknown.

The previous value for the maximum formwork gang size is
6.

Please, enter the maximum formwork gang size:

6

FKeys: 1 Help 2 Quit 3 Why?

5 Volunteer 6 Backup 7 Expand 8 Review

Screen C17

MAXIMUM PLASTERER GANG SIZE

You may type unknown.

The previous value for the maximum plasterer gang size is
12.

Please, enter the maximum plasterer gang size:

12

FKeys: 1 Help 2 Quit 3 Why?

5 Volunteer 6 Backup 7 Expand 8 Review

Screen C18

BRICKWORK TARGET RANGE

In this form you can answer whether a range of usual targets for bricklayers is available.

The previous value for brickwork target range is available.

Please, choose the correct answer:

available
not available

FKeys: 1 Help 2 Quit 3 Why?

5 Volunteer 6 Backup 7 Expand 8 Review

NOTE: option "available" selected

Screen C19

RANGE OF TARGETS FOR THE BRICKLAYING GANGS

In this form you can enter a range of targets you consider as normal for the bricklaying gangs. This range is expressed in terms of square meters of facing half brick wall per week, and it is used for estimating the initial output of bricklayers (without considering the repetition effect).

Please enter the minimum and the maximum target for bricklayers:

Minimum target: 20.00 m2/week
Maximum target: 38.00 m2/week

FKeys: 1 Help 2 Quit

4 FldHelp

Screen C20

RANGE OF REPETITION EFFECT ON BRICKLAYING GANGS

In this form you can enter a range of repetition effect that you consider as normal for the bricklaying gangs. The repetition effect reflects the percentage the productivity rates are expected to be reduced to if the number of units to be built doubles. The maximum effect is related to the situation in which all houses have identical design, while the minimum effect implies houses with distinct design.

Please, enter the minimum and the maximum repetition effect:

Minimum repetition effect:	98 %
Maximum repetition effect:	96 %

FKeys: 1 Help 2 Quit

4 FldHelp

Screen C21

RANGES FOR THE PRODUCTIVITY OF BRICKLAYERS

The initial productivity of bricklayers (the expected productivity without considering the repetition effect) is estimated by using three indices: design simplicity, geographical continuity, and brickwork concentration. The values of these indices range from 0 to 1. Considering all the other factors constant, you can choose a range of productivity variability for each factor. For instance, a range of 10% for the Design Simplicity factor means that the productivity of bricklayers will range from -5% to +5% around the average, considering the other two factors constant.

Please, enter the brickwork productivity factors' range:

Design simplicity factor.....:	40 %
Brickwork concentration factor:	5 %
Geographical continuity factor:	5 %

FKeys: 1 Help 2 Quit

4 FldHelp

Screen C22

HOUSE DESIGN SIMPLICITY INDICES

Each house design type has a design simplicity index associated to it. The value of this index ranges from 0 to 1, from the most complex design to the most simple one, respectively. This index is used for estimating the productivity of bricklayers.

Please, enter the design simplicity indices:

Rectangular detached house.....	1.00
L-shaped detached house.....	0.90
Irregular detached house.....	0.60
Rectangular semi-detached house..	1.00
L-shaped semi-detached house....	0.90
Irregular semi-detached house...	0.60

FKeys: 1 Help 2 Quit

4 FldHelp

Screen C23

BLOCK DESIGN SIMPLICITY INDEX

Each block design type has a design simplicity index associated to it. The value of this index ranges from 0 to 1, from the most complex design to the most simple one, respectively. This index is used for estimating the productivity of bricklayers.

Please, type the following design simplicity indices:

Rectangular terraced house block with no staggers and no steps..	0.70
Irregular terraced house block with no staggers and no steps...	0.60
Rectangular terraced house block with steps but no staggers....	0.50
Irregular terraced house blocks with steps but no staggers.....	0.40
Rectangular terraced house block with staggers but no steps....	0.30
Irregular terraced house block with staggers but no steps.....	0.20
Rectangular terraced house block with steps and staggers.....	0.10
Irregular terraced house block with steps and staggers.....	0.05

FKeys: 1 Help 2 Quit

4 FldHelp 5 Prev Screen

Screen C24

MINIMUM FINISHING RATE

The finishing rate is expressed in terms of number of houses per week.

You may type unknown.

The previous value for the minimum finishing rate is
1.0.

Please, enter the minimum rate for finishing activities:

FKeys: 1 Help 2 Quit 3 Why? 5 Volunteer 6 Backup 7 Expand 8 Review

Screen C25

MAXIMUM FINISHING RATE

The finishing rate is expressed in terms of number of houses per week.

You may type unknown.

The previous value for the maximum finishing rate is
5.0.

Please, enter the maximum rate for finishing activities:

FKeys: 1 Help 2 Quit 3 Why? 5 Volunteer 6 Backup 7 Expand 8 Review

Screen C26

FINISHING RATES

The finishing activities maximum economic rate estimate is based on how complex the finishings are and on the availability of management in the company. This rate ranges between the minimum and the maximum finishing rate previously input. The finishing rate is expressed in terms of number of houses per week.

Please, confirm or overwrite the following rates:

FINISHINGS COMPLEXITY	AVAILABILITY OF MANAGEMENT				
	very low	low	medium	high	very high
very complex	1.0	1.5	2.0	2.5	3.0
complex	1.5	2.0	2.5	3.0	3.5
medium	2.0	2.5	3.0	3.5	4.0
simple	2.5	3.0	3.5	4.0	4.5
very simple	3.0	3.5	4.0	4.5	5.0

FKeys: 1 Help 2 Quit

4 FldHelp 5 Prev Screen

Screen C27

A4.3 Build Module

UNIVERSITY OF SALFORD
DEPARTMENT OF QUANTITY AND BUILDING SURVEYING
HOUSE PLANNER - V. 2.20
BUILD MODULE

Hit any key to continue

Screen B1

NAME OF THE PROJECT

Could you type the name of the project (max 6 characters):

epsom

FKeys: 2 Quit

Screen B2

PEAK SHELL RATE

I propose the peak shell rate of 3.2 house(s) per week.

The maximum shell rate is 3.2 house(s) per week, considering the maximum number of bricklayers in the current context as 18.

Please, confirm or overwrite the proposed value, or type F3 for explain:

3.2 house(s)/week

FKeys: 1 Help 2 Quit 3 ScrnHelp 4 FldHelp

Screen B3

SHELL RATE

The proposed shell rate (3.2 houses/week) corresponds to the maximum shell rate for this particular project.

The maximum finishing rate was calculated by the following formula:

$$\text{max_shell_rate} = \text{n_house} * \text{brick_output} * \text{max_num_bricklayers} / \text{equiv_half_brick}$$

where n_house is the total number of houses (48); brick_output is the estimated average output of bricklayers (40.06 m2/week), expressed in terms of the equivalent amount of half brick wall; max_num_bricklayers is the maximum number of bricklayers for the present job (18); and equiv_half_brick is the total work content on the bricklaying trade, also expressed by the equivalent amount of half brick wall (10927 m2).

Hit any key to continue

NOTE: this screen displays an explanation required from Screen B3

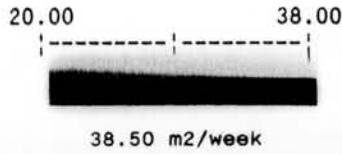
Screen B4

OUTPUT OF BRICKLAYERS

The expected output of bricklayers in the current project, expressed in terms of equivalent sq.meters of half brick wall, is displayed below as well as the minimum and the maximum targets for the current context.

The peak shell rate of 3.2 houses/week is feasible. The number of bricklayers required for this job is 18, and the total duration of shell/roofing activities is 18 weeks.

Please, press RETURN to confirm or F5 to change peak shell rate:



FKeys: 1 Help 2 Quit 3 ScrnHelp 4 FldHelp 5 Prev Screen

Screen B5

OUTPUT OF BRICKLAYERS

The output of bricklayers is estimated according to four indices. The value of each index ranges from 0 to 1. The higher the index the higher is the productivity of bricklayers.

These are the productivity indices for the current job:

INDEX	VALUE	0.....0.5.....1
Design simplicity	1.00	
Design repetitiveness	0.96	
Geographical continuity	1.00	
Brickwork concentration	0.10	

Hit any key to continue

NOTE: this screen displays an explanation required from Screen B5

Screen B6

PEAK FINISHING RATE

I propose the peak shell rate of 2.7 house(s) per week.

The maximum finishing rate in the current context is 3.5 house(s) per week.

Please, confirm or overwrite this value, or type F3 for explain:

2.7 house(s)/week

FKeys: 1 Help 2 Quit 3 ScrnHelp 4 FldHelp 5 Prev Screen

Screen B7

FINISHING RATE

The proposed finishing rate was calculated by the following formula:

$$\text{finishing_rate} = \text{shell_rate} / \text{shell_finishing_ratio}$$

The value of the shell_finishing_ratio is based on the type of project organization and on the likelihood of vandalism in the area. In this particular job, this value was established by the following rule:

IF organization_type is conventional
AND vandalism is not relevant
THEN shell_finishing_ratio = 1.2

Hit any key to continue

NOTE: this screen displays an explanation required from Screen B7

Screen B8

FINISHING PARAMETERS

The number of plasterers needed for carrying out the finishing stage at a rate of 2.7 house(s) per week is 6. The most critical resource for the finishing speed is management.

The total duration of finishing activities for this rate is 21 weeks.

Please, press <RETURN> to confirm or F5 to change peak finishing rate:

2.7 house(s)/week

FKeys: 1 Help 2 Quit

4 FldHelp 5 Prev Screen

Screen B9

PEAK FOUNDATION RATE

I propose the peak foundation rate of 3.8 house(s) per week.

The maximum foundation rate in the current context is 7.3 house(s)/week.
The most critical resource for the foundation speed is bricklayers .

Please, confirm or overwrite this value, or press F3 to explain:

3.8 house(s)/week

FKeys: 1 Help 2 Quit 3 ScrnHelp 4 FldHelp 5 Prev Screen

Screen B10

FOUNDATION RATE

The proposed foundation rate was calculated by the following formula:

$$\text{foundation_rate} = \text{shell_rate} * \text{foundation_shell_ratio}$$

The value of the foundation shell_ratio is based on the type of project organization. In this particular case, this value was established by the following rule:

IF organization_type is conventional
THEN foundation_shell_ratio = 1.2

Hit any key to continue

NOTE: this screen displays an explanation required from Screen B10
Screen B11

FOUNDATION PARAMETERS

Foundation excavation rate.....	36 m3/week
Formwork rate.....	0 m2/week
No. of formwork joiners.....	0
Concreting rate.....	42 m3/week
No. of bricklayers for foundations:	4
Total duration of activities.....	18 weeks

Please, press <RETURN> to confirm or F5 to change peak foundation rate:

3.8 house(s)/week

FKeys: 1 Help 2 Quit

4 FldHelp 5 Prev Screen

Screen B12

DISTRIBUTION OF TWO FLOOR HOUSES ON SITE

Please, enter how the two floor houses are distributed:

concentrated in the beginning
equally distributed
concentrated in the end
unknown

FKeys: 1 Help 2 Quit 3 Why? 5 Volunteer 6 Backup 7 Expand 8 Review

Screen B13

CONSTRUCTION PROGRAMME
PROJECT NAME: epsom CURRENT CONTEXT: default CURRENT DATE: 26-Jan-91 13:50

WEEK 1 1111111112 2222222223 3333333334 4444444445
No. 1234567890 1234567890 1234567890 1234567890 1234567890

- 1 set up site
- 2 clear site
- 3 vibrocompacting
- 4 site shaping
- 5 main drainage
- 6 roads to subbase
- 7 kerb race
- 8 ducts/gullies
- 9 base course



BUFFER BETWEEN SITE PREPARATION AND FOUNDATIONS

The foundation stage is due to start at week No.12. Please, confirm or overwrite the stage buffer proposed below or press F4 to explain:

1 week(s)

STAGE: site preparation DEPENDENCY: ducts/
FKeys: 1 Help 2 Quit 4 FldHelp

Screen B14

CONSTRUCTION PROGRAMME

PROJECT NAME: epsom CURRENT CONTEXT: default CURRENT DATE: 26-Jan-91 13:57

WEEK 1 111111112 222222223 333333334 444444445
 No. 1234567890 1234567890 1234567890 1234567890 1234567890

1 set up site					
2 clear site	■				
3 vibrocompacting	■				
4 site shaping	■				
5 main drainage	■				
6 roads to subbase	■	■			
7 kerb race	■	■	■		
8 ducts/gullies	■	■	■	■	
9 base course	■	■	■	■	■
10 excavate footings	0022233	444	344433	21	
11 concrete footings	0022233	444	344433	21	
12 brickwork to DPC	002223	344	434443	321	
13 service entries	00222	334	443444	3321	
14 house drainage	0022	233	444344	43321	
15 hardcore	0022	233	444344	43321	

STAGE: foundations DEPENDENCY: service entries TRADE: general labourer
 Hit any key to continue

Screen B17

CONSTRUCTION PROGRAMME

PROJECT NAME: epsom CURRENT CONTEXT: default CURRENT DATE: 26-Jan-91 13:58

WEEK 1 111111112 222222223 333333334 444444445
 No. 1234567890 1234567890 1234567890 1234567890 1234567890

16 concrete slab	0022	233	4443		
------------------	------	-----	------	--	--

BUFFER BETWEEN
FOUNDATION AND SHELL/ROOFING

The shell/roofing stage is due to start at week No.11.
 Please, confirm or overwrite the stage buffer proposed below, or press F4 to explain.

1 week(s)

STAGE: foundations DEPENDENCY: hardco
 FKeys: 1 Help 2 Quit 4 F1dHelp

Screen B18

FOUNDATIONS DURING WINTER MONTHS

The foundation stage is scheduled to be carried out during the winter months. I suggest to change this schedule in order to avoid that inclement weather interferes in the continuity and productivity of weather sensitivity activities.

Please, type F3 to confirm or F4 to keep the schedule unchanged:

The possible actions are:

Postpone the whole job
Slow down job start

FKeys: 2 Quit 3 Confirm 4 Cancel action

NOTE: option "cancel action" selected

Screen B19

CONSTRUCTION PROGRAMME
PROJECT NAME: epsom CURRENT CONTEXT: default CURRENT DATE: 26-Jan-91 14:20

WEEK 1 1111111112 2222222223 3333333334 4444444445
No. 1234567890 1234567890 1234567890 1234567890 1234567890

16 concrete slab	0022	233	444344	43321
17 brickwork 1st lift	012	333433	334333331	
18 scaffold 1st stage				
19 brickwork 2nd lift	01	233343	3334333331	
20 scaffold 2nd stage				
21 1st floor joists	0	012122	1212212121	1
22 brickwork 3rd lift	001212	2121221212	11	
23 scaffold 3rd stage				
24 brickwork 4th lift	00121	2212122121	211	
25 scaffold 4th stage				
26 brickwork to peaks	0123	3343333433	3331	
27 roof carcass	0123	3343333433	3331	
28 SVP gutters & RWP	012	3334333343	33331	
29 tile roof	012	3334333343	33331	
30 strip scaffold				

STAGE: shell/roofing DEPENDENCY: tile roof TRADE: scaffolder
Hit any key to continue

Screen B20

CONSTRUCTION PROGRAMME

PROJECT NAME: epsom CURRENT CONTEXT: default CURRENT DATE: 26-Jan-91 14:03

WEEK 111111112 222222223 333333334 444444445 555555556
 No. 1234567890 1234567890 1234567890 1234567890 1234567890

31 external openings 01 23334333 32 glazing - -	<div style="border: 1px solid black; padding: 5px;"> <p style="text-align: center;">BUFFER BETWEEN SHELL/ROOFING AND FIRST FIX</p> <p>The first fix plaster stage is due to start at week No.22. Please, confirm or overwrite the stage buffer proposed below, or press F4 to explain.</p> <div style="border: 1px solid black; width: 100px; margin: 10px auto; text-align: center;">0 week(s)</div> </div>
---	--

STAGE: shell/roofing DEPENDENCY: extern
 FKeys: 1 Help 2 Quit 4 FldHelp

Screen B21

CONSTRUCTION PROGRAMME

PROJECT NAME: epsom CURRENT CONTEXT: default CURRENT DATE: 27-Jan-91 22:21

WEEK 111111112 222222223 333333334 444444445 555555556
 No. 1234567890 1234567890 1234567890 1234567890 1234567890

31 external openings 01 23334333 32 glazing - - 33 joinery 1st fix 0112323 34 plumbing 1st fix 011232 35 heating 1st fix 011232 36 electric. 1st fix 01123 37 internal rendering 0112 38 plasterboard 0112 39 gypsum plaster 0112 40 skim coat 0112 41 floor screed 011	<div style="border: 1px solid black; padding: 5px;"> <p style="text-align: center;">BUFFER BETWEEN FIRST FIX/PLASTER AND SECOND FIX</p> <p>The second fix/finals stage is due to start at week No.28. Please, confirm or overwrite the stage buffer proposed below, or press F4 to explain.</p> <div style="border: 1px solid black; width: 100px; margin: 10px auto; text-align: center;">0 week(s)</div> </div>
--	---

STAGE: first fix/plaster DEPENDENCY: skim c
 FKeys: 1 Help 2 Quit 4 FldHelp

Screen B22

CONSTRUCTION PROGRAMME

PROJECT NAME: epsom CURRENT CONTEXT: default CURRENT DATE: 26-Jan-91 14:20

BUFFER BETWEEN FIRST FIX/PLASTER AND SECOND FIX/FINALS

This buffer was established from the following rules:

```

31 extern This buffer was established from the following rules:
32 glazin
33 joiner if management_availab is 'very high'
34 plumbi or management_availab is 'high'
35 heatin or management_availab is 'medium'
36 electr then buffer = 0
37 intern
38 plaste if management_availab is 'very low'
39 gypsum or management_availab is 'low'
40 skim c then buffer = 1
41 floor

```

COND FIX
age is
28.
rite the
low, or
you want
choose

Hit ESC to quit

0 week(s)

STAGE: first fix/plaster DEPENDENCY: skim c
FKeys: 1 Help 2 Quit 4 FldHelp

NOTE: this screen displays an explanation required from Screen B22

Screen B23

CONSTRUCTION PROGRAMME

PROJECT NAME: epsom CURRENT CONTEXT: default CURRENT DATE: 26-Jan-91 14:03

WEEK 1111111112 222222223 333333334 444444445 555555556
No. 1234567890 1234567890 1234567890 1234567890 1234567890

31 external openings	01	2333433334	333331
32 glazing	-		
33 joinery 1st fix		011232332	3332332332 31
34 plumbing 1st fix		01123233	2333233233 231
35 heating 1st fix		01123233	2333233233 231
36 electric. 1st fix		0112323	3233323323 3231
37 internal rendering		011232	3323332332 33231
38 plasterboard		011232	3323332332 33231
39 gypsum plaster		011232	3323332332 33231
40 skim coat		011232	3323332332 33231
41 floor screed		01123	2332333233 233231
42 joinery 2nd fix		011	2323323332 33233231
43 plumbing 2nd fix		011	2323323332 33233231
44 heating 2nd fix		011	2323323332 33233231
45 porch joinery			

STAGE: second fix/finals DEPENDENCY: floor screed TRADE: joiner
Hit any key to continue

Screen B24

CONSTRUCTION PROGRAMME

PROJECT NAME: epsom CURRENT CONTEXT: default CURRENT DATE: 26-Jan-91 14:05

WEEK 222222223 333333334 444444445 555555556 666666667
 No. 1234567890 1234567890 1234567890 1234567890 1234567890

46 porch roof tiling			
47 electric. 2nd fix	01	1232332333	233233231
48 gas meter	-	-	-
49 electric meter	-	-	-
50 plumbing testing	0112323323	332332332	31
51 loft insulation			
52 artex on ceilings	011232332	333233233	231
53 joinery final fix	01123233	233323323	3231
54 wall tiling			
55 internal painting	0112323	323332332	33231
56 floor tiling			
57 external painting	011232	332333233	233231
58 ironmongery	01123	233233323	3233231
59 handover	0112	323323332	33233231
60 wearing course			

STAGE: landscape DEPENDENCY: handover TRADE: subcontractor
 Hit any key to continue

Screen B25

CONSTRUCTION PROGRAMME

PROJECT NAME: epsom CURRENT CONTEXT: default CURRENT DATE: 26-Jan-91 14:07

WEEK 111111112 222222223 333333334 444444445 555555556
 No. 1234567890 1234567890 1234567890 1234567890 1234567890

61 white lining			
62 permanent kerbs			
63 landscaping			
64 fencing			
65 house footpath			
66 place top soil			
67 public footpath			
68 external brickwork			
69 ext. foundations			
70 elect. connection			
71 gas connection			
72 water connection			
73 BT connection			
74 water mains			
75 gas mains			

STAGE: landscape DEPENDENCY: water mains TRADE: gas board
 Hit any key to continue

Screen B26

CONSTRUCTION PROGRAMME

PROJECT NAME: epsom CURRENT CONTEXT: default CURRENT DATE: 26-Jan-91 14:10

WEEK 1111111112 222222223 333333334 444444445 555555556
 No. 1234567890 1234567890 1234567890 1234567890 1234567890

76 electric mains	---	---	
77 BT mains	---	---	
78 street lighting		-----	
79 clear away			■

STAGE: landscape DEPENDENCY: handover TRADE: general labourer
 Hit any key to continue

Screen B27

RESOURCES TO BE SCHEDULED

Please, enter the resources you want to be scheduled:

formwork joiner
 joiner
 plasterer
 bricklayer
 none

FKeys: 1 Help 2 Quit 3 Why? 7 Exp 8 Rev <Ins> Add Remove

NOTE: option "none" selected

Screen B28

TYPE OF OUTPUT

Please, choose the kind of output you would like to have:

```
display general programme
print general programme
print schedule of milestones
print list of activities
none
```

FKeys: 1 Help 2 Quit 3 Why?

7 Exp 8 Rev <Ins> Add Remove

NOTE: option "none" selected

Screen B29

NEXT STEP

Please, choose the next step:

```
quit HOUSE PLANNER
run BUILD MODULE again
run INPUT MODULE
perform WHAT IF questions
```

FKeys: 1 Help 2 Quit 3 Why?

7 Expand 8 Review

NOTE: option "perform WHAT IF questions" selected

Screen B30

OBJECTS TO CHANGE FOR WHAT IF SESSION

Choose the objects you would like to change the value:

bricklayer availability
management availability
bricklayers' over time index
max duration
max period for first handover
finishing complexity
temporary roads
No. houses with access

FKeys: 1 Help 2 Quit 3 Why?

7 Exp 8 Rev <Ins> Add Remove

NOTE: option "management availability" selected

Screen B31

AVAILABILITY OF MANAGEMENT

Could you inform what is the situation within the company in terms of availability of management for the current job.

The previous value for the availability of management is medium.

Please, type the correct answer:

very high
high
medium
low
very low
unknown

FKeys: 1 Help 2 Quit 3 Why?

7 Expand 8 Review

NOTE: after changing the value of this variable, the system goes back to Screen B3 and starts a new cycle

Screen B32

APPENDIX 5: AN EXAMPLE OF SCHEDULE OF CONSTRUCTION ACTIVITIES

ACTIVITY LIST

PROJECT NAME: epsom		CONTEXT NAME: default		DATE: 26-Jan-91 19:14		RUN No. 1				
No.	NAME	STAGE	TRADE	TYPE	DEPENDENCY	LINK-TYPE	FACTOR	DUR. (w)	1ST WEEK	MAN- HOURS
1	set up site	site preparation	general labourer	barchart	none	start-start		2	1	
2	clear site	site preparation	general labourer	barchart	set up site	start-start	provide service	2	1	
3	vibrocompacting	site preparation	subcontractor	barchart	clear site	start-start	multi-layers	2	2	
4	site shaping	site preparation	general labourer	barchart	vibrocompacting	parallel	avoid damage	3	2	
5	main drainage	site preparation	drain layer	barchart	site shaping	start-start	multi-layers	11	3	
6	roads to subbase	site preparation	general labourer	barchart	main drainage	start-start	multi-layers	11	4	
7	kerb race	site preparation	general labourer	barchart	roads to subbase	start-start	multi-layers	11	5	
8	ducts/gullies	site preparation	general labourer	barchart	kerb race	start-start	multi-layers	11	5	
9	base course	site preparation	general labourer	stretched	ducts/gullies	end-end	multi-layers	6	10	
10	excavate footings	foundations	general labourer	continuous	site shaping	start-start	multi-layers	18	4	
11	concrete footings	foundations	general labourer	continuous	excavate footings	start-start	multi-layers	18	4	
13	service entries	foundations	drain layer	continuous	brickwork to DPC	start-start	flexibility	18	6	
14	house drainage	foundations	drain layer	continuous	service entries	end-start	resources	18	7	
15	hardcore	foundations	general labourer	continuous	service entries	end-start	multi-layers	18	7	
12	brickwork to DPC	foundations	bricklayer	continuous	concrete footings	start-start	structural	18	5	32
16	concrete slab	foundations	general labourer	continuous	hardcore	end-start	multi-layers	18	7	
17	brickwork 1st lift	shell/roofing	bricklayer	continuous	concrete slab	end-start	multi-layers	18	11	51
18	scaffold 1st stage	shell/roofing	scaffolder	stretched	brickwork 1st lift	start-start	provide service	18	11	
19	brickwork 2nd lift	shell/roofing	bricklayer	continuous	scaffold 1st stage	end-start	provide service	18	12	51
20	scaffold 2nd stage	shell/roofing	scaffolder	stretched	brickwork 2nd lift	end-start	provide service	18	12	
21	1st floor joists	shell/roofing	2nd joiner	continuous	scaffold 2nd stage	end-start	provide service	18	13	
22	brickwork 3rd lift	shell/roofing	2nd bricklayer	continuous	1st floor joists	end-start	multi-layers	18	14	44
23	scaffold 3rd stage	shell/roofing	scaffolder	stretched	brickwork 3rd lift	start-start	provide service	18	14	
24	brickwork 4th lift	shell/roofing	2nd bricklayer	continuous	scaffold 3rd stage	end-start	provide service	18	15	44
25	scaffold 4th stage	shell/roofing	scaffolder	stretched	brickwork 4th lift	end-start	provide service	18	15	
26	brickwork to peaks	shell/roofing	bricklayer	continuous	scaffold 4th stage	end-start	provide service	18	16	8
27	roof carcass	shell/roofing	joiner	continuous	brickwork to peaks	parallel	multi-layer	18	16	
28	SVP gutters & RWP	shell/roofing	plumber	continuous	roof carcass	end-start	structural	18	17	
29	tile roof	shell/roofing	roof tiler	continuous	SVP gutters & RWP	parallel	multi-layers	18	17	
30	strip scaffold	shell/roofing	scaffolder	stretched	tile roof	end-start	provide service	18	17	
31	external openings	shell/roofing	joiner	continuous	tile roof	start-start	environment	18	18	
32	glazing	shell/roofing	glazier	stretched	external openings	start-start	structural	18	19	
45	porch joinery	second fix/finals	joiner	barchart	floor screed	end-start	lack of space	18	27	
46	porch roof tiling	second fix/finals	roof tiler	barchart	porch joinery	end-start	structural	18	28	
30	strip scaffold	shell/roofing	scaffolder	stretched	tile roof	end-start	provide service	21	17	
33	joinery 1st fix	first fix/plaster	joiner	continuous	glazing	start-start	environment	21	21	
34	plumbing 1st fix	first fix/plaster	plumber	continuous	joinery 1st fix	start-start	flexibility	21	22	
35	heating 1st fix	first fix/plaster	heating engineer	continuous	plumbing 1st fix	parallel	provide service	21	22	
36	electric. 1st fix	first fix/plaster	electrician	continuous	plumbing 1st fix	start-start	flexibility	21	23	
37	internal rendering	first fix/plaster	plasterer	continuous	electric. 1st fix	end-start	multi-layers	21	24	41
38	plasterboard	first fix/plaster	plasterer	continuous	internal rendering	start-start	multi-layers	21	24	8
39	gypsum plaster	first fix/plaster	plasterer	continuous	plasterboard	start-start	multi-layers	21	24	17
40	skim coat	first fix/plaster	plasterer	continuous	plasterboard	start-start	multi-layers	21	24	10

APPENDIX 5: AN EXAMPLE OF SCHEDULE OF CONSTRUCTION ACTIVITIES (cont.)

ACTIVITY LIST

PROJECT NAME: epsom

CONTEXT NAME: default

DATE: 26-Jan-91 19:14

RUN No. 1

No.	NAME	STAGE	TRADE	TYPE	DEPENDENCY	LINK-TYPE	FACTOR	DUR. (w)	1ST WEEK	MAN- HOURS
41	floor screed	first fix/plaster	plasterer	continuous	skim coat	start-start	avoid damage	21	25	14
42	joinery 2nd fix	second fix/finals	joiner	continuous	floor screed	end-start	multi-layers	21	27	
43	plumbing 2nd fix	second fix/finals	plumber	continuous	joinery 2nd fix	start-start	multi-layers	21	27	
44	heating 2nd fix	second fix/finals	heating engineer	continuous	plumbing 2nd fix	parallel	provide service	21	27	
47	electric. 2nd fix	second fix/finals	electrician	continuous	plumbing 2nd fix	start-start	lack of space	21	28	
45	porch joinery	second fix/finals	joiner	barchart	floor screed	end-start	lack of space	21	27	
46	porch roof tiling	second fix/finals	roof tiler	barchart	porch joinery	end-start	structural	21	28	
48	gas meter	second fix/finals	gas board	stretched	porch roof tiling	end-start	environment	21	29	
49	electric meter	second fix/finals	electric. board	stretched	electric. 2nd fix	start-start	provide service	21	29	
50	plumbing testing	second fix/finals	plumber	continuous	gas meter	end-start	provide service	21	30	
53	joinery final fix	second fix/finals	joiner	continuous	artex on ceiling	start-start	avoid damage	21	32	
54	wall tiling	second fix/finals	wall tiler	stretched	joinery final fix	start-start	multi-layers	21	32	
51	loft insulation	second fix/finals	subcontractor	stretched	plumbing testing	end-start	environment	21	31	
52	artex on ceilings	second fix/finals	decorator	continuous	plumbing testing	end-start	environment	21	31	
55	internal painting	second fix/finals	decorator	continuous	wall tiling	start-start	multi-layers	21	33	
56	floor tiling	second fix/finals	floor tiler	stretched	internal painting	start-start	avoid damage	21	34	
57	external painting	second fix/finals	decorator	continuous	internal painting	start-start	resource	21	34	
58	ironmongery	second fix/finals	joiner	continuous	floor tiling	start-start	provide service	21	35	
59	handover	second fix/finals		continuous	ironmongery	end-start	none	21	36	
60	wearing course	landscape	subcontractor	barchart	handover	end-end	avoid damage	1	56	
67	public footpath	landscape	subcontractor	stretched	wearing course	end-end	avoid damage	21	34	
78	street lighting	landscape	subcontractor	stretched	electric mains	end-start	provide service	26	28	
62	permanent kerbs	landscape	kerber	barchart	wearing course	end-start	avoid damage	1	55	
69	ext. foundations	landscape	general labourer	barchart	external brickwork	end-end	structural	33	18	
68	external brickwork	landscape	bricklayer	barchart	house footpath	end-end	multi-layers	32	20	
63	landscaping	landscape	subcontractor	stretched	handover	end-end	avoid damage	21	35	
65	house footpath	landscape	general labourer	stretched	internal painting	end-end	avoid damage	21	32	
64	fencing	landscape	subcontractor	stretched	landscaping	end-end	avoid damage	21	34	
66	place top soil	landscape	general labourer	stretched	house footpath	end-end	avoid damage	21	31	
72	water connection	landscape	water board	stretched	gas connection	end-end	multi-layers	21	26	
71	gas connection	landscape	gas board	stretched	elect.connection	end-end	multi-layers	21	27	
70	elect.connection	landscape	electric. board	stretched	electric meter	end-end	multi-layers	21	28	
73	BT connection	landscape	British Telecom	stretched	elect.connection	start-start	multi-layers	21	29	
74	water mains	landscape	water board	stretched	main drainage	start-start	provide service	21	5	
75	gas mains	landscape	gas board	stretched	water mains	start-start	multi-layers	21	6	
76	electric mains	landscape	electr. board	stretched	gas mains	start-start	multi-layers	21	7	
77	BT mains	landscape	British Telecom	stretched	electric mains	start-start	multi-level	21	8	
61	white lining	landscape	subcontractor	barchart	wearing course	end-start	multi-layers	1	57	
79	clear away	landscape	general labourer	barchart	handover	start-end	none	1	57	

APPENDIX 6: VARIABLES CONSIDERED IN PREDICTIVE VALIDATION

1 TOTAL DURATION

1.1 Gross duration: (weeks)

1.2 Net duration (weeks)

2 PACE OF WORK

2.1 Foundation stage

2.1.1 Main variables

Total duration of activities: (weeks)

Peak rate: (houses/week)

Foundation-shell ratio:

Max foundation rate: (houses/week)

Most critical resource:

2.1.2 Allocation of resources

Excavation rate: (m³/week)

Formwork rate: (m³/week)

No. formwork joiners:

Concreting rate: (m³/week)

No. foundation bricklayers:

Brick/block amount: (m² equiv. half brick wall)

2.1.3 Foundation profile:

Foundation peak ratio:

Beginning-end ratio:

2.1.4 Foundation strategy:

Are temporary roads needed?

2.2 Shell/roofing stage

2.2.1 Main variables

Total duration of activities: (weeks)

Peak rate: (houses/week)

Shell/finishing ratio:

Max shell rate: (houses/week)

2.2.2 Allocation of resources:

Max. No. bricklayers:

Bricklayers' productivity: (m²/week)

Brick/block amount: (m² equiv. half brick wall)

2.2.3 Shell profile:

Shell peak ratio:

Beginning-end ratio:

2.3 Finishing stage

2.3.1 Main variables

Total duration of activities: (weeks)

Peak rate: (houses/week)

Max finishing rate: (houses/week)

Most critical resource:

Finishing complexity:

2.3.2 Allocation of resources

Management availability:

No. plasterers:

Plastering work content: (hours/house)

2.3.3 Finishing profile:
 Finishing peak ratio:
 Beginning-end ratio:

2.4 HANDOVER

2.4.1 Total duration: (weeks)

2.4.2 Handover profile:

3 ACTIVITY CONTENT

3.1 No. of activities:

3.2 Missing activities:

3.3 Redundant activities:

4 HOUSE COMPLETION TIME: (weeks)

4.1 Foundations: (weeks)

4.2 Shell/roofing: (weeks)

4.2.1 Brick/blockwork: (weeks)

4.3 First fix/plaster: (weeks)

4.3.1 Plaster: (weeks)

4.4 Second fix/finals: (weeks)

4.5 Buffers

4.5.1 Site preparation-foundations: (weeks)

4.5.2 Foundations-shell: (weeks)

4.5.3 Shell-first fix/plaster: (weeks)

4.5.4 First fix/plaster-second fix/finals: (weeks)

4.6 Different activity lead-lag times

5 DIFFERENT ACTIVITY DEPENDENCIES:

6 DURATION OF BAR CHART ACTIVITIES

6.1 Set up site: (weeks)

6.2 Clear site: (weeks)

6.3 Exc.&fill cellars: (weeks)

6.4 Site shaping: (weeks)

6.5 Vibro-compaction: (weeks)

6.6 Piling: (weeks)

6.7 Roads

6.7.1 Total: (weeks)

6.7.2 Base course: (weeks)

6.7.3 Others: (weeks)

6.8 Permanent kerbs: (weeks)

6.9 Wearing course: (weeks)

6.10 House external works: (weeks)

6.11 Public footpath: (weeks)

6.12 Service mains: (weeks)

BIBLIOGRAPHICAL REFERENCES

- AHUJA, H. & NANDAKUMAR, V. (1985). Simulation model to forecast project completion time. **Journal of Construction Engineering and Management**, New York, ASCE, 111(4): pp.325-342.
- ALEXANDER, J. H. et al. (1986). Knowledge level engineering: ontological analysis. In: FIFTH NATIONAL CONFERENCE ON ARTIFICIAL INTELLIGENCE, Philadelphia, USA, 11-15 Aug.1986. **Proceedings**. Philadelphia, AAAI. V.2, pp.963-968
- ALLAM, S. I. G. (1988). Multi-project scheduling: a new categorization for heuristic rules in scheduling problems. **Construction Management and Economics**, London, Spon, 6(2): pp.93-115.
- ALLWOOD, R. J. et al. (1985). **Evaluation of expert system shells for construction industry applications**. Loughborough, Univ. of Technology, Dept. of Civil Engineering.
- ALSHAWI, M. et al. (1990). The application of expert systems technology in project planning and control. In: INTERNATIONAL SYMPOSIUM ON BUILDING ECONOMICS AND CONSTRUCTION MANAGEMENT. Sydney, 14-21 Mar.1990. **Building Economics and Construction Management**. Design Economics and Expert Systems. Sydney, CIB & Univ. of Technology. V.2, pp.373-384
- ARDITI, D. (1985). Construction productivity improvement. **Journal of Construction Engineering and Management**, New York, ASCE, 111(1): pp.1-14.
- ARDITI, D. & ALBULAK, M. Z. (1986). Line-of-balance scheduling in pavement construction. **Journal of Construction Engineering and Management**, New York, ASCE, 112(3): pp.411-424.
- ASHLEY, D. B. & LEVITT, R. E. (1987) Expert systems in construction: work in progress. **Journal of Computing in Civil Engineering**, New York, ASCE, 1(4): pp.303-311.
- ATKIN, B. (1987) A time/cost planning technique for early design evaluation. In: BRANDON, P. S. (Ed.) **Building cost modelling and computers**. London, Spon. pp.145-153.
- ATTARWALA, F. T. & BASDEN, A. (1985) A methodology for constructing expert systems. **R & D Management**, 15(2): pp.141-149.
- BAKER, B. N. et al. (1979) The value of project planning and control techniques in perspective. In: SIXTH INTERNET CONGRESS, Munich, 1979. **Proceedings**. Munich, INTERNET. pp.27-36
- BASDEN, A. (1983) On the application of expert systems. **International Journal of Man-machine Studies**, London, Academic Press, 19: pp.461-477.
- BASDEN, A. et al. (1987) **Developing expert systems in wide and shallow domains**. Salford, Univ. of Salford, Dept. of Civil Engineering. Unpublished paper

- BASDEN, A. (1990) Towards a methodology for building expert systems. **Codex**. Uxbridge, Creative Logic, 2(1): pp.15-19.
- BEESTON, D. (1987) A future for cost modelling. In: BRANDON, P. S. (Ed.) **Building cost modelling and computers**. London, Spon. pp.17-24.
- BENNETT, J. & ORMEROD, R. (1984) Simulation applied to construction projects. **Construction Management and Economics**, London, Spon, 2(2): pp.225-263.
- BERRY, D. C. & BROADBENT, D. E. (1986) Expert systems and the man-machine interface. **Expert Systems**, Oxford, Learned Information, 3(4): pp.228-231.
- BERRY, D. C. & BROADBENT, D. E. (1987) Expert systems and the man-machine interface. Part two: the user interface. **Expert Systems**, Oxford, Learned Information, 4(1): pp.18-28.
- BIRREL, G. S. (1980) Construction planning - beyond the critical path. **Journal of the Construction Division**, New York, ASCE, 106(3): pp.389-407.
- BISHOP, D. (1965) **Labour requirements for house building: advantages of continuity of work and experience**. Garston, Building Research Station. Current Paper, Construction Series 18
- BISHOP, D. (1966) **Architects and productivity**. Garston, Building Research Station. Current Paper, Design Series 57
- BISHOP, D. (1972) Productivity in the building industry. **Philosophical Transactions of the Royal Society of London**, London, Royal Society, A272: pp.533-563.
- BISHOP, D. (1982) Productivity: whose responsibility? In: BRANDON, P. S. (Ed.) **Building cost techniques: new directions**. London, Spon. pp.27-39
- BORN, G. (1989) Guidelines for quality assurance of expert systems. **Specialist Group on Expert Systems Newsletter**, London, British Computer Society, 22: pp.25-43.
- BOUSSABAIN, A. & DUFF, A. R. (1990) Estimating activity durations by expert systems. In: SEVENTH INTERNATIONAL SYMPOSIUM ON AUTOMATION AND ROBOTICS IN CONSTRUCTION. Bristol, 5-7 June 1990. **Proceedings**. Bristol, CIB & Bristol Polytechnic. V.2, pp.629-636
- BRACHMAN, R. J. et al. (1983) What are expert systems. In: HAYES-ROTH, F. et al. (Eds.) **Building expert systems**. Reading, Massachusetts, Addison-Wesley. pp.31-57.
- BRANDON, P. S. et al. (1988) **Expert systems: the strategic planning of construction projects**. The RICS/ALVEY research for chartered quantity surveyors. London, RICS.

- BRANDON, P. S. (1990) Expert systems - after the hype is over. In: INTERNATIONAL SYMPOSIUM ON BUILDING ECONOMICS AND CONSTRUCTION MANAGEMENT. Sydney, 14-21 Mar.1990. **Building Economics and Construction Management**. Design Economics and Expert Systems. Sydney, CIB & Univ. of Technology. V.2, pp.314-344
- BREUKER, J. & WIELINGA, B. (1989) Models of expertise in knowledge acquisition. In: GUIDA, G. & TASSO, C. (Eds.) **Topics in expert system design**. Amsterdam, North-Holland. pp.265-295
- BROMILOW, F. J. (1978) Multi-project planning and control in construction authorities. **The Building Economist**: pp.208-213.
- BROMILOW, F. J. (1987) **Report on time and cost performance of Department of Housing and Construction building contracts**. Melbourne, CSIRO.
- BUCHANAN, B. G. et al. (1983) Constructing an expert systems. In: HAYES-ROTH, F. et al. (Eds.) **Building expert systems**. Reading, Massachusetts, Addison-Wesley. Ch.5, pp.127-167
- BUCHANAN, B. G. & SHORTLIFFE, E. H. (1984) The problem of evaluation. In: BUCHANAN, B. G. & SHORTLIFFE, E. H. (Eds.) **Rule-based expert systems**. The MYCIN experiments of the Stanford heuristic programming project. Reading, Massachusetts, Addison-Wesley. Ch.30, pp.571-588
- BUILDING RESEARCH STATION. (1956) **The programming of house building**. Garston. Digest No.91.
- BURTON, A. M. et al. (1989) A formal evaluation of knowledge elicitation techniques for expert systems: domain 1. In: MORALEE, D. J. (Ed.) **Research and Development in Expert Systems IV**. Cambridge, Cambridge Univ. Press. pp.285-286. British Computer Society Workshop Series.
- BUSINESS ROUNDTABLE. (1982) **Modern management systems**. In: BUSINESS ROUNDTABLE. **A construction industry cost effectiveness project report**. New York. Report A6
- CHRISTIAN, J. & CALDERA, H. (1989) The development of a knowledge based expert system for the selection of earthmoving equipment. In: TOPPING, B. H. V. **The application of artificial intelligence techniques to civil and structural engineering**. Edinburgh, Civil-comp. pp.55-59
- CHRISTIAN, J. & KALLOURIS, G. (1990) Predictive cost-time models for construction activities. In: INTERNATIONAL SYMPOSIUM ON BUILDING ECONOMICS AND CONSTRUCTION MANAGEMENT. Sydney, Australia, 14-21 Mar.1990. **Building Economics and Construction Management**. Managing Projects. Sydney, CIB & Univ. of Technology of Sydney. V.4, pp.157-168
- CIRIA (1983) **Buildability: an assessment**. London. Special Publication 26
- CLAPP, M. A. (1966) Weather conditions and productivity: detailed study of five building sites. **Building**, London, The Builder, 211: pp.171-180, 14 Oct.1966.

- CLAPP, M. A. (1978) **Bricklayers' labour and materials - a study of resource inputs and productivity.** Garston, Building Research Establishment. Note 177/78.
- CLEAL, D. M. & HEATON, N. O. (1988) **Knowledge based systems: implications for human-computer interfaces.** Chichester, Ellis Horwood.
- COHEN, P. R. & FIEGENBAUM, E. A. (1982) **The handbook of artificial intelligence.** London, Pitman. V.3
- COOKE, N. M. & McDONALD, J. E. (1986) A formal methodology for acquiring and representing expert knowledge. **Proceedings of the IEEE, New York, IEEE, 74(10): pp.1422-1430.**
- COOPER, C. N. (1989) **CRANES - a rule-based assistant with graphics for construction planning engineers.** In: TOPPING, B. H. V. **The application of artificial intelligence techniques to civil and structural engineering.** Edinburgh, Civil-comp. pp.47-54
- CREATIVE LOGIC. (1989) **Leonardo: User guide.** Uxbridge, Creative Logic
- DARWICHE et al. (1988) **OARPLAN: generating project plans by reasoning about objects, actions and resources.** **AI for Engineering Design, Analysis and Manufacturing, London, Academic Press, 2(3): pp.169-181**
- DAVIES, M. & HAKIEL, S. (1988) **Knowledge harvesting: a practical guide to interviewing.** **Expert Systems, Oxford, Learned Information, 5(1): pp.42-49.**
- DAVIS, E. W. (1974) **CPM use in top 400 construction firms.** **Journal of the Construction Division, New York, ASCE, 100(CO1): pp.39-49.**
- DE LA GARZA, J. M. & IBBS, C. W. (1987) **Issues in construction scheduling knowledge representation.** In: LANSLEY, P. R. & HARLOW, P. A. (Eds.) **Managing construction worldwide.** Systems for managing construction. London, Spon. V.1, pp.543-553
- DE LA GARZA et al. (1988) **Knowledge elicitation techniques for construction scheduling.** In: ADELI, H. (Ed.) **Micro-computer based expert systems in civil engineering.** New York, ASCE.
- DEPARTMENT OF ENVIRONMENT (1971). Directorate of Quantity Surveyor Development. **Cost consequences of design decisions.** Cost of Contractors' Operations (COCO). London.
- DUFF, A. R. (1980) **A stochastic analysis of activity duration.** **Construction Papers. Ascot, CIOB, 1(1): pp.63-69.**
- DUFF, A. R. et al. (1987) **Factors affecting productivity improvement through repetition.** In: LANSLEY, P. R. & HARLOW, P. A. (Eds.). **Managing construction worldwide.** Productivity and human factors in construction. London, Spon. V.2, pp.634-645

- * ECHEVERRY, D. et al. (1989) A knowledge based approach to support the generation of construction schedules. In: TOPPING, B. H. V. (Ed.) **Artificial intelligence techniques and applications for civil and structural engineers**. Edinburgh, Civil-comp. pp.115-122
- EDEN, J. F. (1972) The assembly process in house building. **Building**, London, The Builder, 222: pp.98-104, 23 June 1972.
- FENVES, S. (1987) Expert systems on civil engineering - state of the art. In: FOURTH INTERNATIONAL SYMPOSIUM ON ROBOTICS AND ARTIFICIAL INTELLIGENCE IN BUILDING CONSTRUCTION. Haifa, 22-25 Jun.1987. **Proceedings**. Haifa, TECHNION. pp.XV-XXXV
- FERRY, D. J. & BRANDON, P. S. (1980) **Cost planning of buildings**. 4 ed. London, Granada.
- FIKES, R. & KEHLER, T. (1985) The role of frame-based representation in reasoning. **Communications of the ACM**, New York, ACM, 28(9): pp.904-920.
- FIKSEL, J. & HAYES-ROTH, F. (1989) Knowledge systems for planning support. **IEEE Expert**, Los Alamitos, USA, IEEE Computer Society, 4(3):pp.16-23.
- FINE, B. (1977) **Production management**. London, Fine & Curtis.
- FINE, B. (1982a) The control of site costs. In: BURGESS, R. A. (Ed.) **Construction projects: their financial policy and control**. Harlow, Construction Press. pp.79-83
- FINE, B. (1982b) The use of simulation as a research tool. In: BRANDON, P. S. (Ed.) **Building cost techniques: new directions**. London, Spon. pp.61-69
- FINE, B. (1987) Kitchen sink economics and the construction industry. In: BRANDON, P. S. (Ed.) **Building cost modelling and computers**. London, Spon. pp.25-30
- FINLAY, P. N. & WILSON, J. M. (1987) The paucity of model validation in operational research projects. **Journal of the Operations Research Society**, London, 38(4): pp.303-308
- FINLAY, P. N. et al. (1988) The validation of expert systems - contrasts with traditional methods. **Journal of the Operations Research Society**, London, 39(10): pp.933-938
- FLANAGAN, R. (1980) **Tender price and time prediction for construction work**. Birmingham, University of Aston. Ph.D. Thesis.
- FLEMING, M. C. (1967) House building productivity in Northern Ireland. **Urban Studies**, Glasgow, Univ. of Glasgow, 4(2): pp.122-136.
- FORBES, W. S. (1969) **A survey of the progress in house building**. Garston, Building Research Station. Current Paper No.25/69
- FORBES, W. S. (1971) **Dimensional disciplines and the output of bricklayers: a case study**. Garston, Building Research Station. Current Paper No.34/71

- FORBES, W. S. & STJERNSTEDT, R. (1972) **The Finchampstead Project.** Garston, Building Research Station. Current Paper 23/72
- FORBES, W. S. (1977) **The rationalization of house building.** Garston, BRE. Current Paper No.48/77
- FRASER, R. & EVANS, R. W. (1980) A study of Scottish house building performance. **Construction Papers**, Ascot, CIOB, 1(2): pp.17-27.
- FUNDAÇÃO JOÃO PINHEIRO (1984). Diretoria de Projetos. **Diagnóstico Nacional da Indústria da Construção.** Relatório Síntese. 2 ed. Belo Horizonte. V.1
- GAINES, B. R. (1987) Foundations of knowledge engineering. In: BRAMER, M. A. **Research and Development in Expert Systems III.** Cambridge, Cambridge Univ. Press. pp.13-24. British Computer Society Workshop Series.
- GASCHNIG, J. et al. (1983) Evaluation of expert systems. In: HAYES-ROTH, F. et al. (Eds.) **Building expert systems.** Reading, Massachusetts, Addison-Wesley. Ch.8, pp.241-280
- GATES, M. & SCARPA, A. (1972) Learning and experience curves. **Journal of the Construction Division**, New York, ASCE, 98(CO1): pp.79-101.
- GILLIES, A. (1990) Software quality: a collaborative research project. In: ITI QUALITY WORKSHOP. Salford, Jan.1990. **Research Notes.** Salford, Univ. of Salford, IT Institute.
- GLEICK, J. (1987) **Chaos: making a new science.** London, Cardinal.
- GRAY, C. (1983) **Buildability - the construction contribution.** Ascot, CIOB. Occasional Paper No.29.
- GRAY, C. & LITTLE, J. (1985a) A systematic approach for the selection of an appropriate crane for a construction site. **Construction Management and Economics**, London, Spon, 3(2): pp.121-144.
- GRAY, C. & LITTLE, J. (1985b) **The classification of work packages to determine the relationship between design and construction.** Reading, Univ. of Reading, Dept. of Construction Management. Occasional Paper No.18
- GRAY, C. (1986) 'Intelligent' construction time and cost analysis. **Construction Management and Economics**, London, Spon, 4(4): pp.135-150.
- GRAY, C. (1987) Expert system development for predicting time of construction at the early design stage. In: BRANDON, P. S. (Ed.) **Building cost modelling and computers.** London, Spon. pp.429-440.
- GRAY, C. (1988) Integrated expert systems for modelling the construction management task. In: BRITISH-ISRAELI SEMINAR ON BUILDING ECONOMICS. Haifa, 26 May 1988. **Proceedings.** Haifa, TECHNION. pp.77-81
- GREEN, C. J. R. & KEYES, M. M. (1987) Verification and validation of expert systems. In: WESTERN CONFERENCE ON EXPERT SYSTEMS (WESTEX). Anaheim CA, USA, 1987. **Proceedings.** Anaheim, USA, IEEE. pp.38-43

- HAMILTON, G. & HARRISON, A. (1986) **Expert systems for the construction and building industry**. Bracknell, BSIRIA.
- HARMON, P. & KING, D. (1985) **Expert systems - artificial intelligence in business**. New York, John Willey.
- HARRISON, F. L. (1985) **Advanced project management**. Aldershot, Gower.
- HART, A. (1986) **Knowledge acquisition for expert systems**. London, Kogan Page.
- HART, A. (1990) Software quality - what and how? In: ITI QUALITY WORKSHOP. Salford, Jan.1990. **Research Notes**. Salford, Univ. of Salford, IT Institute.
- HAYES-ROTH, B. & HAYES-ROTH, F. (1979) A cognitive model of planning. **Cognitive Science**, New Jersey, Ablex, 3: pp.275-310.
- HAYES-ROTH, B. (1985) A blackboard architecture for control. **Artificial Intelligence**. Amsterdam, Elsevier, 26: pp.251-321
- HAYES-ROTH, F. et al. (1983) An overview of expert systems. In: HAYES-ROTH, F. et al. (Eds.). **Building expert systems**. Reading, Massachusetts, Addison-Wesley. pp.3-29.
- HEINECK, L. F. M. (1983) **On the analysis of activity durations**. Leeds, University of Leeds. Ph.D. Thesis
- HENDRICKSON, C. et al. (1987) Expert system for construction planning. **Journal of Computing in Civil Engineering**, New York, ASCE, 1(4): pp.253-269.
- HENDRICKSON, C.; MARTINELLI, D. & REHAK, D. (1987) Hierarchical rule-based activity duration estimation. **Journal of Construction Engineering and Management**, New York, ASCE, 113(2): pp.288-301
- HERBSMAN, Z. & ELLIS, R. (1990) Research of factors influencing construction productivity. **Construction Economics and Management**, London, Spon, 8(1): pp.49-61.
- HOC, J. M. (1988) **Cognitive psychology of planning**. London, Academic Press. Translated by C. Greenbaum.
- HOLLNAGEL, E. (1989) Issues in the reliability of expert systems. In: HOLLNAGEL, E. (Ed.) **The reliability of expert systems**. Chichester, Ellis Horwood. Ch.7, pp.168-209
- HORNER, M. W. & TALHOUNI, B. T. (1990) Causes of variability in bricklayers' productivity. In: INTERNATIONAL SYMPOSIUM ON BUILDING ECONOMICS AND CONSTRUCTION MANAGEMENT. Sydney, 14-21 Mar.1990. **Building Economics and Construction Management**. Managing the building firm. Sydney, CIB & Univ. of Technology. V.6, pp.238-250
- IBBS, C. W. (1986) Future directions for computerized construction research. **Journal of Construction Engineering and Management**, New York, ASCE, 112(3): pp.326-345.

- IBBS, C. W. & DE LA GARZA, J. M. (1987) Knowledge engineering for a construction scheduling analysis system. In: ADELI, H. (Ed.) **Expert systems in construction and structural engineering**. London, Chapman & Hall. pp.137-159
- JAAFARI, A. (1984) Criticism of CPM for project planning analysis. **Journal of Construction Engineering and Management**, New York, ASCE, 110(23): pp.222-233.
- JACKSON, M. J. (1986) **Computers in construction planning and control**. London, Allen & Unwin.
- JONES, P. F. (1978) Four principles of man-computer dialogue. **Computer Aided Design**, Guildford, IPC, 10(3): pp.197-202.
- KÄHKÖNEN, K. E. E. (1989) A knowledge based system approach to determine durations on site activities. In: TOPPING, B. H. V. (Ed.) **Artificial intelligence techniques and applications for civil and structural engineers**. Edinburgh, Civil-comp. pp.71-76
- KÄHKÖNEN, K. E. E. & ATKIN, B. L. (1990) Modelling activity dependencies for construction project planning. In: INTERNATIONAL SYMPOSIUM ON BUILDING ECONOMICS AND CONSTRUCTION MANAGEMENT. Sydney, 14-21 Mar.1990. **Building Economics and Construction Management**. Managing the building firm. Sydney, CIB & Univ. of Technology. V.6, pp.251-262
- KARTAM N. & LEVITT, R. E. (1989) Intelligent planning of construction projects. **Journal of Computing in Civil Engineering**. New York, ASCE, 4(2): pp.155-176.
- KIDD, A. L. & COOPER, M. B. (1985) Man-machine interface issues in the construction and use of an expert system. **International Journal of Man-machine Studies**, London, Academic Press, 22: pp.91-102.
- KIDD, A. L. & WELBANK, M. (1984) Knowledge acquisition. In: **Expert systems: state of the art report**. London, Pergamon. Ch.7
- * LANSDOWN, J. (1982) **Expert systems: their impact in the construction industry**. London, RIBA.
- LAUFER, A. & TUCKER, R. L. (1987) Is construction project planning really doing its job? A critical examination of focus, role and process. **Construction Management and Economics**, London, Spon, 5(3): pp.243-266.
- LAUFER, A. & TUCKER, R. L. (1988) Competence and timing dilemma in construction planning. **Construction Management and Economics**, London, Spon, 6(4): pp.339-355.
- LAW, P. et al. (1987) Death of a craftsman. **Building**, London, Building, 7481: pp.26-29.
- LEGARD, D. A. (1983) Probabilistic analysis of an idealized model of construction projects. **Construction Management and Economics**, London, Spon, 1(1): pp.31-45.

- LEMESSANY, J. & CLAPP, M. A. (1978) **Resource inputs to construction: the labour requirements of house building**. Garston, Building Research Establishment. Current Paper No.76/78
- LEOPOLD, E. & BISHOP, D. (1983a) Design philosophy and practice in speculative house building: part 1. **Construction Management and Economics**. London, Spon, 1(2): pp.119-144.
- LEOPOLD, E. & BISHOP, D. (1983b) Design philosophy and practice in speculative house building: part 2. **Construction Management and Economics**. London, Spon, 1(2): pp.233-268.
- LEVITT, R. E. & KUNZ, J. C. (1985) Using knowledge of construction and project management for automated schedule updating. **Project Management Journal**, 16(5): pp.57-76.
- LEVITT, R. E. (1986) Expert systems in construction. In: KIM, S. S. et al. (Eds.) **Survey of the state-of-the-art expert/knowledge based systems in civil engineering**. Champaign, Illinois, US Army Corps of Engineers. Ch.2.
- LEVITT, R. E. & KUNZ, J. C. (1987) **Using artificial intelligence techniques to support project management**. Stanford, Stanford University. Working Paper #1
- LEVITT, R. E. et al. (1988) Artificial intelligence techniques for generating construction project plans. **Journal of Construction Engineering and Management**, New York, ASCE, 114(3): pp.329-343.
- LEVITT, R. E. (1990) Knowledge planning systems: an engineering perspective. In: **FIRST INTERNATIONAL CONFERENCE ON EXPERT PLANNING SYSTEMS**. Brighton, 27-29 June 1990. **Expert planning systems**. London, IEEE. pp.181-185
- LOGCHER, R. D. (1987) Adding knowledge based systems technology to project control systems. In: O'CONNOR, M. J. & de la GARZA, J. M. (Eds.) **Proceedings of the workshop on expert systems for construction scheduling**. Champaign, Illinois, US Army Corps of Engineers.
- LOGCHER, R. D. (1989) Better AEC products: directions in research at MIT. In: **SYMPOSIUM ON CURRENT RESEARCH AND DEVELOPMENT IN INTEGRATED DESIGN, CONSTRUCTION AND FACILITY MANAGEMENT**. Stanford, USA, 28-29 Mar.1989. **Proceedings**. Stanford, Stanford University.
- LUDVIGSEN, P. J. et al. (1988) Formal evaluation of the knowledge based system DEMOTOX. **Journal of Computing in Civil Engineering**, New York, ASCE, 2(4): pp.398-412.
- LUMSDEN, P. (1968) **The line-of-balance method**. Oxford, Pergamon.
- MASON, D. (1984) The CPM technique in construction: a critique. In: **AACE. Transactions of the American Society of Cost Engineers**. Montreal. pp. E2.1-E2.10.
- McDERMOTT, J. (1981) R1's formative years. **AI Magazine**, 2(2): pp.21-29.

- McGARTLAND, M. R. & HENDRICKSON, C. (1985) Expert systems for construction project monitoring. **Journal of Construction Engineering and Management**, New York, ASCE, 111(3): pp.293-307.
- McLEISH, D. C. A. (1981) Manhours and interruptions in traditional house building. **Building and Environment**, Oxford, Pergamon, 16(1): pp.59-67.
- MITTAL, S. & DYM, C. L. (1985) Knowledge acquisition from multiple experts. **AI Magazine**, 6(2): pp.32-36.
- MOTTA, E. et al. (1989) A methodology and tool for knowledge acquisition in KEATS-2. In: GUIDA, G. & TASSO, C. (Eds.) **Topics in expert system design: methodologies and tools**. New York, North Holland. pp.297-322
- NATIONAL BUILDING AGENCY (1969) **Metric housing in brick: design guide**. London, NBA. V.1
- NATIONAL HOUSE BUILDING CORPORATION. (1990) **Private house building quarterly statistics**. London, NHBC, Quarter 1/1990.
- NAVINCHANDRA, D. et al. (1988) GHOST: project network generator. **Journal of Computing in Civil Engineering**, New York, ASCE, 2(3): pp.239-254.
- NEALE, R. H. & NEALE, D. E. (1989) **Construction planning**. London, Thomas Telford.
- NEWTON, S. (1986) **Design decision making and computer intelligence**. Portsmouth, Portsmouth Polytechnic.
- NUTTAL, J. F. (1965) **The control of repetitive construction**. Garston, Building Research Station. Current Paper, Research Series 34.
- O'BRIEN, J. J. (1984) **CPM in construction management**. 3 ed. New York, McGraw-Hill.
- O'KEEFE, R. M. et al. (1987) Validating expert system performance. **IEEE Expert**, Los Alamitos, USA, IEEE Computer Society, 2(4): pp.81-90.
- ORTOLANO, L. & PERMAN, C. (1987) Software for expert systems development. **Journal of Computing in Civil Engineering**, New York, ASCE, 1(4): pp.225-240.
- ORTOLANO, L. et al. (1990) Expert system for sewer network maintenance: validation issues. **Journal of Computing in Civil Engineering**, New York, ASCE, 4(1): pp.37-54.
- PARSONS, R. M. (1983) Is total CPM really the answer for super-projects? **Civil Engineering**. New York, ASCE, 53(11): pp.70-71.
- PEER, S. (1974) Network analysis and construction planning. **Journal of the Construction Division**. New York, ASCE, 100(CO3): pp.203-210.
- PIGOTT, P. T. (1972) **A productivity study of house building**. Dublin, An Foras Forbatha.

- PREECE, A. (1989) Verification of rule-based expert systems in wide domains. In: SHADBOLT, N. (Ed.) **Research and development of expert systems IV**. Cambridge, Univ. of Cambridge. pp.66-77. British Computer Society Workshop Series
- RODDICK, J. (1988) **The dance of millions**. Latin America and the debt crisis. London, Latin America Bureau.
- RODERICK, I. F. (1977) **Examination of the use of critical path methods in building**. Garston, BRE. Current Paper No.12/77
- ROTH, S. (1987) CALLISTO: an intelligent system for supporting project management. In: O'CONNOR, M. J. & DE LA GARZA, J. M. (Eds.) **Proceedings: Workshop on expert systems for construction scheduling**. Champaign, Illinois, US Army Corps of Engineers. pp.51-57
- ROYER, K. (1986) The federal government and the critical path. **Journal of Construction Engineering and Management**, New York, ASCE, 112(2): pp.220-225.
- SAGALOWICZ, D. (1984) Development of an expert system. **Expert Systems**, Oxford, Learned Information, 1(2): pp.137-141.
- SATHI, A. et al. (1986) Callisto: an intelligent project management system. **AI Magazine**, 7(4): pp.34-52.
- SCHUTZER, D. (1987) **Artificial intelligence; an applications-oriented approach**. New York, Van Nostrand Reinhold.
- SHADDAD, M. Y. I. & PILCHER, R. (1984) The influence of management on construction system productivity - towards a conceptual system causal research model. In: **FOURTH INTERNATIONAL SYMPOSIUM ON ORGANIZATION AND MANAGEMENT OF CONSTRUCTION**, Waterloo, Canada, Apr.1984. **Organizing and managing construction**. Computers and productivity. Waterloo, Univ. of Waterloo & CIB. V.2, pp.613-627
- SHANLEY, L. F. & KEARNEY, B. J. (1970) **An examination of labour content in house building**. Dublin, An Foras Forbatha.
- SHIPPAM, R. (1968) **House building productivity in USA**. Garston, Building Research Station. Current Paper No. 28/68.
- SLATTER, P. E. (1987) **Building expert systems: cognitive emulation**. Chichester, Ellis Horwood.
- SODIPO, K. O. (1987) **The application of Savoir to the decision making process in contract strategy**. Manchester, UMIST. Ph.D. Thesis.
- STALLWORTHY, E. A. (1979) Developments in project cost control. **Engineering and process economics**, Amsterdam, Elsevier, 4: pp.29-36.
- STEFIK, M. & BOBROW, D. G. (1986) Object-oriented programming: themes and variations. **AI Magazine**, 6(4): pp.40-62.
- STOCKLEY, J. E. (1987) Knowledge acquisition for expert systems. In: BRANDON, P. S. (Ed.) **Building cost modelling and computers**. London, Spon. pp.477-489

- STRETTON, A. & STEVENS, G. (1990) PREDICTE: an expert system for estimating indicative construction times for multi-storey buildings at concept stages. In: INTERNATIONAL SYMPOSIUM ON BUILDING ECONOMICS AND CONSTRUCTION MANAGEMENT. Sydney, 14-21 Mar.1990. **Building Economics and Construction Management**. Design Economics and Expert Systems. Sydney, CIB & Univ. of Technology. V.2, pp.590-601
- SUWA, M. et al. (1982) An approach to verifying completeness and consistency in a rule based expert system. *AI Magazine*, 3(4): pp.16-21.
- TATE, A. (1976) **Project planning using a hierarchic non-linear planner**. Edinburgh, Univ. of Edinburgh, Dept. of Artificial Intelligence. Research Report No.25.
- TATE, A. (1985) A review of knowledge based planning techniques. *The Knowledge Engineering Review*, Cambridge, Cambridge Univ. Press, 1(2): pp.4-17.
- TAYLOR, J. R. (1989) Control of software reliability. In: HOLLNAGEL, E. (Ed.) **The reliability of expert systems**. Chichester, Ellis Horwood. Ch.3, pp.37-63
- THOMAS, H. R. et al. (1986) Learning curve models of construction productivity. *Journal of Construction Engineering and Management*, New York, ASCE, 112(2): pp.245-258.
- THOMAS, H. R. & YIAKOUMIS, I. (1987) Factor model of construction productivity. *Journal of Construction Engineering and Management*, New York, ASCE, 113(4): pp.623-639.
- TRIMBLE, G. (1984) Resource-oriented schedule. *International Journal of Project management*, Guildford, Butterworth, 2(2): pp.70-74.
- TRIMBLE, G. (1986) Expert systems: some practical issues. In: HAMILTON, G. & WAGER, D. (Eds.) **Expert systems for construction and services engineering**. London, CICA & BSIRIA. pp.91-98
- UNITED NATIONS. (1965) Economic Commission for Europe. **Effect of repetition on building operations**. New York, UN.
- UNIVERSITY OF READING. (1981) Department of Construction Management. **Cost planning and computers**. Croydon, PSA.
- VERSCHUREN, C. P. (1984) Effect of repetition on the programming and design of buildings. In: FOURTH INTERNATIONAL SYMPOSIUM ON ORGANIZATION AND MANAGEMENT OF CONSTRUCTION. Waterloo, Canada, Apr.1984. **Organizing and Managing Construction**. Computers and productivity. Waterloo, Univ. of Waterloo & CIB. V.2 , pp.651-661
- WAGER, D. M. (1984) **Expert systems and the construction industry**. Cambridge, CICA.
- WALKER, A. (1971) A study of the variation of output in building operatives. *The Architect and Surveyor*, 16: pp.10-14.

- WARSZAWSKI, A. (1987) The potential contribution of novel information/automation technologies to the construction process. In: **FOURTH INTERNATIONAL SYMPOSIUM ON ROBOTICS AND ARTIFICIAL INTELLIGENCE IN BUILDING CONSTRUCTION**. Haifa, 22-25 June 1987. **Proceedings**. Haifa, TECHNION. pp.IX-XIV
- WARSZAWSKI, A. (1988) Expert systems for construction planning. In: **BRITISH-ISRAELI SEMINAR ON BUILDING ECONOMICS**. Haifa, 26 May 1988. **Proceedings**. Haifa, TECHNION. pp.82-99
- WATERMAN, D. (1986) A. How do expert systems differ from conventional programs? **Expert Systems**, Oxford, Learned Information, 3(1): pp.16-19.
- WATTS, R. (1987) **Measuring software quality**. Manchester, NCC.
- WATSON, I. et al. (1989) A knowledge analysis methodology using an intermediate knowledge representation based on conceptual graphs. In: **NINETH INTERNATIONAL WORKSHOP ON EXPERT SYSTEMS AND THEIR APPLICATIONS**. Avignon, 1989. **Proceedings**. V.1, pp.183-198
- WATSON, I. (1989) **A methodology for knowledge analysis**. Liverpool, Univ. of Liverpool. Ph.D. Thesis
- WAUGH, L. M. & FROESE, T. M. (1990) Constraint knowledge for construction scheduling. In: **FIRST INTERNATIONAL CONFERENCE ON EXPERT PLANNING SYSTEMS**. Brighton, 27-29 June 1990. **Expert planning systems**. London, IEEE. pp.114-118
- WEISS, S. M. & KULIKOWSKI, C. A. (1983) **A practical guide to designing expert systems**. London, Chapman & Hall.
- WELBANK, M. (1983) **A review of knowledge acquisition techniques for expert systems**. Ipswich, British Telecom.
- WHITE, A. (1985) The critical path method and construction contracts: a polemic. **Construction Management and Economics**, London, Spon, 3(1): pp.15-24.
- WIELINGA, B. J. & BREUKER, J. A. (1985) Interpretation of verbal data for knowledge acquisition. In: O'SHEA, T. (Ed.) **Advances in Artificial Intelligence**. Amsterdam, Elsevier. pp.3-12
- WIELINGA, B. J. & BREUKER, J. A. (1986) Models of Expertise. In: DU BOULAY, B. et al. (Eds) **Advances in artificial intelligence**. Amsterdam, North Holland. pp.306-318
- WIELINGA, B. J. & SCHREIBER, G. (1989) In: SHADBOLT, N. (Ed.) **Research and Development in Expert Systems VI**. Cambridge, Cambridge Univ. Press. pp.288-301. British Computer Society Workshop Series
- WIJESUNDERA, D. H. & HARRIS, F. C. (1989) The integration of an expert system into the construction planning process. In: TOPPING, B. H. V. **The application of artificial intelligence techniques to civil and structural engineering**. Edinburgh, Civil-comp. pp.31-37
- WILKINS, D. (1984) Domain independent planning: representation and plan generation. **Artificial Intelligence**, Amsterdam, North Holland, 22(3): pp.269-301.

YOUNG, R. (1989) Role of intermediate representations in knowledge elicitation. In: MORALEE, D. S. (Ed.) **Research and Development in Expert Systems IV**. Cambridge, Cambridge Univ. Press. pp.285-286. British Computer Society Workshop Series.